Concept Design of a Rock Handling System:

Feeding the Inclined Fall Pipe System aboard the Multipurpose Vessel 'Living Stone'

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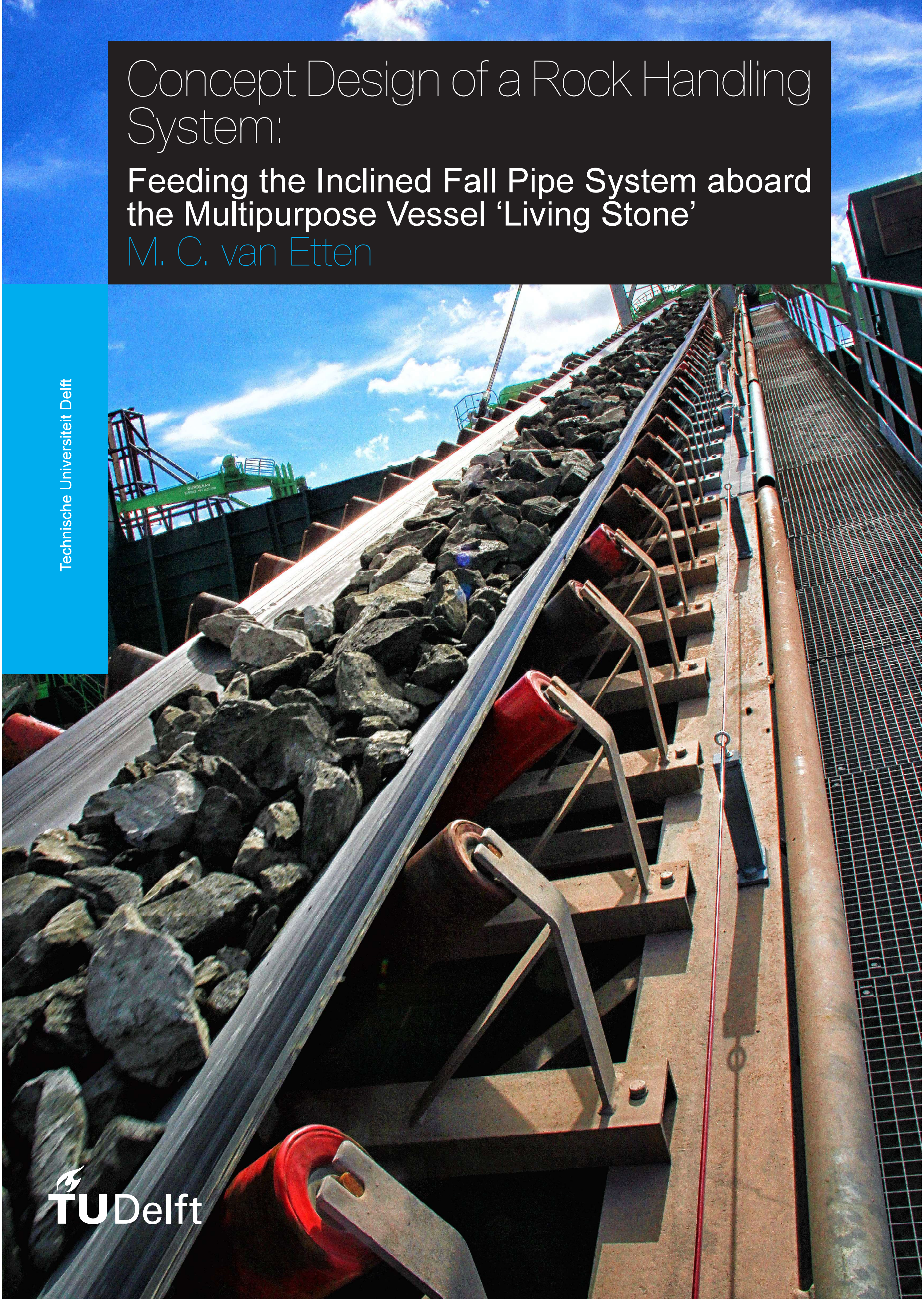

Concept Design of a Rock Handling System:

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by

M. C. van Etten

to obtain the degree of Master of Science
at the Delft University of Technology,
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This thesis is confidential and cannot be made public until June 22, 2022.

TU Delft

Preface

The thesis laying in front of you is submitted for the degree of Master of Science in Mechanical Engineering at the Delft University of Technology. While focussing on the track Transport Engineering over the last years, the interest in the offshore environment did not fade away. That is why I decided to look for a thesis combining the two fields of interest. I am grateful that Tideway Offshore Solutions gave me this opportunity including an unforgettable offshore experience.

I would like to express my gratitude to my graduation committee for their excellent guidance and feedback throughout the entire process of my MSc Project; Dr. Dingena Schott, Dr. Sape Miedema, Ir. Wouter van den Bos, Ir. Connie Visser and Ir. Joost de Haan. My sincere appreciation goes out as well to Prof. Gabriel Lodewijks for his advice and input during the first half of my thesis.

Furthermore, I would like to thank Ing. Tom van Uden for his input, assistance and discussions on the project as one of my supervisors at Tideway Offshore Solutions. Also within the company, my thanks goes out to Ir. Artur Izaak for all his help on Solidworks. To be honest, I have to thank the entire engineering department and Seahorse crew for the good talks, discussions on rock science, but most important the good laughs we had every now and then.

Finally, I want to use this possibility to say that the unconditional support of my parents, sisters, girlfriend and friends is worth a big thank you. Their loving support throughout all my studies made me able to realise all this.

Marc van Etten
Delft, June 2017

Summary

Erosion of the seabed around offshore structures, due to current and waves, is a common occurrence. Scour protection by rock placement can be done in order to limit erosion and its consequences. Tideway Offshore Solutions will use the multipurpose vessel 'Living Stone' to execute such rock placement operations. Aboard the Living Stone a newly designed inclined fall pipe system will be installed to transfer the rocks through shallow and possibly high current water towards the seabed. The goal of this thesis is to design a concept of a rock handling system to feed the inclined fall pipe system aboard of the Living Stone. The concept requires to be capable of handling armourstone with gradings up to 60-300kg and continuous mass flows up to — tonnes per hour.

With the use of the VDI 2221 design cycle the function, principle and solution structures were created to realise a morphological overview. Multiple concepts were created and evaluated on criteria including the maximum allowance of peak production, proven technology, maximum solvability, minimum required space and minimum costs. Thereafter, a preliminary layout was created for the concept ranked highest. In order to be sure the concept is capable of generating the demanded mass flows in terms of capacity and accuracy, discrete element modelling was used. With the use of EDEM-software the performance of the in Solidworks created model was studied. After calibration of the simulated material, the performance of the concept was tested by varying the outlet area and the feeders' velocity. This resulted in the associated mass flows and their fluctuations. The accuracy of the mass flow was defined as a percentage of the mass flow in which the flow fluctuated.

The configuration was studied and set for further simulations, using Box-Behnken design of experiments and Minitab-software. The mass flow, depending on the installed shear height and the velocity of the feeder, was validated with empirical theory for apron feeders. This work demonstrated that the ratio between the outlet area, defined as the outlet diameter but realised by the shear height and feeder width, and the maximum particle diameter is of great influence on the mass flow. The smaller the ratio, due to an increase of particle size and/or decrease in outlet area, the less accuracy of the simulated mass flow. The difference between the simulated and theoretical mass flow increases exponential with the decrease of the ratio between outlet diameter and maximum particle diameter.

This work shows that for the calculation of the mass flow, the value of the extraction efficiency factor depends on the ratio between outlet area and maximum particle diameter. It is advised to determine the extraction factor using the ratio. In order to generate a continuous mass flow, the work shows that the outlet diameter or width should be six times the maximum particle diameter. This was used to determine the required feeder width per maximum particle diameter.

It can be said that the inclined apron feeder concept design is the recommended concept design for a rock handling system to feed the inclined fall pipe system aboard of the Living Stone. It was demonstrated that the inclined apron feeder concept design can generate a continuous and accurate mass flows up to — tonnes per hours for gradings up to 10-60kg. Furthermore, it showed that it is capable of handling gradings up to 60-300kg armourstone, but not within the demanded accuracy. However, it is questionable if the demanded accuracy of 10% of the capacity is realistic for that grading.

Further work on the ratios larger than six is recommended. This will result in a better insight in the magnitude of the extraction efficiency factor for this application. Additionally, the effect of different particle size distributions, shapes and material on the performance of the apron feeder and the extraction efficiency are subjects for further work. Real life experiments with armourstone and the used particle size distribution need to be done to realise a more reliable validation of the work area and the extraction efficiency factor. Furthermore, it is recommended to perform real life experiments on the behaviour of armourstone on the chute and in the pipe. This way the mass flow via the chute and through the pipe can be studied within more detail to investigate the wear and tear of the system.

Contents

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List of Acronyms

AoR	angle of repose.
CoR	coefficient of restitution.
DEM	Discrete Element Method.
ELL	extreme lower limit.
EUL	extreme upper limit.
GEMM	Generic EDEM Material Model.
IFP	Inclined Fall Pipe.
IFPS	Inclined Fall Pipe System.
KPI	key performance indicators.
LT	length-to-thickness.
NLL	nominal lower limit.
NUL	nominal upper limit.
PSD	particle size distribution.
RHS	Rock Handling System.
RUL	reasonable upper limit.
tph	(metric) tonnes per hour.

List of Symbols

$A_{extraction}$	Area of the extracted rock bed $[m^2]$.
A_{outlet}	Area of the outlet $[m^2]$.
$B_{conveyor}$	Width of the conveyor $[m]$.
$C_{extraction}$	Extraction efficiency factor [-].
D_{50}	Mean diameter of the grading $[m]$.
D_{max}	Maximum particle diameter $[m]$.
D_n	Nominal particle diameter $[m]$.
$D_{particle}$	Particle diameter $[m]$.
M_{50}	Mean mass of the grading $[kg]$.
W_{15}	Weight of 15 percent of the grading $[kg]$.
W_{85}	Weight of 85 percent of the grading $[kg]$.
Ω	Feeder inclination factor [-].
Ψ	Release angle [°].
Θ	Inclination of the hopper measured vertically [°].
ρ_{bulk}	Bulk density of rock $[kg/m^3]$.
$\rho_{particle}$	Particle density of rock $[kg/m^3]$.
θ	Angle of inclination of the feeder [°].
d_{out}	Outlet opening diameter $[m]$.
g	Gravity $[m/s^2]$.
h_{shear}	Height of the shear bar $[m]$.
k_{Θ}	Hopper inclination factor [-].
k	Fitting parameter depending on the particle shape [-].
n_{RRM}	Uniformity index [-].
n	Porosity [-].
v_{feeder}	Velocity of the feeder $[m/s]$.

1 Introduction

This work is the result of the thesis done in cooperation between the Delft Technical University and the company Tideway Offshore Solutions, with the goal to design a conceptual bulk handling system.

1.1. Tideway Offshore Solutions

Tideway Offshore Solutions is a Dutch subsidiary company of the DEME-group located in Breda, the Netherlands. The Belgian company DEME operates in many fields, such as dredging & land reclamation, marine & offshore solutions, marine infrastructure and environmental solutions to name but a few. Tideway is specialised in offshore dredging, landfall construction, cable installation, seabed preparation, deep sea harvesting and rock placement operations. These operations focus on the oil and gas energy and the renewable energy market worldwide. For the rock placement operations, Tideway has four fall pipe vessels available for operation. The fall pipe vessel fleet consists of the Rollingstone, the Seahorse, the Flintstone and the newly built Living Stone. The latter was launched on September 18, 2016.

1.2. Scour protection

Applications for subsea rock placement can include multiple purposes. Protection of pipelines against damaging anchors and fishing nets, preparation of the seabed for pipe or cable laying and platform installation, and preventing scouring around maritime structures are examples of the applications.

The seabed around bottom founded structures such as offshore jackets and monopiles can be flushed away due to environmental conditions such as currents and waves, appearing in shallow water. This can cause instability of the oil-gas production platforms or wind turbines. In water with great depth the current on the seabed is not significant and not as strong as they could be closer to the surface. However in shallow waters, with a maximum water depth up to 50 meters, this is not the case. When the water depth decreases, the current close to the surface can now also have an effect on the seabed. These currents will have effect on the sub sea structure and the flows around it. In figure 1.1, the flows around a monopile in shallow water are shown, including the turbulent flow. These flows cause the scour around the structure. To prevent this, a range of rocks with certain size and weight can be installed around the foundation of a structure to protect the area around it from scouring.

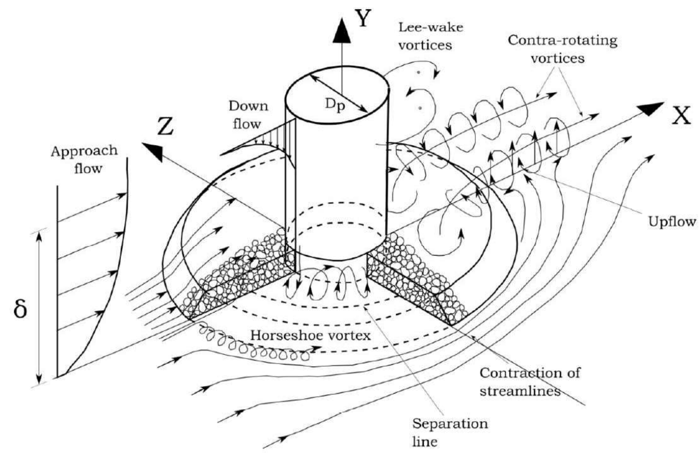

Figure 1.1: Current and waves around a structure causing scour

1.3. Rock placement

During the last decades rock placement, also known as rock dumping or rock installation, has been developed and executed for the offshore market. The type of rock installation can be categorized by the water depth of the operation. The two types are shallow water depths up to 50 meters and greater depth in the range of 50 meters and further. The deepest point of subsea rock placement is to a water depth of 2,200 meters.

1.3.1. Methods

Rock placement can be done in multiple ways using multiple types of vessels and equipment. As can be seen in figure 1.2 it can be performed by the use of a:

- Crane on a flat deck barge
- Side stone dumping vessel
- Split hopper barge
- Fall pipe vessel

The use of a crane on a barge or ship is useful in very shallow water but does not have a great capacity. Operations with greater capacity and in shallow water are more likely to be performed by the side stone dumping vessel and the split hopper barge. The disadvantage of these methods is the long free fall of the rock through the open water. In case of high current, which is not uncommon in shallow water, the rock can be drifted over a horizontal distance more than desired with a poor accuracy and precision as result. Furthermore, the approximate minimum distance between the vessel and the structure is 5 meter and therefore it is hard to place rocks close to the structure. Also a fall pipe vessel using the vertical fall pipe is not able to install the rock close to the target in shallow water, since the working area of the remotely operated underwater vehicle at the end of the fall pipe is limited in shallow water.

1.3.2. Inclined Fall Pipe

There is a method which is able to install rock with great accuracy and precision close to the structure in shallow waters. This can be done by the use of an Inclined Fall Pipe System (IFPS). The IFP is a pipe typically positioned under a certain angle which guides the rock through the water. This way the rock flow is protected against the current and since the allowable clearance of the pipe is only a few horizontal meters, it can guide the rock much closer to the structure. These two advantages improve the accuracy and precision of the operation. The lack of precision with side stone dumping is shown in figure 1.3. The lack of accuracy and precision due to current when using a side stone dumping vessel can be seen in figure 1.4. The solution to these problems is shown in figure **??**; the Inclined Fall Pipe. By using this system and installing rock onto the seabed with precision, the construction stability is ensured during its entire design life.

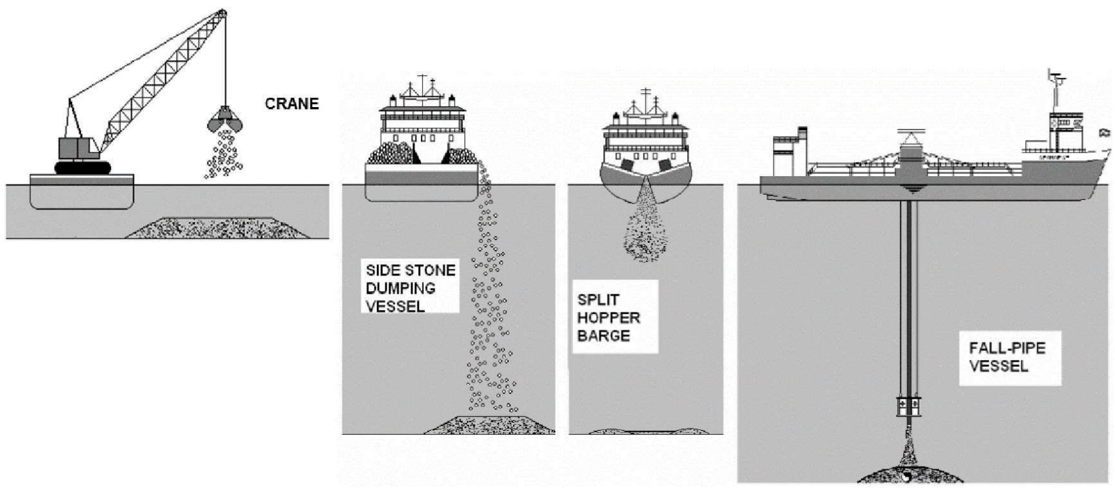

Figure 1.2: Rock placement methods

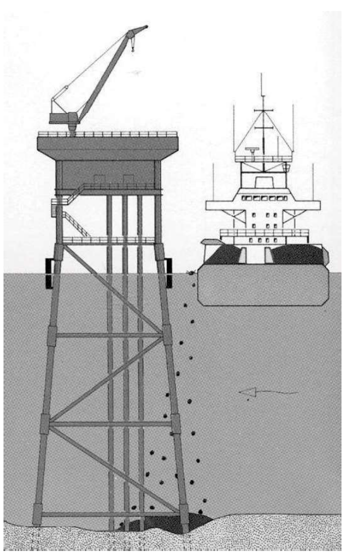

Figure 1.3: Side stone dumping

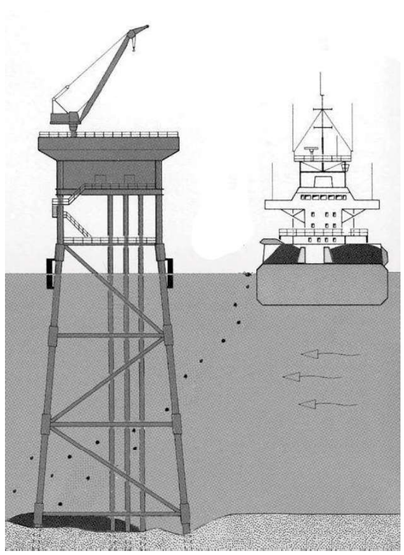

Figure 1.4: Side stone dumping with current

1.4. Living Stone

The Living Stone is the newest vessel of DEME and will be operated by DEME's Dutch subsidiary Tideway. This multipurpose vessel is one of the vessels servicing the offshore energy market. The Living Stone can be equipped with a vertical and inclined fall pipe system and two cable carousels, among other equipment.

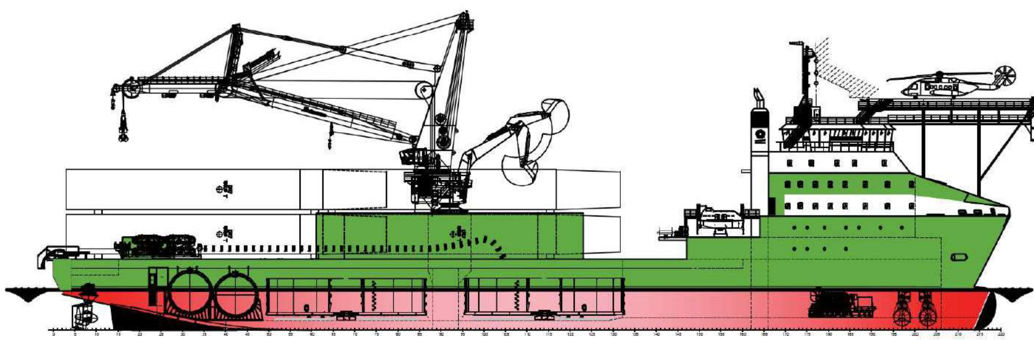

Figure 1.5: Cross section of the multipurpose vessel Living Stone

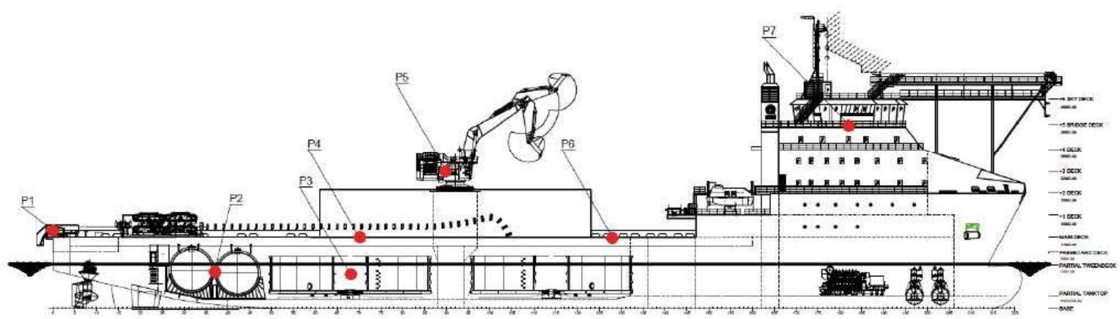

Figure 1.6: Cross section of the Living Stone with the rock placement configuration including the excavator

In figure 1.6 the cross section of the multipurpose vessel Living Stone with a rock placement configuration is shown. In this figure the following key operation equipment are shown per position and labelled below.

P1: Cable chute

P2: Cable carousel

P3: Hatch

P4: Excavator

P5: Inclined Fall Pipe system location

The newly designed IFPS and the to be designed Rock Handling System (RHS) during this thesis will both be installed on this vessel. The position for the location of the Rock hold, the excavator and the IFPS are fixed.

1.5. Problem description

A new Rock Handling System needs to be able to generate a continuous flow in order to feed the Inclined Fall Pipe System on the multipurpose vessel Living Stone. This system should be capable of handling an armourstone grading up to a range of 60 to 300 kg with a capacity of — (metric) tonnes per hour (tph) and a grading of 10 to 60 kg with — tph.

This last grading is taken into account in order to also be capable of handling the flow for a moon pool operation. Furthermore, the option to transfer the flow to the moon pool must taken into account.

The boundaries of this project, and the application of this system, are together the scope of this work. As the problem description already reveals, this work is about a new Rock Handling System to feed the Inclined Fall Pipe System and handle the flow required for the moon pool on the new multipurpose vessel. Both flows need to be controllable. This because the system is dependent of a possible fluctuating vessel velocity and different rock layer designs

The pieces of equipment used at the start and finish of the process, known as the Rock Hold and the Inclined Fall Pipe, have a fixed design and position. A note on that however, is that the walls facing the Inclined Fall Pipe System are removable and adjustable, and that the design of the chute on the Inclined Fall Pipe is not fixed.

Furthermore, the use of the Rock Handling System in combination with the Inclined Fall Pipe System is only investigated for shallow water.

1.6. Research question

The research question is the main question to which the thesis will provide an answer. The research question of this thesis is as follows.

- `What is a feasible conceptual design for a Rock Handling System to feed the Inclined Fall Pipe System for the multipurpose vessel Living Stone?`

In order to answer the main research question the following sub questions need to be answered. These questions are, together to the design cycle as discussed in the next chapter, the approach of this thesis will be introduced.

- `Which boundaries apply on the rock handling system?`
- `What systems can handle the applicable material flow?`
- `What are the criteria for this design?`
- `How to simulate and evaluate the dynamic behaviour of the material flow?`
- `What is the sensitivity of this system in terms of the flow limitations and system dimensions?`

1.7. Report outline

In the coming chapters, to begin with the second one, the material and equipment which is fixed for this problem will be looked into. In chapter 3, the concept will be generated. This starts with the design method, which will be used as the backbone for the concept realisation. Design specifications, function, principle, solution and module structures, are results needed to get to concepts. Furthermore, the concepts will be discussed and one final resulting concept will be picked. In the DEM chapter the validation will be discussed before the simulations will be introduced in chapter 5. In that simulations chapter the whole resulting flow through all pieces of equipment used will be investigated. Special investigation will be done on the flow through the hopper outlet. The other chapters will introduce the sensitivity of the results, followed by the conclusions and recommendations. The subquestions as formulated in section 1.6 are answered in the chapters as described below in table 1.1.

Table 1.1: Outline of the report

Subquestion	Chapter
Which boundaries apply on the Rock handling system?	2
What systems can handle the applicable material flow?	3
What are the criteria for this design?	3
How to simulate and evaluate the dynamic behaviour of the material flow?	4
What is the sensitivity of this system in terms of the flow limitations, system dimensions and ship motions?	6

2
Rock and equipment

The material to be handled in rock placement operations for scour protection is quarry stone. The rock can be loaded from in-harbour, offshore or permanent facilities into a single or multiple rock holds on the ship. Since this project is all about rock handling, it is important to know what material and its properties can be expected. Therefore, the rock, or for this application better known as armourstone, will be introduced in this chapter. Furthermore in this chapter, the equipment involved in this work will be discussed. This provides an insight in the boundaries and space of the system to be designed.

2.1. Armourstone

Armourstone is defined as coarse aggregates used in hydraulic structures and other civil engineering works [25]. The production of armourstone needs to be done according the standard `NEN-EN-13383`. Amongst other items, this standard includes the geometrical requirements and sample testing.

2.1.1. Grading

Suppliers of the armourstone are quarries all over the world. The production of rock is commonly done by drilling and blasting. Depending on the desired dimensions of the rock, the extracted raw material is resized by a crusher. After this stage, the rock is sorted into different grading by all types of sorters. The standard [25] divides armourstone products into three types of grading.

- `Coarse grading`
  This grading is the smallest grading for armourstone. Since the particles are that small, the grading curve for these gradings is obtained by sieve tests with sieves between 22.4 and 360 mm. The coarse grading starts at 45 to 125 mm and goes up to a maximum grading of 90 to 180 mm.

- `Light grading`
  The rock in this grading becomes too heavy to obtain a grading by sieve tests. Creating a grading curve is done by weighing the a minimum sample of 200 stones, depending on the grading. The light grading starts at 5 to 40 kg and knows a limiting 15 to 300 kg grading. The two gradings used in this project will be categorised in the Light grading, shown in figure 2.2.

- `Heavy grading`
  This grading includes the biggest sizes armourstone, starting with grading weight from 300 kg up to 15 000 kg. The samples to obtain a grading curve vary from 25 stones to 140 stones minimum.

In figure 2.2 all the gradings categorised as light grading are shown in the top row. However, these numbers are the nominal lower limit (NLL) and the nominal upper limit (NUL). As shown in figure 2.1 the grading curve also includes the extreme lower limit (ELL) and extreme upper limit (EUL). The corresponding values to these limits are given by figure 2.2. The corresponding column shows the allowable mass percentage of a rock with a lower or higher mass in the grading. For the 60 to 300 kg grading, rocks between 30 kg and 40 kg can occupy up to 5% of the total mass. On the upper limit, this means that up to 3 percent of the total mass can consist of rock with a mass of 450 kg or more. Take in mind that for example an uniform batch including only 120 kg rocks fits the 60 to 300 kg grading limitations.

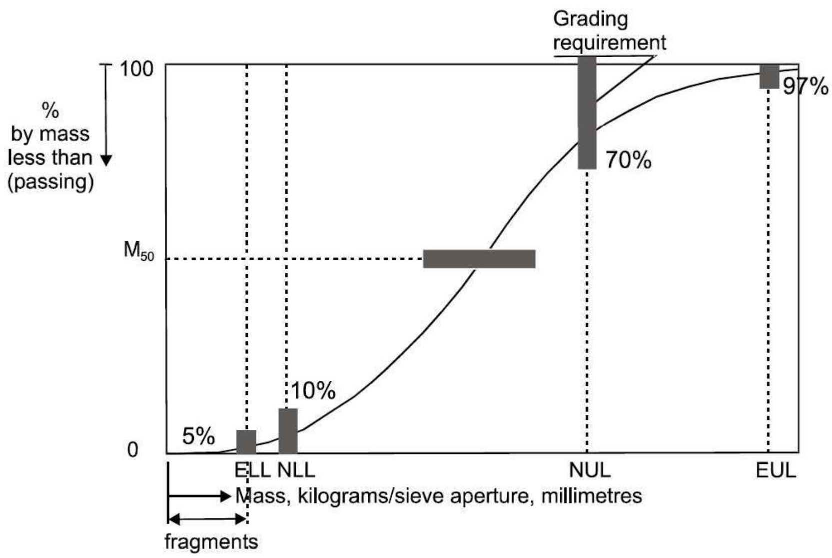

Figure 2.1: Limitations for a grading curve [5]

Grading kg	5 to 40	10 to 60	40 to 200	60 to 300	15 to 300
Category	$LMA_{5/40}$	$LMA_{10/60}$	$LMA_{40/200}$	$LMA_{60/300}$	$LMA_{15/300}$
Average mass kg	10 to 20	20 to 35	80 to 120	120 to 190	45 to 135
M_{50} kg	14 to 28	27 to 47	101 to 152	162 to 236	70 to 211
Mass kg	**Percentage (by mass) less than particle mass**				
450	-	-	-	97 to 100	97 to 100
300	-	-	97 to 100	70 to 100	70 to 100
200	-	-	70 to 100	-	-
120	-	97 to 100	-	-	-
80	97 to 100	-	-	-	-
60	-	70 to 100	-	0 to 10	-
40	70 to 100	-	0 to 10	-	-
30	-	-	-	0 to 2 [a]	-
15	-	-	0 to 2 [a]	-	0 to 10
10	-	0 to 10	-	-	-
5	0 to 10	-	-	-	-
3	-	-	-	-	0 to 2 [a]
2	-	0 to 2 [a]	-	-	-
1,5	0 to 2 [a]	-	-	-	-

[a] Fragments.

Figure 2.2: Requirements for mass distribution of category light grading [5]

In theory this means that in the worst scenario, a single stone can represent 3 percent of weight of the pile. Grading sample test for a light grading is done by testing a minimum of 200 stones with an average of 120 to 190 kg stones. This means that 3 percent of the total mass weight of a sample can be covered by the single stone of 1140 kg. In theory this is a stone allowed in the supplied pile of armourstone within the standard grading limits. In practice, a rule of thumb for a reasonable maximum weight of the biggest stone in the pile is twice the value of the NUL. The NUL for the 60 to 300 kg grading is 300 kg. Therefore, maximum weight of the heaviest stone in the pile can be 600 kg. This maximum weight is set as the maximum stone weight of the 60 to 300 kg grading and for this project called as the reasonable upper limit (RUL). Furthermore, grading curves can be obtained by the equation of Rossin-Rammler [5]. Using such curve provides more insight on the possible appearance of rock towards the grading limits. More on this grading curve can be found in section 4.3.2. Not only the biggest particles need to be taken into account, also the smallest. Since the smallest particles will always occur because of interaction between rock-rock and rock-equipment, the practical lower limit is almost dust. This means that the whole range of the particles occurring in this project are from almost 0 kg to 600 kg, a very wide range.

2.1.2. Length thickness ratio

Another production induced property is the length-to-thickness (LT) of the rocks. There are many types of shapes in a pile of rock and the lumps are often represented as cube shaped rocks. The LT-ratio is one of the other geometrical requirements in the standard `NEN-EN-13383`. As figure 2.3 shows, this ratio is defined as the maximum length of the lump, divided by its minimum distance, between parallel lines through which the particle would just pass. The distribution of LT-ratio of the supplied armourstone differs per quarry. Following the standard, the supplied armourstone grading can have up to 20 percent of the rock mass with a LT-ratio larger than 3. This means that 20 percent of the supplied mass, may have an even larger ratio. In fact, the LT-ratio for that allowable 20 percent is unlimited. For the 60 to 300 kg grading quarries often use grizzles to remove undersized material, and the eye selection to remove oversize material. Eye selection is also used to remove armourstone with a high ratio of LT [30]. Furthermore, due to transportation and handling, heavy boulders with LT ratio larger than 3.5 break easily and are therefore scarce. An average LT-ratio for the 10-60kg grading is 2.27 and for gradings including heavier rocks this ratio decreases [19]. The calculation for this LT-ratio including its maximum length of a rock can be found in appendix **??**. To use an image, in figure 2.3 a rock with different LT-ratios is given.

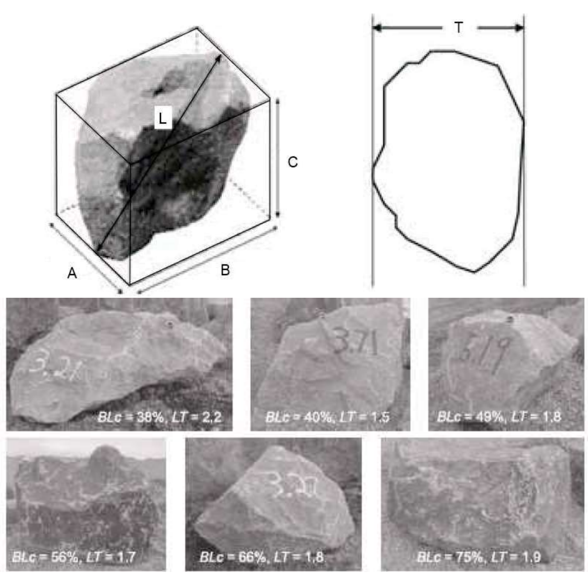

Figure 2.3: Multiple rocks with different LT-ratios [5]

2.1.3. Density

A material property independent of the rocks production is the density. The density of armourstone can be separated into normal and high density rock. Examples of normal density rock are Granite and Limestone. For high density, Olivine and Eclogite are used. Furthermore, the rock has a particle ($\rho_{particle}$) and bulk density (ρ_{bulk}). Typically, the porosity (n), of the the rock at a pile is equal to 40 percent, which is used to determine the bulk density by multiplying (1 - n) with the $\rho_{particle}$. The values for the armourstone density is shown in table 2.1.

Table 2.1: Typical density of the armourstone

	Normal density	High density
$\rho_{particle}$	2650 $[kg/m^3]$	3100 $[kg/m^3]$
ρ_{bulk}	1600 $[kg/m^3]$	1860 $[kg/m^3]$

2.1.4. Gradation

Another characteristic of the grading curve is how wide the curve or grading is. This is determined by diving the mass of 85 percent, W_{85}, by the mass of 15 percent of the grading, W_{15} [30]. For the light grading 60 - 300 kg used in this project the gradation has for W_{85}/W_{15} of 2.8 - 6.0. For the grading 10 - 60 kg, this value is 3.2 - 7.7. This means that both gradings have a wide gradation as these values are within the range of 2.7 - 16.0, shown in table 2.2 [30]. A term for gradings of armourstone with a wide gradation is 'riprap'.

Table 2.2: Types of gradation [30]

	W_{85} / W_{15}
Narrow gradation	1.7 - 2.7
Wide gradation	2.7 - 16.0
Very wide gradation	16.0 - 125+

2.2. Equipment

Most of the equipment on board of the Living Stone is already designed and ready to be implemented. The designs of equipment and their position are fixed. However, there are some parts that can easily be adjust without consequences. The design and the boundaries of the components involved in this work will be discussed.

2.2.1. Rock Hold

The rock hold on the Living Stone has a capacity of 12,000 tonnes, equal to 7,700 m^3. As mentioned in chapter 1.5, the problem description, not all walls of the rock hold are fixed. The walls facing the IFPS, in figure 2.9 coloured in yellow, can be adjusted and are removable. The walls on the side of the vessel are not adjustable since, walkways and other constructions are implemented.

2.2.2. Excavator

The excavator which is going to be installed in the middle of the rock hold is a Liebherr excavator with a — m^3 bucket with a width of — meter. Figure 2.4 shows the given average cycle time of the excavator provided by the supplier, divided in the processes. On the very right side in the same figure, the calculated cycle time depending on the excavator's rotation based on the slew speed is shown [2] [20]. The supplied average cycle time is calculated based on an offload point at one side of the rock hold halfway its height. This results in an average production estimation of — tph, including the bucket fill factor of 0.95 and operator efficiency factor of 0.90. A side note to these factors is that the bucket fill factor is more likely to be lower since this has a value between 0.7 and 0.9 for well blasted rock [24]. Per created concept the cycle time will be looked into. Together with figures 2.6 and 2.7 it can be seen if a buffer is required in advanced or not. The cycle time will be investigated in chapter 3.6.

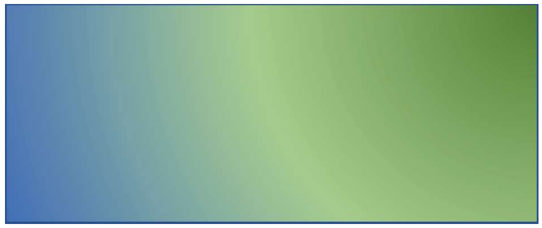

Figure 2.4: The average cycle time of the excavator per process (left) and the cycle time per angle of rotation (right)

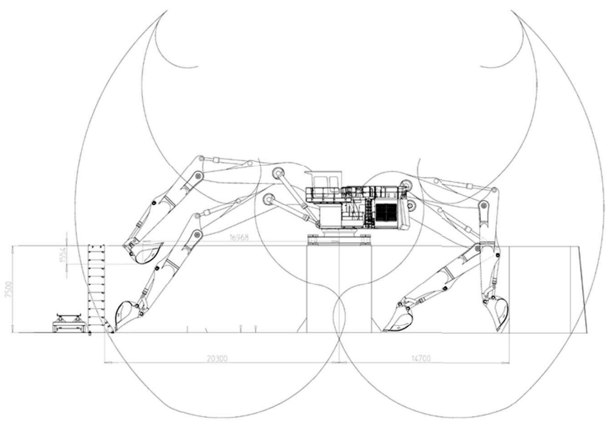

Figure 2.5: Reachable area of the Liebherr Excavator

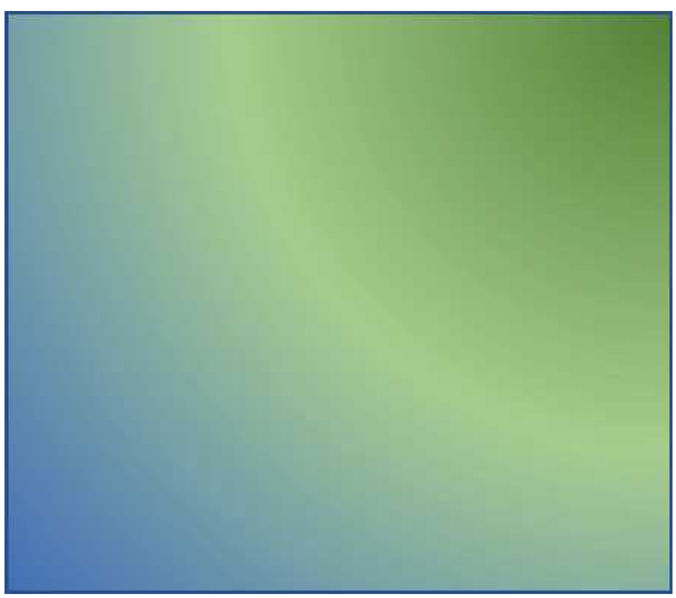

Figure 2.6: The required hopper volume per cycle time to generate — tph over the operation time within the reach of 90°

Figure 2.7: The required hopper volume per cycle time to generate — tph over the operation time within the reach of 180°

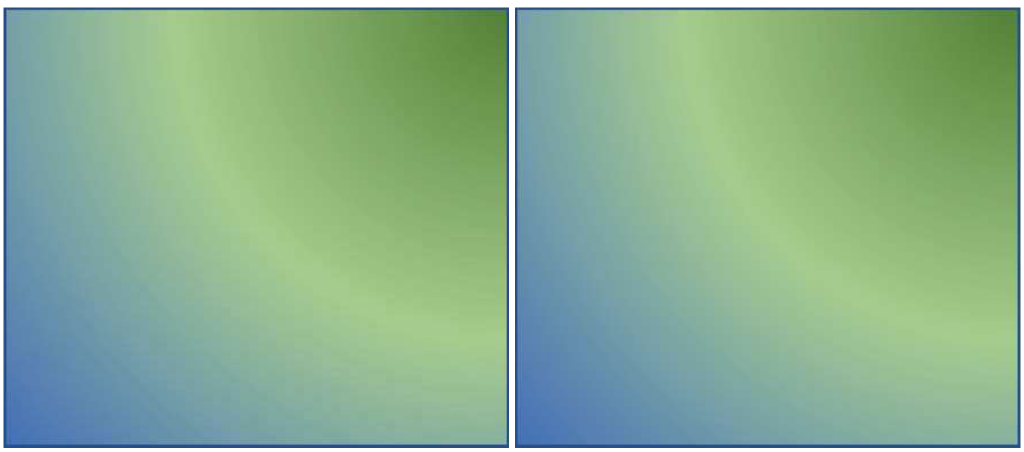

Figure 2.8: Area to keep clear around the IFP in red

2.3. Summary

This chapter provides an answer to the first sub question:

- `Which boundaries apply on the rock handling system?`

The boundaries of the system were defined as the grading of the armourstone and limitations aboard of the vessel. According to the standard `NEN-EN-13383`, there is no absolute upper limit of the grading. However, a reasonable upper limit of the largest rock occurring in the grading is twice the extreme upper limit of that grading. This is within the limits of a grading curve when using the Rosin-Rammler curve. These upper limits for the grading are based on the weight of the rock. However, the LT-ratio of the armourstone is another characteristic of the rock. An average of 2.27 was found but higher LT-ratios up to 3.5 can appear for individual rocks as well.

The limitation aboard on the Living Stone were defined as the fixed locations of the rock hold, the inclined fall pipe system and the excavator. Limitations on the excavator are in terms of its maximum reach and cycle time. For the inclined fall pipe system an area to be kept clear around the structure needs to be taken into account.

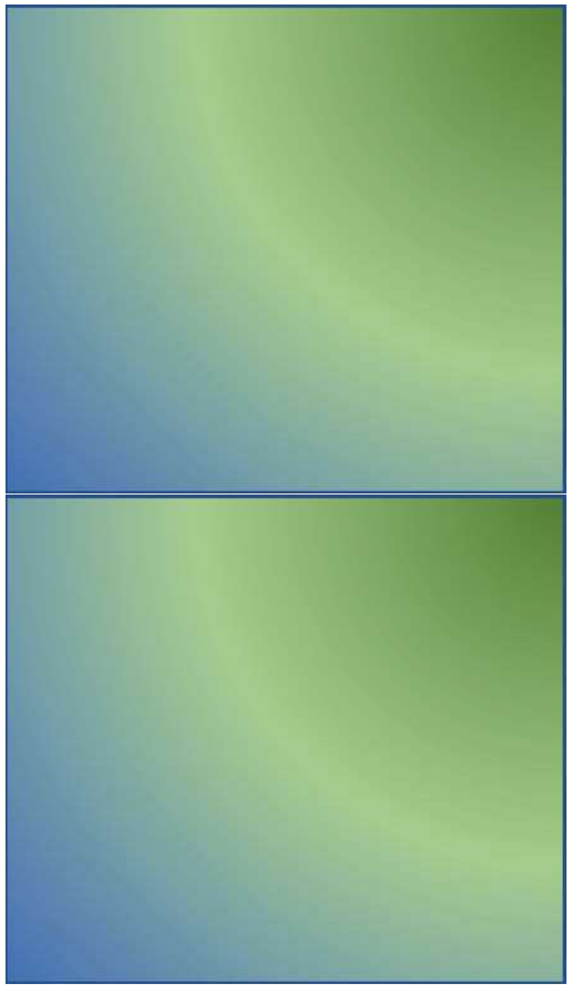

Figure 2.9: Left: IFPS not in use. Right: IFPS used

3
Concepts

This chapter will lead to the final concept which will be worked out in further detail and implemented in DEM. First a design method is picked and this will be the backbone of this chapter in order to get to the final concept.

3.1. Method

For this work a design cycle with detailed stages and results is used. This is the VDI 2221, a systematic industry-independent approach to the development and design of technical systems and products created by the "Verein Deutscher Ingenieure".This design method has been developed over the past 50 years. The VDI 2221 design cycle can be seen in figure 3.1.

During the first stage of this design method, section 3.2, the task of the design needs to be clarified and defined. This leads to a better understanding of the system and its functions. Basic calculations will provide a valuable insight in the design requirements. This will be the result of this first stage; the specification. The specifications will include all the design criteria, which will be used to evaluate the concept design(s).

In the second stage of the VDI 2221 design method, the functions of the concept design will be investigated. This is done by dividing the (current solution) systems into their functions, as shown in section 3.3. The result of this stage is a functional structure which will function also as the basis of the morphological chart.

During the third stage, section 3.4, a search of solution principles and their combination will be performed. The morphological chart will now get the different types of solutions for each function. This morphological chart is filled and this results in the principle solutions.

In stage four, section 3.5, multiple concepts will be selected by dividing the solutions in realizable modules. By connecting the realizable solutions the concepts will be shown in the module structure.
The fifth stage of this work is shown in section 3.6. The demands and wishes will be considered and further calculations will be done and one concept will be picked.

In the final stage, key parameters in the chosen concept are investigated and the final model is created before it will be implemented into DEM.

After this stage the concepts is validated by looking into the performances in terms of the mass flow and its fluctuation. This will be done from chapter 4.
By following this design process, the sub questions and eventually the main research question will be answered and a feasible concept will be produced.

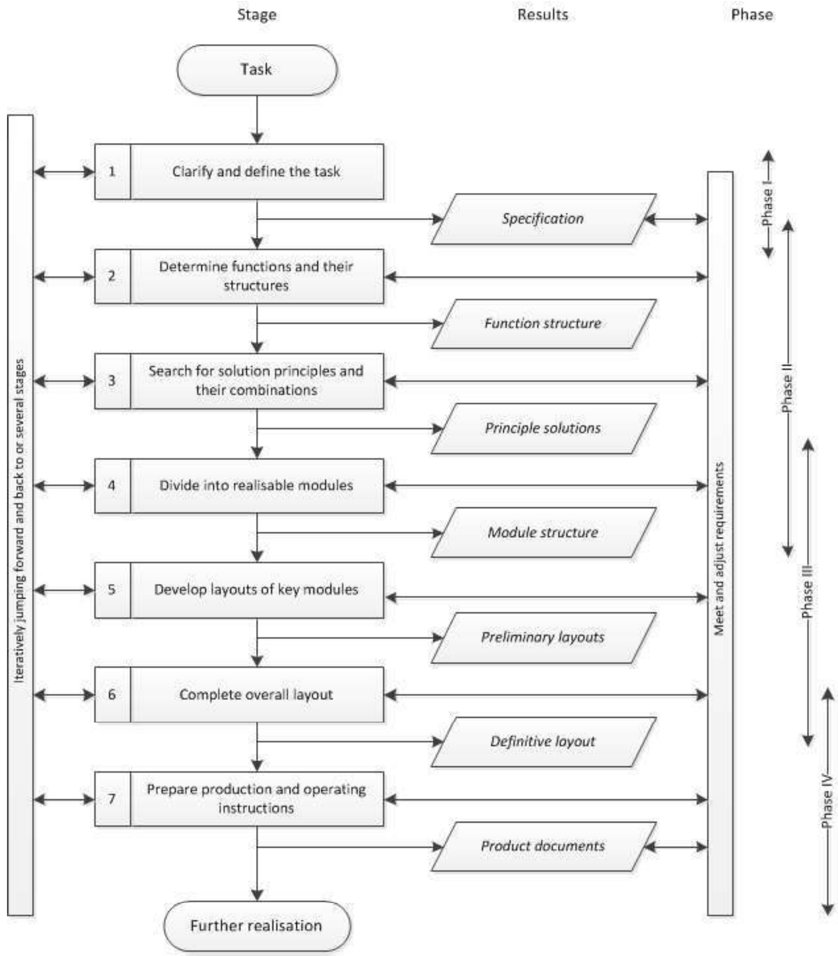

Figure 3.1: VDI 2221 design cycle

3.2. Design Specifications

For the design specifications, requirements are divided in demands and wishes. Most of the fixed requirements, or so called demands, are already mentioned in the research questions. The list of all demands is as follows:

- `Rock size`
  There are two armourstone gradings applicable for this RHS. The first one is the 60 to 300 kg grading, used for the IFPS. The second one is the 10 to 60 kg grading, used for the vertical fall pipe. The armourstone limits are discussed in section 2.1.1 and section 2.1.2. The most important one is the maximum possible rock weight up to 600 kg. An LT-ratio of 3.5 will be taken into account for this already scarce rock.

- `Capacity`
  Both grading have their own application and therefore, their own capacity. The corresponding capacities are — tph and — tph. It is expected that a capacity peak of — tonnes per hour for one hour can be useful for —% of the projects. The capacities per grading are listed in table 3.1. For the 10 to 60 kg grading the maximum capacity of — tph is required for at least — minutes. In between peak hours at — tph, a capacity of — tph is required.

With these requirements, there are limitations involved as well. Next item will introduce these limitations.

Table 3.1: Capacity requirements

Grading	Tonnes per hour	Cubic meters per hour	
		Normal density rock	High density rock
60-300 $[kg]$	— $[t/h]$	— $[m^3/h]$	— $[m^3/h]$
10-60 $[kg]$	— $[t/h]$	— $[m^3/h]$	— $[m^3/h]$

- Location limitations
  The design of this RHS is free but some of the components used by this system are fixed. The input and output of the system, known as the location of the excavator, the rock hold and the inlet of the IFP are fixed. Another criteria is that the excavator operator has to be able to see what he is doing. Therefore, there is a maximum height of the system of 11.5 meter measured from the main deck. Another important parameter to take into account is the maximum reach of the excavator. The reachable area for offloading the bucket is the area in red in figure 3.2. Furthermore, the equipment need to be installed and operate on-board of the vessel and not hanging over the sides. As well as the area around the IFPS needs to be cleared as shown in figure 2.8

Figure 3.2: Side and top view of the initial situation: the red offload area of the excavator from the centre of the rock hold.

The wishes for this project are the following. These will be taken into account when a choice between concepts have to be made.

- Proven technology
  It is desirable that the concept for this RHS uses proven technology. This means that the solution or sub solution does not need further research to investigate if that technology will work for this application or not. This includes the system's robustness and reliability.

- Maximum solvability of blockage
  The supplied batch with a certain rock grading quality can have a certain range within the limit of the standard. Despite the check by eye, it can happen that in the 12000 tonnes, some odd rocks are included. The system must be able to fix an unexpected blockage.

- `Maximum allowance of peak production`
  The requirement of the peak production is set at — tonnes for one hour. However, different concepts can have different allowance in this peak production. Some concepts will be able to handle setbacks better than others. Setbacks as for example a lower bucket fill factor might occur during production.

- `Minimum costs`
  The costs of the solution must be as low as possible. This involves the purchase, installation and operational costs.

- `Minimum space`
  The required space per concept is of influence as well. Especially for concepts within the rock hold, occupying large space will decrease the vessel capacity. Besides that, since the vessel is for multipurpose and installations need to be removable, it is desirable to realise a compact system.

3.3. Functions

The second stage of the VDI 2221 design cycle is to determine the functions and their structure. This results in a function structure. For Bulk Handling there are four different functions [22], known as:

- `Storage`
  This function is the beginning and the end of the bulk handling process. This is categorized by a velocity and acceleration equal to zero. In this project the bulk starts at the rock hold and finishes on the seabed. Therefore, the rock hold and the seabed both have the storage function.
- `Transshipment`
  This function is the start of the motion of the bulk. Therefore, both the velocity and acceleration moves from or to zero, in order to move the bulk from or to the storage. A piece of equipment with the transshipment function is for example an excavator with a poly grab.
- `Transfer`
  In case of a transition of the bulk material between two pieces of equipment the transfer function comes in. At this point the direction of the bulk flow commonly changes. That is why the velocity is bigger than zero and the acceleration is not equal to zero. A hopper or chute are pieces of equipment that take the transfer function.
- `Transportation`
  The Transportation function is mostly responsible for the moving the bulk over greater distances. The velocity of transportation is constant and larger than zero. Well known pieces of equipment for the transportation function, producing constant velocity over great distance are conveyors.

The order of the function can be set as above, but is not fixed yet. The general function of the vessel and the functions in more details on the new Living Stone and the vessels Rollingstone and Seahorse, are shown in appendix **??**. The rock hold functioning as the storage and the IFPS functioning as the last transshipment are fixed. The functions in between are not fixed. This list and logical order of functions will create the function structure, the result of this stage. The next stage will investigate the principle behind those functions. It can happen that equipment can have multiple functions. For this application it can be useful to designate the rock hold the functions of storage and transfer if possible.

3.4. Principles and solutions

With stages 3 and 4 of the VDI 2221, the principles and the corresponding solutions will be investigated. Per function one or more principles can be found and for each principle multiple solutions can be found. The result of the stages are the functional structure, the principle structure and the principle solution structure. These structures combined is the morphological overview. This can be seen in figure 3.4. All the principle solutions must be capable of handling the rock flow and the rock grading as discussed in chapter 3.2. The remaining principle solutions will be discussed below.

3.4.1. Transshipment: Bucket

The disadvantages of the use of a polygrab are shown at the Seahorse vessel. Segregation in the flow and leftovers in the rock hold will occur when a polygrab is used. Therefore, the excavator will use a bucket to move the rocks around the rock hold.

3.4.2. Transfer: Hopper

For the transfer function the principles and their corresponding solutions are limited. In this project the transfer function is the process where a batch process turns into a continuous process. Often this is done by implementing a hopper. The transfer function can also be seen as a chute, directing the material flow. This is the case at the end of the designed RHS before the rock enters the IFPS. Also, the hopper location is not fixed and could move around possibly decreasing cycle times.

3.4.3. Transportation: Conveyor

There are multiple tens of types of conveyors used in varying industries. Troughed belt, bucket, sandwich and pouch conveyors to name but a few. However, for this application the industries and so the equipment handling the material are limited. Bulk flow with these gradings are often handled by wheel loaders, like it is done in the quarries. Most often the material is crushed and reduced in size before transportation on a conveyor to reach the — tonnes per hour in a continuous process. Equipment used in for instance the mining industry can handle such material flow. Vibratory feeder, low profile feeders, apron feeders and other chain conveyors as shown in figure 3.3 can be applicable to this work.

Figure 3.3: Top: Vibratory feeder [23](left), Low profile feeder [34](right), Bottom: Chain conveyor [17](left), Apron feeder [23](right)

3.5. Concepts

The multiple possibilities are shown in the morphological overview in figure 3.4. The overview is based on the function structure, the principle structures and the solutions.

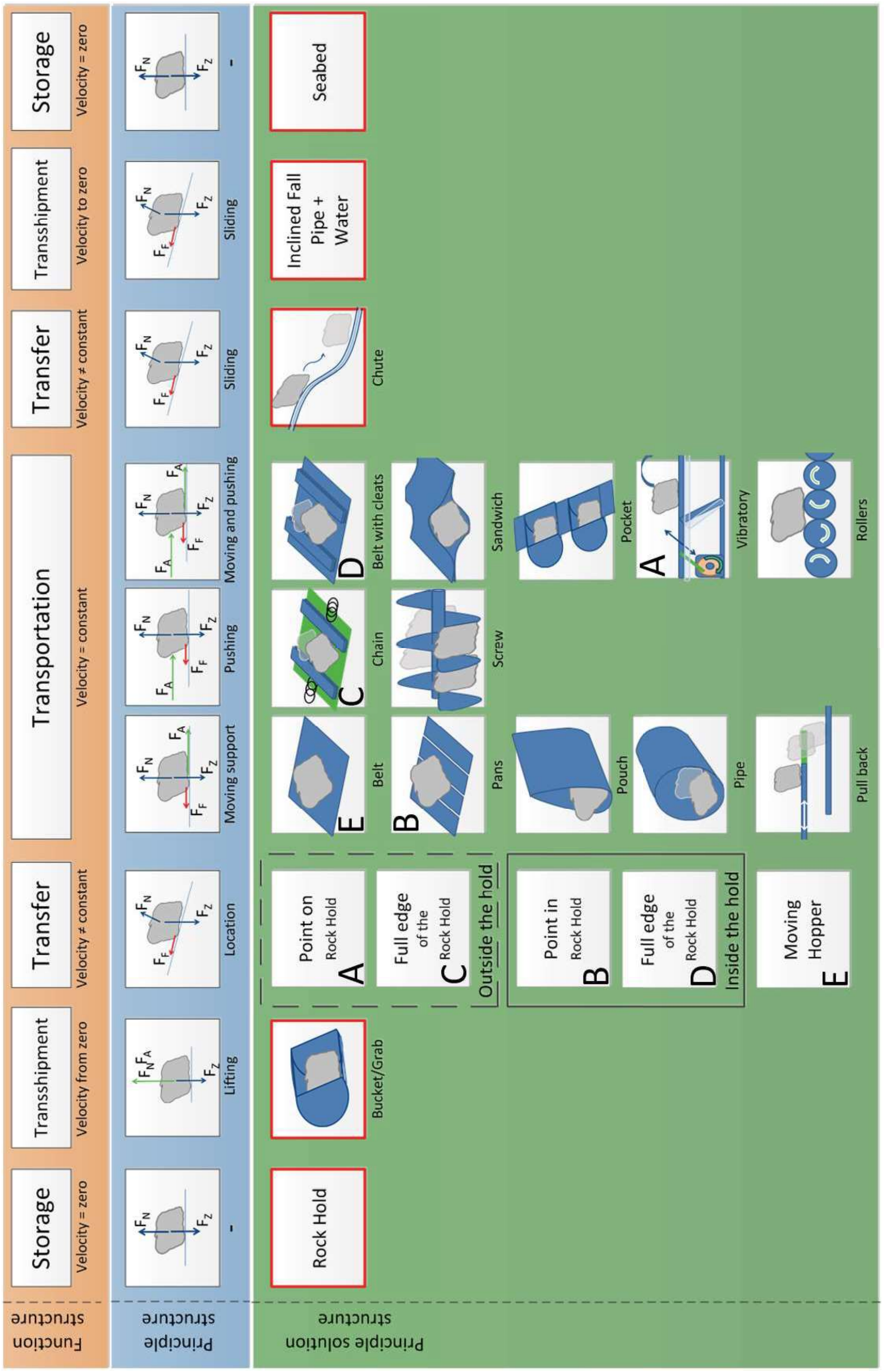

Figure 3.4: Morfological overview with letters A till E for the transfer and transportation function, corresponding to the concepts as introduced in this section

The main difference between the concepts is the location of the transfer function, known as the hopper. The five concepts are explained briefly and are accompanied with figure 3.5 through 3.9.

- Concept A
  - Hopper at one point outside the rock hold's volume
  - Vibratory feeder

  The first concept is comparable with current rock placement vessels as it has a hopper (1) located on top of the rock hold. Advantage is that there is no space occupied in the rock hold by this system. However, because it is placed on top of the rock hold the cycle time increases due to the high precision and accuracy of the operating process compared to the initial cycle. The cycle time also increases due to the fact that the boom lifting/lowering and stick extending/retraction motion of the excavator takes more time. Another downside of this system is when a blockage occurs. For this system multiple conveyors can be used. Vibratory feeders extracting the material out of the hopper is a likeable option.

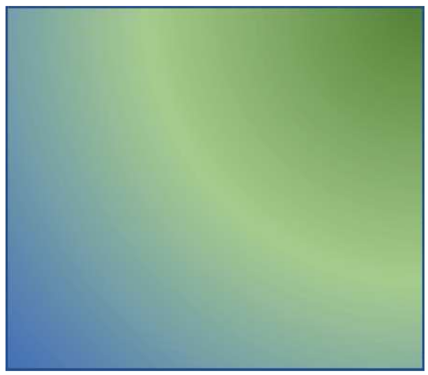

Figure 3.5: Concept A

- Concept B
  - Hopper at one point inside the rock hold's volume
  - Apron feeder

The second concept includes a small hopper inside the rock hold's volume in the extraction area (1). Since the material is already there, the material will be extracted by the apron feeder (2), while a decreasing pile on top of the apron feeder is fed by the excavator. An advantage for the excavator operator is that there is less need to offload with accuracy and precision. This results in shorter cycles. In comparison with the other concepts, the pile in the hopper can be reached by the excavator. In case of a blockage due to whatever reason, this can be solved with the help of the excavator.

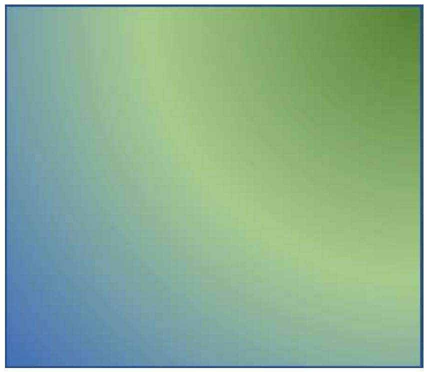

Figure 3.6: Concept B

- Concept C
  - Hopper over the edge outside the rock hold's volume
  - Chain conveyor

The third concepts reduces the initial cycle time by generating a long offload area. The beam (1) on top of the long edge of the rock hold can be seen as the conveyor with side skirts to increase the offload range. The excavator's rotation decreases because the conveyor is a long chain conveyor and can be reached faster due to its shorter required rotation. The operator can start offloading earlier, but on the other hand needs to reach up higher. During the time before rock placement, the conveyor can be filled and because of its great length, hold a lot of rock. The block at the end of the chain conveyor (2) can function as the hopper. With a shear bar installed at the end, the flow can be controlled. In a different configuration with the vertical hopper (3), the rocks can be stored in the vertical hopper (3) instead of (2). Again, the downside of this system is that in case of a blockage it is hard to reach the cause.

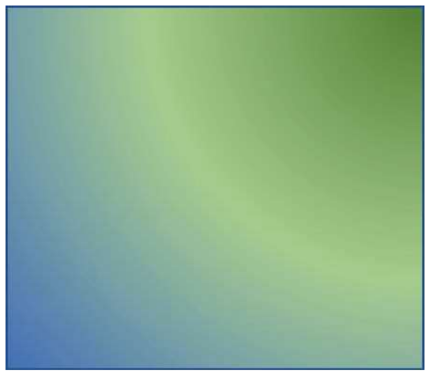

Figure 3.7: Concept C

- Concept D
  - Hopper over the edge inside the rock hold's volume
  - Apron feeder

Concept D is a mixture of concepts B and C. This means that a long conveyor is lowered into the rock hold's volume. By doing this, the range of offload increases and the volume of the hopper increases. This causes lower cycle times and thus a longer operation time. To generate a continuous flow out of the large batch dropped by the excavator, a strike off height is placed at the end of the rock hold. This way, only a certain amount of material leaves the system as desired.

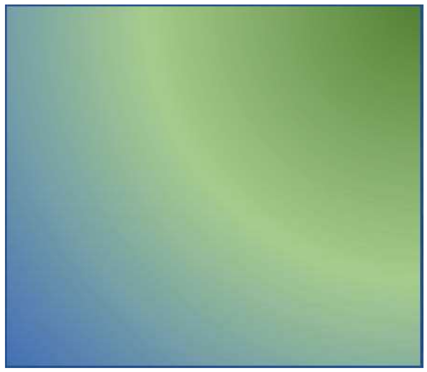

Figure 3.8: Concept D

- Concept E
  - Moving hopper
  - Low profile feeder

The hopper (1) and conveyor (2) in this concept are capable to rotate over 90° to their new position (3). Since it is able to rotate to the side where the excavator is working, the excavator only has to rotate over 90° to reach its offloading point. Compared to concept A, a smaller hopper is required because of the shorter cycle time. In case of excavating at the location of the conveyor, the conveyor is capable of rotating to the other side to make room for the excavator. In each position the material will be fed to a second conveyor, transporting the material to the IFP. Downside of this concept is the weight and the need to rotate: A hopper needs to be transported over the rock bed, even when it starts with a full hopper.

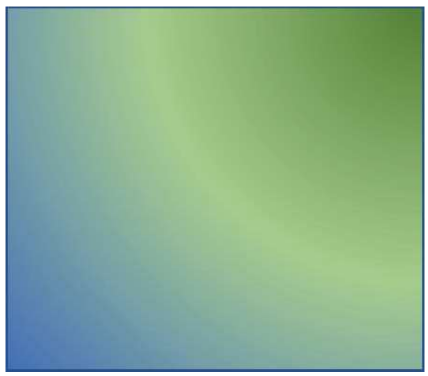

Figure 3.9: Concept E

3.6. Layout development

This stage of the design cycle will investigate the dimensions of the key modules. Since it is of great influence on the allowance of peak production, the cycle time and hopper volume per concept is looked into. For the feeders, the rough dimensions are explained and the concept ranking will be discussed.

3.6.1. Feeder

For this grading and type of material the use of a chain conveyor, low profile feeder, apron feeder or vibratory feeder was applicable. Only for the concept A where there is no or even a small decline in the transportation, a vibratory conveyor could be used. However, from experience aboard the Fall Pipe Vessel the Seahorse, a vibratory feeder is highly advised against because of the intense vibrations causing problems with equipment aboard. For the concepts where the excavator unload the bucket directly on the conveyor, an apron feeder is more preferable than the chain conveyor and low profile feeder due to the impact. Also, since the chain conveyors in mining convey soft rock, a higher wear is expected. The use of an apron feeder is preferable for the concepts B. A downside for the apron feeder is its maximum length of 15 meter [32]. Therefore, it is not applicable for concept C and D. For concepts A and E, the low profile feeder could be an option, since direct loading on the feeder will not be done.

Table 3.2: Selection of feeder type per concept

Concepts	Vibratory F.	Low profile F.	Chain C.	Apron F.
A	x	x	x	
B				x
C			x	
D				x
E		x	x	

3.6.2. Concept cycle time

In section 2.2.2 the initial cycle time is introduced with a resulting initial cycle time of — seconds. However, for each concept the cycle time is slightly different and with great impact. The cycle times are introduced in figure 3.10. Within these cycle times the positions in x-, y- and z-direction, the process orders and their interdependence are taken into account. Side note to the cycle time at concept A and C where the hopper is fixed on top of the rock hold, is that the cycle time increases with the lowering of the rock bed. The lower the rock bed, the higher the cycle time since the excavator has to dig lower and reach higher. This is not the case in the concepts B, D and E since the feeder or hopper is on the bottom of the rock hold or it moves downwards with the rock bed level. The different cycle times are explained in further detail in appendix **??**.

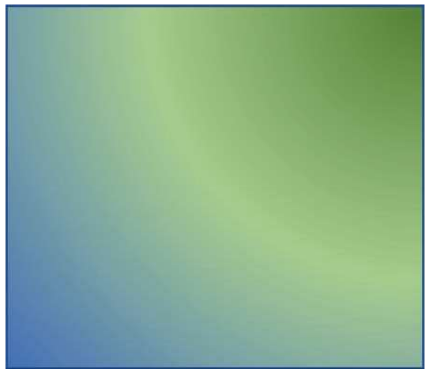

Figure 3.10: Cycle times per concept

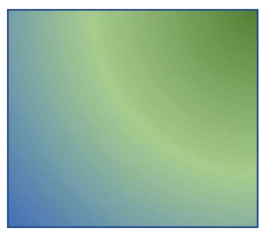

Figure 3.11: Average capacity per rotation of the excavator for concept B

Figure 3.12 shows that the cycle time to generate — tph is approximately — seconds. As seen in figure 3.10 not every concept is capable of doing that. To be able to generate a — tph flow, a hopper needs to function as a buffer as well. Within figure 3.12, the needed volume per concept is shown. The dotted line in that same figure shows the required volume in case of a 95% bucket fill factor (bff) and operator factor (of), resulting in less material per cycle and bigger hopper volumes required per cycle time.

3.6.3. Hopper outlet diameter

One parameter to get an idea on the size of the hopper can be the hopper outlet diameter. In this section the hopper diameter for the concepts is calculated. To be able to handle both vertical flows the bigger grading is used for calculating the minimal hopper outlet diameter. Also a rectangular outlet can be picked but for these calculations a circular outlet was chosen.

Determining the hopper outlet diameter or size, which will determine the width of the conveyor, can be done by investigating the mass flow through the hopper. Using equations 3.1 and 3.2 [32] the required outlet size is calculated. Due to high costs it is desired to purchase a less wide feeder.

$$\dot{m} = 0.58 \cdot \rho_{bulk} \cdot \sqrt{g} \cdot (d_{out} - kD_{particle})^{2.5} \cdot k_{\Theta} \quad (3.1)$$

Parameter k = 2.5 for non-spherical particles [32], parameter $D_{particle}$ as shown in table 3.3 and the factor k_{Θ} calculated in equation 3.2 with a hopper angle measured vertical of 30°, were used.

Figure 3.12: Required hopper volume per concept cycle time for — tph within the 90° reach

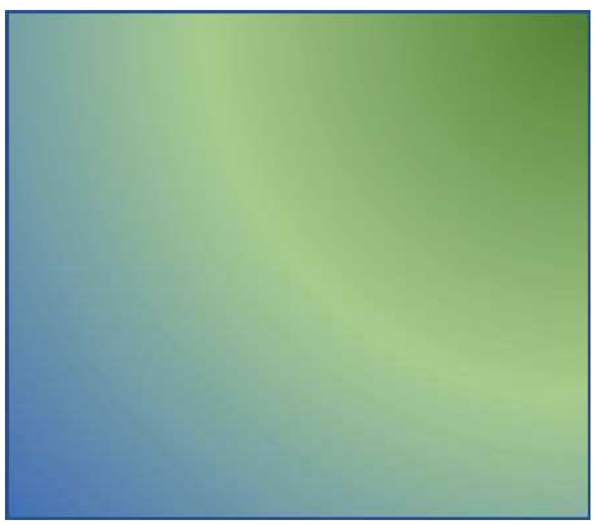

Figure 3.13: Required hopper volume per concept cycle time for — tph within the 180° reach

$$k_\Theta = (\tan \Theta)^{-0.35} \tag{3.2}$$

Since the rock is seen as a perfect cube and in real life the rock will be slightly different, the diameter, D, is calculated using the nominal diameter D_n by using equation 3.3 [5].

$$D_n = 0.84 \cdot D \tag{3.3}$$

Table 3.3: Diameter rock particle for grading 10-60 and 60-300 kg

Grading limit	Weight $[kg]$	Volume $[m^3]$	D_n $[m]$	$D_{particle}$ $[m]$
M_{50} 10-60	43	0.016	0.253	0.302
NUL 10-60	60	0.023	0.283	0.337
EUL 10-60	120	0.045	0.357	0.425
M_{50} 60-300	236	0.089	0.447	0.532
NUL 60-300	300	0.113	0.483	0.576
EUL 60-300	450	0.170	0.554	0.659

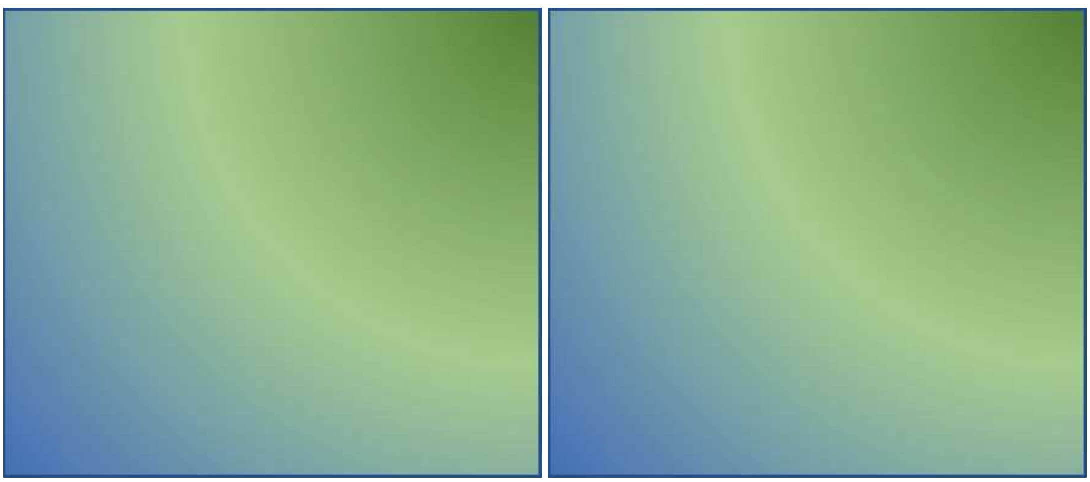

Figure 3.14: Hopper outlet diameter per grading at LT-ratio 1.73 (left) and for different hopper angles (right) using the 60-300 kg grading

The resulting d_{out} of the Beverloo equation 3.1 is shown in figure 3.14. In this figure, it can be seen that the required outlet diameter of the hopper using particles at the NUL is at least — m and — m for the EUL or a outlet with — m sides. Since the share of a 450 kg rock in the sample is 1 to 200, it might not be necessary to create a hopper outlet diameter of at least — m. Furthermore, the pipe diameter is — m and since it is more preferable to get blockage in the hopper than in the pipe, it is useful to make the hopper outlet diameter also — m. The influence of the hopper angle, measured vertically, is shown in the right part of figure 3.14. This shows that the hopper inclination does not have much of an influence for the Beverloo equation. The required volume as determined by using figure 3.12 together with the hopper outlet diameter, creates an impression of an usable hopper. The hopper sizes are already implemented in the Solidworks concepts as shown in figures 3.5 through 3.9.

3.6.4. Feeder width

A square outlet of the hopper is used in case of concepts B, C and D. Calculating the hopper outlet of the apron feeder the equations 3.6 and was used. For the width of the apron feeder equation 3.4 [9] using the maximum length of the particles was used and implemented in equation 3.6. Using the EUL on 450 kg rocks with a LT of 3.5 the feeders width should be — m. This means that one single rock of the RUL with an LT-ratio of 4.5, a very rare rock, is still capable of moving through the hopper outlet.

$$B_{conveyor} = \frac{L_{max}}{0.75} \tag{3.4}$$

3.6.5. Discussion concepts

With the discussed layout and components worked out in more detail, a choice can be made. This was done by using the guidance of De Beer's criterion analysis [10]. The key performance indicators (KPI)'s of the system and the ranking are as objective as possible. Multiple opinion with different views, from managers to offshore operators, are used to determined an average value. The values provided, are positive integers in the range of 1 to 5, bad to good. When providing values at each concept per scalable objective, the values 5 and 1 needs to be allocated at least once. A detailed explanation of the ranking can be found in appendix **??**. Figure 3.15 shows that concept B is ranked as the best concept. This concept will be investigated in the preliminary layout and the flow behaviour for this concept will be looked into in chapter 5. The winning concept is shown again in figure 3.16.

		Concepts					
Criteria		**A**	**B**	**C**	**D**	**E**	**ideal**
Technology		*4*	*5*	*3*	*2*	*1*	*5*
Solvability		*1*	*4*	*5*	*4*	*3*	*5*
Peak operation		*1*	*5*	*3*	*4*	*3*	*5*
Costs		*5*	*4*	*3*	*2*	*1*	*5*
Space		*4*	*3*	*3*	*1*	*5*	*5*
	Σ	*15*	*21*	*17*	*13*	*13*	*25*
	Σ_rel	*60%*	*84%*	*68%*	*52%*	*52%*	*100%*

	Weight	Concepts					
Criteria	**factor**	**A**	**B**	**C**	**D**	**E**	**ideal**
Technology	4.17	*16.7*	*20.8*	*12.5*	*8.3*	*4.2*	*20.8*
Solvability	4.33	*4.3*	*17.3*	*21.7*	*17.3*	*13.0*	*21.7*
Peak operation	3.33	*3.3*	*16.7*	*10.0*	*13.3*	*10.0*	*16.7*
Costs	1.17	*5.8*	*4.7*	*3.5*	*2.3*	*1.2*	*5.8*
Space	2.00	*8.0*	*6.0*	*6.0*	*2.0*	*10.0*	*10.0*
	Σ	*38.2*	*65.5*	*53.7*	*43.3*	*38.3*	*75.0*
	Σ_rel	*51%*	*87%*	*72%*	*58%*	*51%*	*100%*

Figure 3.15: Ranking of the concepts

Figure 3.16: Chosen concept B: an inclined apron feeder into the hopper

3.7. Preliminary layout

Before the dynamic behaviour of the flow and the limitations of the chosen concept can be investigated, some key parameters need to be chosen. This is done in the preliminary layout. For this concept the use of an apron feeder was chosen. An apron feeders consist primarily of two endless tractor chains with either cast manganese or fabricated steel pans connected to the tractor chains. The chains are driven by sprockets that are mounted to the drive shaft.

3.7.1. Angle of the feeder

To increase the volume of rocks on top of the feeder, it is desirable that the feeder is installed under its steepest angle. This is a common technique for offloading rock dumpers. From literature [3][36], the maximum angle of conveying limestone is set at 17° or up to 23 ° measured from horizontal.

3.7.2. Length of the feeder

Taking the angle of the feeder into account together with the maximum reach of the offloading point of the excavator, the feeder length needs to have a minimum total length of 14 m. Besides the higher cost of a longer feeder, there is the release angle which asks the feeder to be as short as possible. To be sure the material will not slip, a check can be done. According to Roberts [28], it is recommended to maintain a height over width ratio smaller than 1 to create a uniform feed. On the other hand, the height of the opening is preferably large to increase the release angle. The higher the release angle, the better slip is prevented. To check if this is the case for this feeder design the following is investigated.

$$\Psi = \tan^{-1}\left(\frac{\frac{h_{shear}}{B_{conveyor}} - \frac{y_c}{B_{conveyor}} \cdot \cos(\theta)}{\frac{L}{B_{conveyor}}}\right) \tag{3.5}$$

The resulting release angle, Ψ, is 7°. With a minimal h_{shear} of — m, L is 4.0 m, y_c is 0.1 m, $B_{conveyor}$ is — m and θ is 17°. Together with an apron friction angle of 28°, it can be seen in figure 3.17 that slip is not likely to occur.

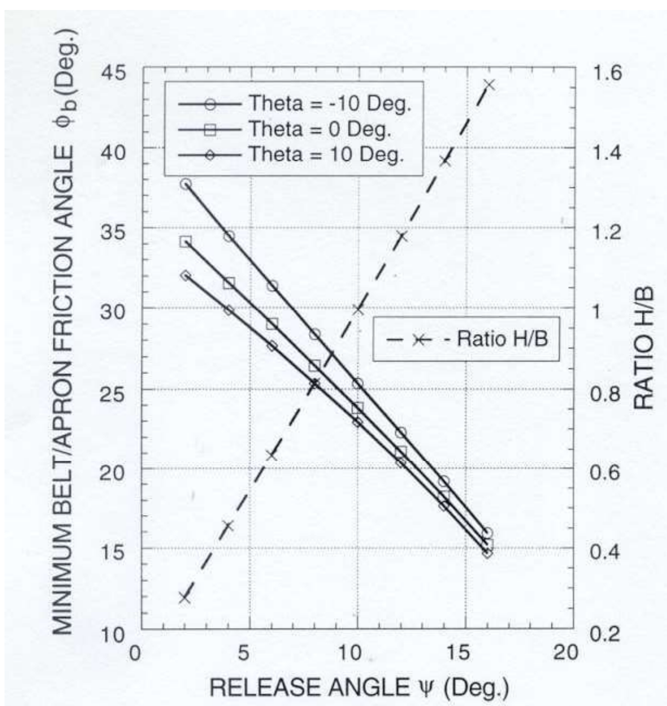

Figure 3.17: Minimum friction angle to prevent slip [28]

3.7.3. Space

Concept B occupies space in the rock hold. In concept B the excavator is not able to reach parallel to the sides of the feeder because it is rotating from one point in the middle. Therefore, a segment is useless and will be occupied with hopper plates. This is also because the bucket is — mm wide and the feeder is only — mm. When this is taken into account the concepts B need a space of at least 38 m^3. It is assumed that the space underneath the feeder is considered lost and not able to be filled with rocks. However, the capacity of the vessel is limited by the load of the bulk and not the volume.

3.7.4. Required Power

As can be seen in figure 3.18, the most required power is needed at the moment of discharging. The initial filling condition requires the most power due to the shear stress in the hopper at discharging. The required initial power can reach up to eight times the flow power instead of the two or four times the flow power as Schulze recommends and the power needed to overcome to shear the material is approximately 60 percent of the total power needed [29] [36]. This amount of required power is calculated using multiple techniques given by W. Bruff, P.C. Arnold and D. Schulze. More about these calculations can be found in appendix **??**. Figure 3.19 shows the results of the calculations. The total power needed depends on the speed of the feeder. Within these calculations the desired continuous velocity is included. In practice, due to the start-up properties of the drive and a lower starting condition this is most likely less than calculated [28]. The use of hydraulic engines are ideal for these low velocity applications. Within this amount, the flow can get started at slow speed while taking an extreme initial filling factor of 10 times the flow conditions as calculated by Schulze. This provides insight in the power needed to make the operation work. During the operation it can be sufficient to use one engine. It is required to install both because of the initial required power when filled, but also in case of a filled start up after an emergency stop.

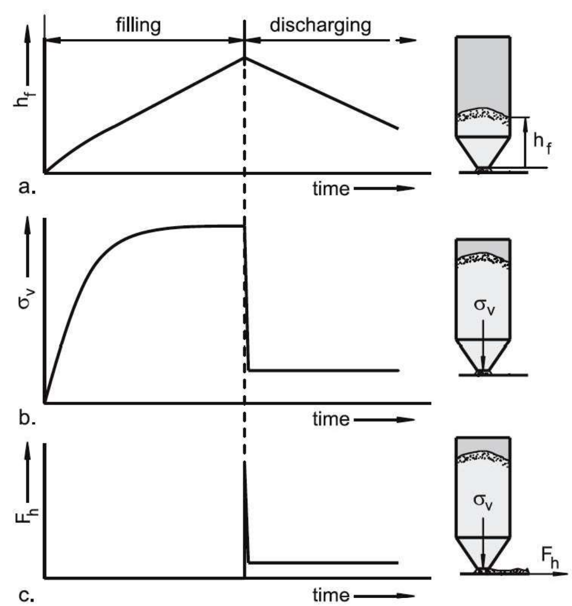

Figure 3.18: Height, stress and force during the process [32]

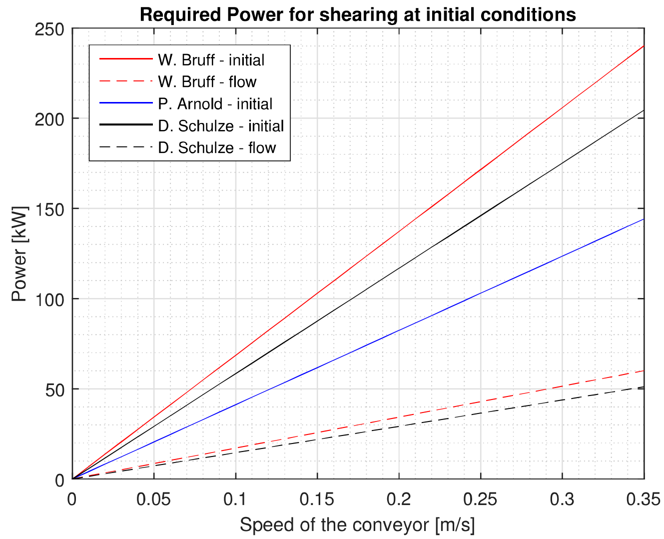

Figure 3.19: Required power for shearing at initial state per method

3.7.5. Capacity

To control the capacity, it is important to control the speed and the rock bed as well as possible. Apron feeders are capable of controlling the speed and with an shear bar, the strike off height can be controlled to create an accurate feed [36]. By using the shear bar at different heights to control the mass flow, the hopper outlet area is adjustable. The capacity will be calculated using equation 3.6 through 3.9 [27],

$$\dot{m} = v_{feeder} \cdot 3600 \cdot A_{extraction} \cdot \rho_{bulk} \cdot \Omega \tag{3.6}$$

$$A_{extraction} = A_{outlet} \cdot C_{extraction} \tag{3.7}$$

$$A_{outlet} = h_{shear} \cdot B_{conveyor} \tag{3.8}$$

$$\Omega = \frac{100 - \theta}{100} \tag{3.9}$$

where $\dot{m}$ is the capacity, $B_{conveyor}$ is the width of the feeder, h_{shear} is the height of the shear bar. $C_{extraction}$ is the extraction factor of 0.75 [9][27], Ω is the inclination factor calculated with equation 3.9 with θ as the inclination of the feeder. The resulting capacity is shown in figure 3.20. Furthermore, according to Roberts [28] it is recommended that the outlet rectangle of wider than the height, so $h_{shear}/B_{conveyor}$ ≤1. This adds another limitation on the height of the outlet when in operation shown as the upper red dotted line in figure 3.20. This figure will be used for the validation of the capacity of the chosen concept.

Hopper outlet size

As mentioned in section 3.7.5, a shear bar is an ideal addition on the installation to create an accurate feed. However, it is questionable if this is true for the application of this work. From literature, a ratio between the outlet diameter and the maximum particle diameter was found. A ratio between 4.5 till 7 was found [26] [1]. In more recent work, it was advised to use a ratio of 6 to 7 [18]. It is now questionable if the design equations for apron feeders are applicable for this concept system and what the resulting behaviour will be.

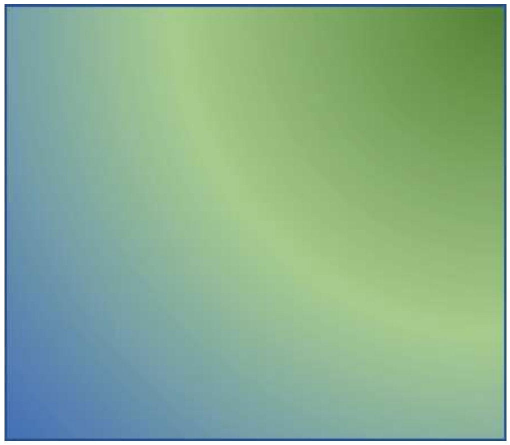

Figure 3.20: Feeder capacity per hopper outlet height and conveying speed

3.8. Summary

This chapter provides an answer to the sub question:

- `What systems can handle the applicable material flow?`
- `What are the criteria for this design?`

The bulk handling process was divided into the functions and solutions of the corresponding principles and were used as the base of a morphological overview. Capable solutions for transportation were found in the mining industry. Equipment such as vibratory feeders, low profile feeder, chain conveyors and apron feeders are on paper capable of generating the required mass flows of rock with the corresponding gradings. Concepts based on these applications and varying locations of the hopper were created and evaluated on the following wishes or criteria. Maximum solvability in case of failure or blockage, proven technology resulting in maximum robustness, maximum allowance of peak production, minimum required space for the solution and minimal costs. These criteria were mentioned from large to small weight factor.

Finally the concept with the highest score in the multi criteria analysis was chosen and developed in further detail. The concept is shown in figure 3.16: An inclined heavy duty apron feeder into the rock hold. With the use of literature based on experience from industry, the concept design was made. It is said that the use of a shear bar will increase the accuracy of the flow rate. However, it is questionable if the system can generate the required flow rate within the limits. Especially since there is a required outlet for hoppers. In the next chapters the research focusses on the dynamic behaviour and will answer the last two sub questions.

4

Discrete Element Modeling

In order to know if the chosen concept is capable of handling the rock and producing the desired rock flows, the bulk behaviour needs to be studied. To investigate the behaviour of a discrete flow of particles, such as rocks, experiments can be done. Because real life experiments are no option for this thesis, the use of simulation software as Discrete Element Method (DEM) is a well promising approach. The behaviour of flows within multiple configurations of parameters and equipment can be investigated with DEM software. By modelling the individual particles, the bulk behaviour on macroscopic level can be studied.

4.1. Working principle of DEM

DEM is a numerical method for computing the motion and effect of particles. In 1971 the general method was originally developed by Cundall and Strack in rock mechanics [7]. After initialisation, including the creation of particles, the environment and the simulation properties, the contacts and overlap between elements is detected. With this information, the interaction forces are calculated. For this work the Hertz-Mindlin (no slip) model is used. The Hertz-Mindlin is the most commonly used contact model within DEM. The Hertz theory realises the contact mechanical behaviour for spheres in normal direction, while Mindlin realises an improved model in tangential direction [12]. Within this contact model a number of forces are taken into account, as shown in figure 4.1. A spring, acting for the elastic force displacement principle. A dashpot, using viscous damping law and energy dissipation. The slider between the two particles, reflecting the Coulomb friction. The meniscus, representing the pendular liquid bridge for cohesive applications. These models generate the resulting force in normal and tangential or shear direction and so the new position for each particle per time step. This process is done per time step for each particle till the simulation ending time is reached. More information on DEM can be found in the EDEM user manual[11].

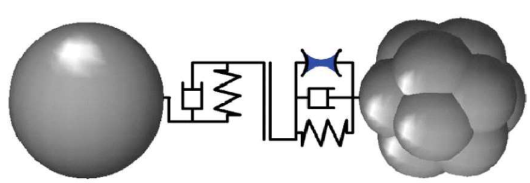

Figure 4.1: Particle - particle contact model [31]

4.2. EDEM™ software

Multiple DEM software packages are on the market. For this thesis EDEM™ is used. This software has some advantages over other options. With its graphical user interface, adjustments are made easily. Results of these adjustments can be seen directly while running. Besides that, it is available at the Delft University of Technology and the user had experience with the software before.

4.3. Model parameters

To make sure that the behaviour of the material in the simulations is similar to the reality or as close as possible, the input parameters needs to be set-up. For the DEM-simulations parameters such as friction, shape and particle size distribution (PSD) need to be defined. For the material properties these are the specific density, Poisson's ratio and the shear modulus G. For the interaction between the particles and the environment such as steel are the coefficient of restitution, static friction and rolling friction coefficients. The material parameters and the interaction parameters have values found in literature or calibrated values as discussed below.

4.3.1. Shape

Particles in DEM are simulated as spheres and one particle can consist multiple spheres. The particles can be recreated almost exactly like particles in real life by including an enormous amount of spheres and therefore contact points. However, this increases calculation time. The less spheres in a particle, the less computational time needed; starting with particles shapes by one sphere. Because of its round shape, the particle starts rolling at the smallest inclination. Even with high rolling friction. This is similar with a particles consisting out of two spheres, expect when it is orientated exactly perpendicular to the tilt direction. Particles built up by three not in line spheres do not have that problem. Depending on their orientation, some particles will flip over and some will slide at a certain angle. This behaviour is similar to real life rocks. Another useful thing of using three spheres in a particle is the LT-ratio. Earlier an average LT-ratio of 2.27 was introduced. This was taken into account in the used particles as can be seen in figure 4.2. However, as noticed in section 2.1.1 the particles can have a smaller and larger LT-ratio. Although the LT-ratio of larger rocks will decrease because of the risk of breaking when having a large LT-ratio, the largest rock of the grading with a LT-ratio of 3.5 is simulated. Also, the smallest LT-ratio, 1.73, can have an influence on the system. The nominal upper limit rocks, weighing 600 kg, with the two LT-ratio's are shown in figure 4.3

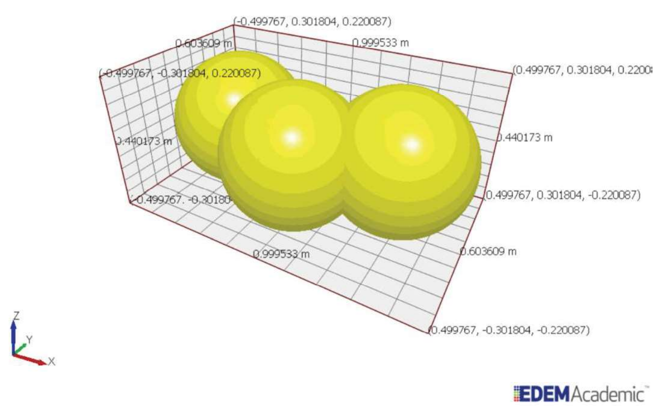

Figure 4.2: Base 3 sphere particle, scaled to the right grading

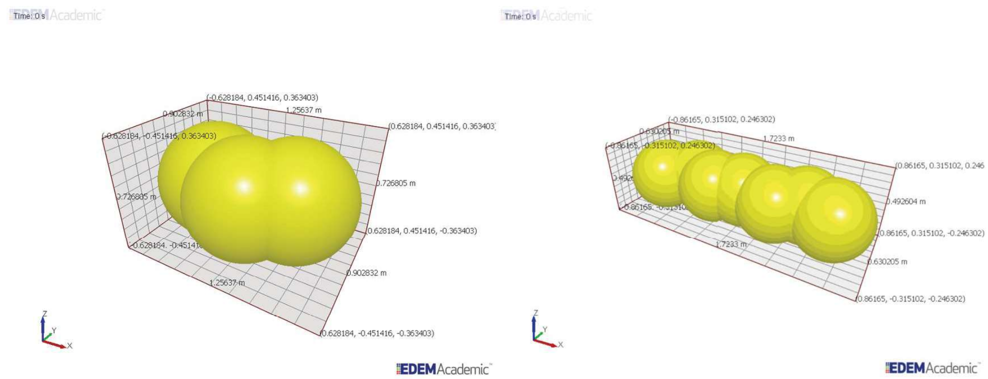

Figure 4.3: 600 kg rocks with a LT-ratio of 1.73 (left) and 3.5 (right)

4.3.2. Particle size distribution

Simulating the limits of the material flow involves the system to handle the most unwanted flow of rock. In section 2.1 the grading curve is introduced. To realise the most conservative rock flow, a grading curve pushed to the right side going through all the upper limits as shown in figure 4.4, the Rosin-Rammler equation 4.1 [5] was used. In this equation, y is the fraction passing value; M_y, is the mass corresponding to that value using a percentage subscript to express that fraction, and n_{RRM} the uniformity index. Using this equation, a set of 100 rocks was made and the mass percentage per rock weight is calculated. These mass percentage are, together with a scale over the base particle, implemented as user defined parameter. More information on creating the used distributions in EDEM is given in appendix **??**.

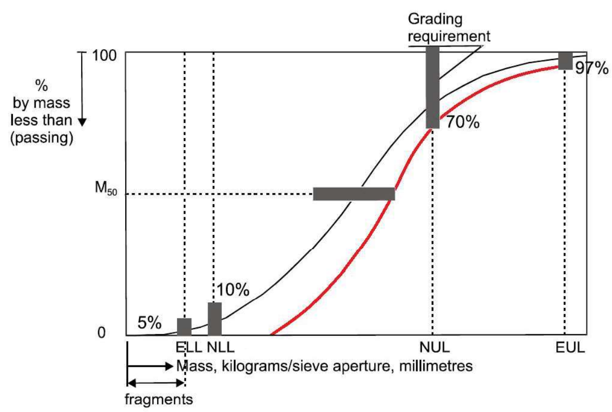

Figure 4.4: Pushed grading curve to its maximum possible appearing

$$y = 1 - e\left\{ln\left(\frac{1}{2}\right)\cdot\left(\frac{M_y}{M_{50}}\right)^{n_{RRM}}\right\} \tag{4.1}$$

Table 4.1: Information for Rosin-Rammler [5]

Grading [kg]	M_{50} max [kg]	n_{RRM}
10 - 60	43	1.85
60 - 300	236	2.20

4.4. Calibration methods

To test if the behaviour is similar to the behaviour of the used rock in real life, tests were executed. The angle of repose test, the bulk density test and the tilt test need to be executed so the material and interaction parameters realise behaviour as expected.

Bulk density

Bulk material has a certain bulk weight, 60 percent of its specific weight for the armour rock with its 0.4 porosity. Since the particles in EDEM do not match the shape of all the particles in real life, the specific weight of the simulated particle needs to be adjusted to match the bulk weight. The simulation of the calibration can be seen in figure 4.5, using a mass grid box of 15.625 m^3 in EDEM within an outer box and loading it with each grading. The target of the simulated bulk weight in the box is 25,000 kg. The resulting bulk weight after iteration is shown in table 4.2.

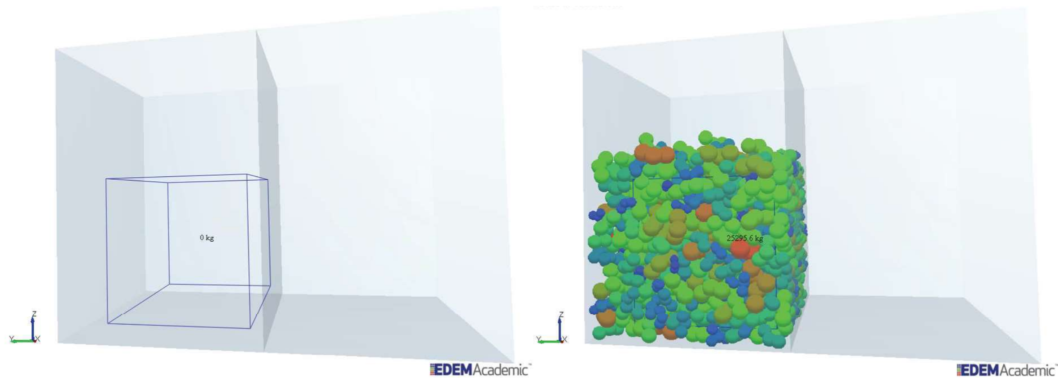

Figure 4.5: Calibration of bulk density filling the box

Table 4.2: Calibration of the density

Simulated density [kg/m^3]	Simulated weight [kg]	Target weight [kg]
2900	25,291	25,000
2900	24,924	–
2900	24,993	–

Angle of repose

For the particle-particle interaction the angle of repose is investigated to set the static friction and rolling friction coefficients. As mentioned in chapter 2.1, the armour stone and grading used in this application can also be called riprap. Figure 4.6 shows the angle of repose (AoR) for riprap at the mean diameter of a grading. The angle of repose for the large gradings is given by figure 4.6 for D_{50}. The value for D_{50} is calculated using equation 3.3. The AoR corresponding to the mean diameter of the used gradings is between 39° and 42°. Figure 4.7 shows the calibration test of a 10-60 kg grading. This is also done for the larger grading, resulting in a expected larger angle as expected according to figure 4.6.

Table 4.3: Diameter of the armourstone [8]

Grading [kg]	LT-ratio 2.27 D_{50} [mm]
10 - 60	256
60 - 300	439

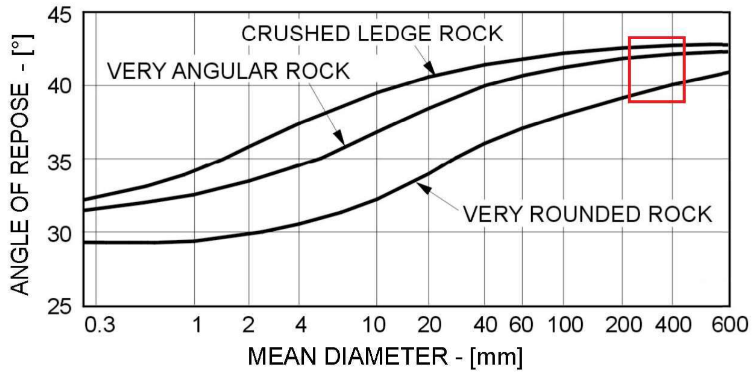

Figure 4.6: Angle of repose for the mean diameter [33], including the used grading diameters in the red box

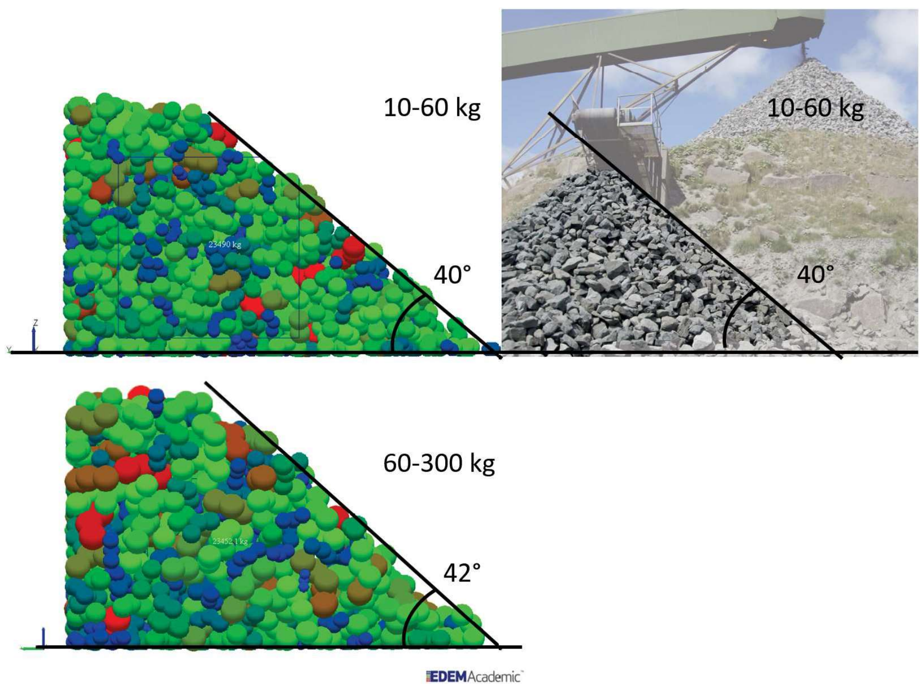

Figure 4.7: AoR of 40° for a simulated (left top) and real (right top) stock pile of 10-60 kg grading and 42° for the simulated 60-300 kg grading (left bottom)

Tilt test

The tilt test will show the interaction between the armour stone and steel. The company performed a quarry test by offloading a dump truck. At a certain angle while offloading, the load will slide down. This angle was observed between 27.5° and 29.5°. This value was used for the calibration of the tilt test between rock and steel. Simulation results are shown in figure 4.8. The simulation tilt test was done by rotating a rock supporting plate. The static friction and rolling friction are adjusted to fit the angle of the moment of sliding. In that same quarry test the internal friction of the rock was tested. Sliding for rock on rock was detected at an angle of 38° in the simulations as well.

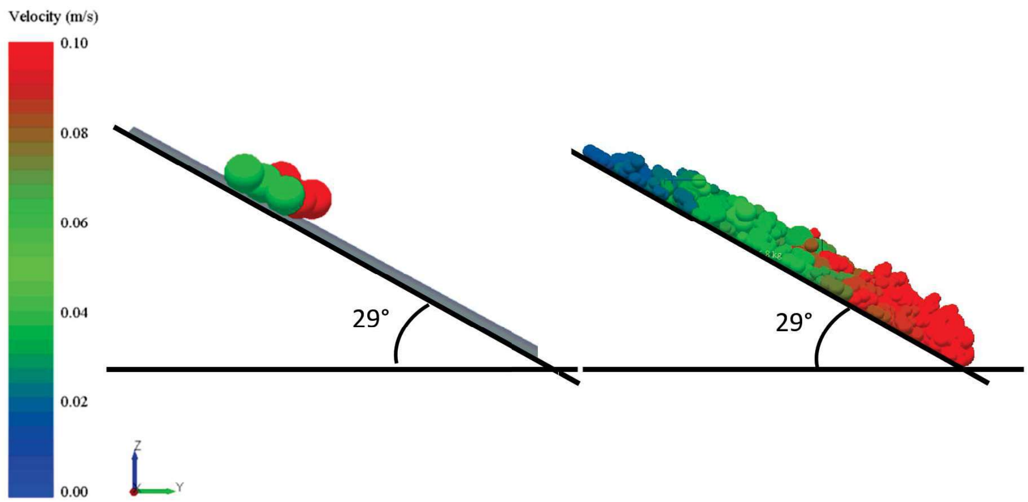

Figure 4.8: Sliding starts (not blue coloured particles) at an angle of 29° for a simulated single particles (left) and a quantity of particles (right)

4.4.1. Material parameters

From literature and the calibration tests done, the following parameters were set with the corresponding values. The material input values are shown in table 4.4.

Table 4.4: Final material input

Material	Parameter	Value	Source
Rock	Density[kg/m^3]	2900	Bulk density test
_	Poisson's ratio [-]	0.3	Gercek [15]
_	Shear modulus [Pa]	1e +07	EDEM [6]
Steel	Density [kg/m^3]	7800	Lindeburg [21]
_	Poisson's ratio [-]	0.3	Gercek [15]
_	Shear modulus [Pa]	7.5e+10	Lindeburg [21]

4.4.2. Interaction parameters

For the interaction parameters the following settings were found by calibration tests and literature, and used in the simulations. In the Generic EDEM Material Model (GEMM), a database suitable material models, a similar and matching set for the parameters was found. The used input values for the interaction parameters are found in table 4.5.

Table 4.5: Final interaction input

Interaction	Parameter	Value	Source
Rock-Rock	Coefficient of restitution	0.2	Chau [35] and GEMM
_	Static friction	0.7	Angle of repose, Tilt test and GEMM
_	Rolling friction	0.1	Angle of repose, Tilt test and GEMM
Rock-Steel	Coefficient of restitution	0.2	EDEM [11]
_	Static friction	0.5	Tilt test
_	Rolling friction	0.01	Tilt test

4.5. Model geometry and motion

The model of the final concept as used in EDEM is shown in figure 4.10. The EDEM model was created by implementing the surfaces of the Solidworks model. In this figure, the target offload zone of the excavator can be seen by the red coloured moving particles. During the simulations the domain was cropped to a selected part of the model, in order to speed up the simulations. In the model, a filled box was used to fill up the partial rock hold with the particles of the desired PSD. A box was placed around the hopper functioning as other particles in the rock hold and keeping the implemented particles above the hopper.

In the initial simulations, the 'moving plane' option was used as a contact body to realise the feeders motion. Later during this study, the use of a feeder with cleats was introduced. This replaced the moving plane by a dynamic geometry of a long cleated plate. The EDEM settings used in the simulations are shown in table 4.6.

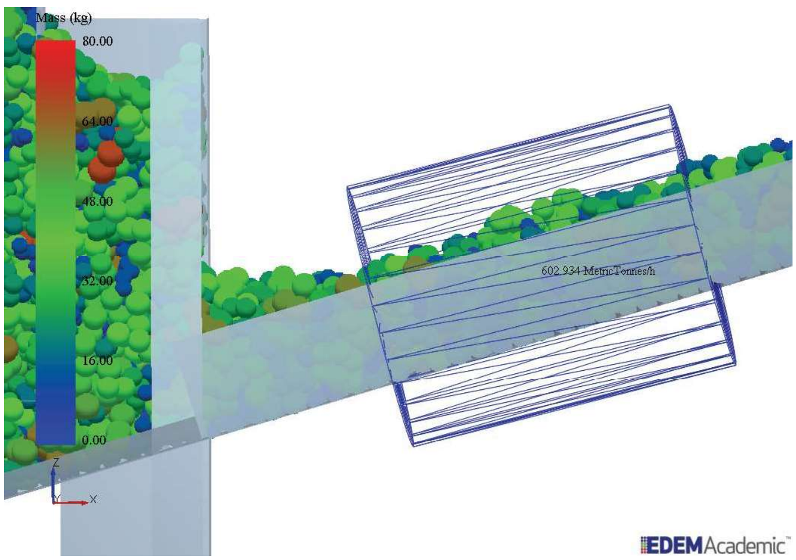

Figure 4.9: During the simulations the mass flow sensor measures the tonnes per hour passing

The resulting mass flow rates were obtained by a two meter long mass flow sensor placed over the feeder as shown in figure 4.9. The mass flow sensor measures the tonnes per hour after settling, resulting in a list of mass flow values per measured point. In order to get an equal amount of data points, the sensor measure frequency increases with the velocity. Each run was done three times with a simulation time of at least 100 seconds depending on the feeder velocity, until the end of the batch.

Figure 4.10: Top view of the model (top) The EDEM model transferred from Solidworks using STL-files of surfaces

Table 4.6: Final rock-rock interaction input

	Setting
Software CAD	Solidworks 2016
Software DEM	EDEM 2.7
Contact model	Hertz Mindlin no slip
Time step	Rayleigh 18%
Grid size	2R min

4.6. Summary

This chapter provides an answer to the sub question:

- `How to simulate and evaluate the dynamic behaviour of the material flow?`

To research the concept's dynamic bulk behaviour, discrete element modelling can be used. By simulating individual particles and their interaction, the resulting bulk behaviour can be studied. After calibration of the bulk, to make sure it behaves as in the real world, the model can be used. The mass flow was measured during the whole simulation by a flow sensor located on the feeder. The list of mass flows will provide information on the average and the fluctuation of the mass flow. Simulating the model with varying feeder velocity and outlet area results in different mass flows and accuracies. This will provide an insight into the performance of the concept, which will answer the main research question.

5 Numerical Simulations

First, the geometry of the system in terms of the hopper, outlet and feeder was studied. After a selection of configuration was set, the performance of the system was looked into. This was done by validating the mass flow rate as calculated in section 3.7.5 with equation 3.6.

5.1. Configuration

The hopper angle, the outlet angle and the feeder angle are the main parameters of the geometry. It is chosen to simulate three levels per factor. A summary is shown in table 5.1. Level -1, 0 and 1 corresponds with the red, blue and green line in figure 5.1.

- `Hopper angle`
  The angle of the hopper will be varied over 30°, 50° and 70° measured horizontally. This minimum hopper angle is chosen since the material will start sliding at this same angle. The steeper the hopper is, the larger it needs to be in order to let the 2.9 meter wide excavator offload. Therefore, the maximum angle was set on 70°. The three levels of this factor are shown at the right bottom in figure 5.1.
- `Outlet angle`
  In the mining industry, dump hoppers and apron feeders often include skirts guiding the rock to the outlet [13], therefore the angle to the outlet of the rock hold is taken into account as well. The three levels for this factor are a 50°, 70° and 90° angle. This range was set starting from 50°, because a wider angle will become almost similar to the 90° angle. The three levels of this factor are shown at the left bottom in figure 5.1.
- `Feeder angle`
  The feeder angle might also be of influence on the capacity and the fluctuation of the flow. Therefore, this factor will also be taken into account. As mentioned in section 3.7, a maximum feeder angle between 17° and 23° is recommended. For this application the maximum angle is limited by the rock hold floor and IFPS, resulting in a maximum of 22°. The minimal feeder angle tested will be set at 12°. The three levels of this factor are shown at the right top in figure 5.1.

Table 5.1: Factors and their levels

Factors	level -1	level 0	level 1
Hopper angle	30°	50°	70°
Outlet angle	50°	70°	90°
Feeder angle	22°	17°	12°

In terms of space and operation time it is ideal to install the feeder as steep as possible. This will increase the volume of rocks above the hopper and decrease the volume of the systems installation. Therefore, the configuration looked for starts at the lower level of the feeder and angle, with taking the

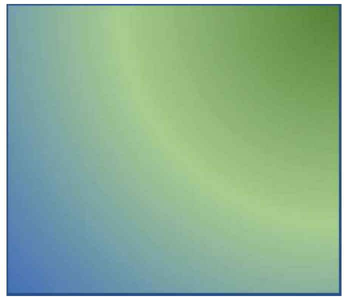

Figure 5.1: Default view with black arrow as rock flow direction (top left), Feeder levels (top right), Outlet levels (left bottom) and Hopper levels (right bottom). The coloured lines represent the levels: red = -1, blue = 0 and green = +1

mass flow rate and fluctuation of the flow into account. The same applies for the hopper angle. A low hopper angle will reach the required width of the excavators bucket per height sooner than a steeper hopper.

5.1.1. Design of Experiments

With Design of Experiments the required information can be generated with a minimum amount of experiments [16]. To provide an insight on the effects of multiple factors and the response, Response Surface Methodology can be used. Their are some commonly used experimental designs to obtain the response surface and to find optimization. In these designs the effects are determined mathematically and statistically [14]. Some examples are the full factorial, fractional factorial, central composite and Box-Behnken to name but a few. The latter will be used in this work.

5.1.2. Box-Behnken

The response surface methodology Box-Behnken design is an efficient fractional factorial design method for optimizing such configuration [14]. For a full factorial design for three factors on three levels a number of 27 runs has to be done, $\# = levels^{factors}$. Using the fractional factorial Box-Behnken design it only takes 15 runs, as shown in table 5.2. An illustration on the Box-Behnken design can be found in figure 5.2. With the use of statistical software Minitab 17, a polynomial equation was created. This was done for the resulting capacity and standard deviation of the runs. The influence of the factors can be described by this polynomial and will be uses to set a final configuration of the three factors for the runs along this work.

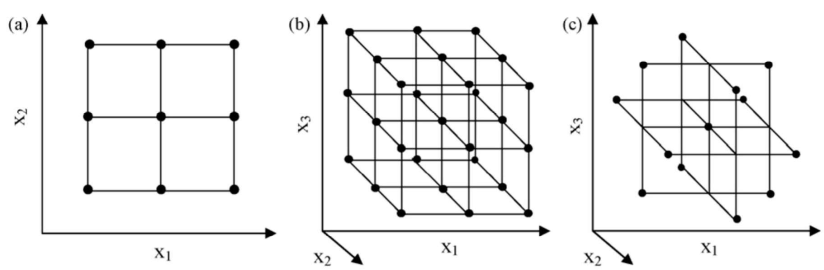

Figure 5.2: Two variable, three level design (left) three variable, three level design (middle), Box-Behnken design (right)

Table 5.2: Number of runs for the used 3 factor 3 levels Box-Behnken design

Runs	Hopper angle [°]	Outlet angle [°]	Feeder angle [°]
1	30	50	17
2	70	50	17
3	30	90	17
4	70	90	17
5	30	70	22
6	70	70	22
7	30	70	12
8	70	70	12
9	50	50	22
10	50	90	22
11	50	50	12
12	50	90	12
13	50	70	17
14	50	70	17
15	50	70	17

5.2. Mass flow

As mentioned in section 3.7.5 the expected theoretical mass flow was calculated by equation 3.6. This equation is based on empirical research involving apron feeders. The mass flow is depending on the outlet area and the speed of the conveyor. Different gradings were simulated for this work. All these simulations were reproduced three times since the orientation and position in the simulations factory of rocks were randomised. In the experiments, the shear height, the velocity of the feeder and the grading ware varied.

It was recommended to keep the ratio of $h_{shear}/B_{conveyor}$ equal or below 1 in order to generate an accurate feed [29]. A minimum shear height of c meter was set since the glsdpar of the 60-300 grading can reach up to c meter for an LT-ratio of 1.73. Therefore, the investigated shear heights are c, b and a meter. For some gradings, simulations were done without a shear bar to research the accuracy with no shear off. The feeder velocities were varied over A, B and C meter per seconds. This was done to study the high and low expected capacity as shown in figure 3.20 To investigate the effect on the grading, the 5-40 kg grading and 63/180 mm coarse grading were added to the simulations. Table 5.3 shows the runs for the mass flow check for the 5-40kg grading. All the runs were done three times for each grading.

Table 5.3: Simulations done for the validation of the mass flow for each gradings 5-40 kg, 10-60 kg and 60-300 kg

Grading	Runs	Shear bar height [m]	Feeder velocity [m/s]	Expected mass flow [tonnes/h]
	1	a	A	-
	2	a	B	-
	3	a	C	-
	4	b	A	-
	5	b	B	-
	6	b	C	-
	7	c	A	-
	8	c	B	-
	9	c	C	-

5.3. Trajectory

To see if the mass flow generated by the concept moves through the fall pipe, the trajectory of the feeder and the motion from the chute is studied. This was done at a maximum velocity of d and a shear height of A meter, causing a mass flow around — tph. On the other hand, the maximum capacity of the 60-300 kg grading was generated.

6

Results

In this chapter, the results of the simulations will be discussed. A first observation results in an adjustment to the feeder. This will be discussed before the experiments as described in previous chapter. Furthermore, the flow of the material while unloading the feeder will be shown, to see if the chute design needs adjustments.

6.1. Feeder

The first observation while running the simulation was the extraction of the feeder. The feeder, modelled as a flat surface of steel, was not capable of extracting as expected. The feeder slides underneath the material. Since an apron feeder does not have an endless and flat surface, it is expected to extract more material than simulated. Therefore, a feeder including 50 mm high cleats every 300 mm was introduced, comparable to the feeder in figure 3.3 and modelled as shown in figure 6.2. The resulting mass flow of both feeders is shown in figure 6.1. Although the difference in mass flow can not be validated with field experiments, the cleated surface is used in the simulations since it produces a mass flow closer to the empirical theory.

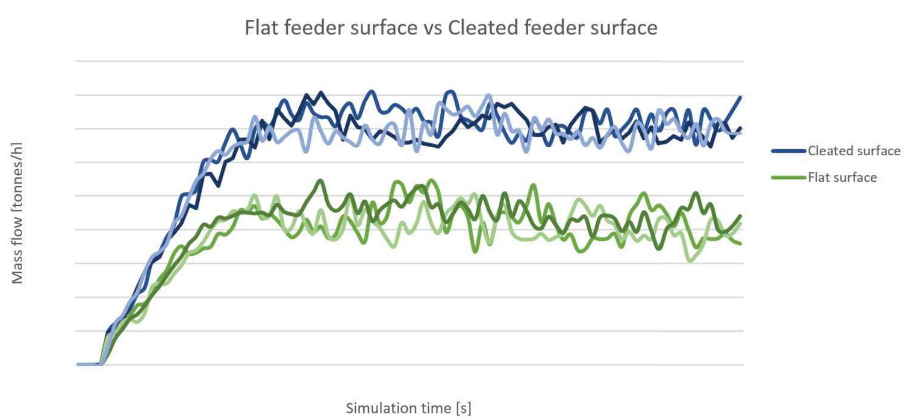

Figure 6.1: Mass flow of a flat surface vs cleated surface

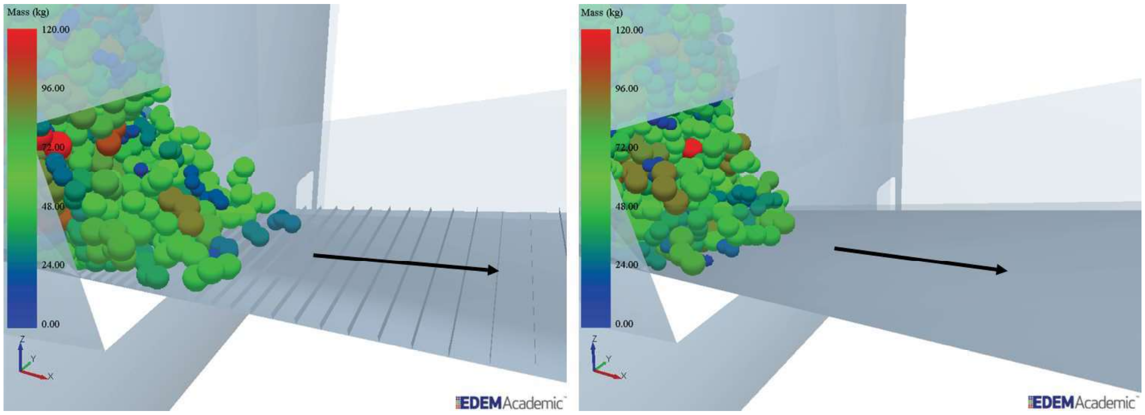

Figure 6.2: Cleated surface (left) and flat surface (right)

6.2. Configuration

The gained polynomials are visualised in the factorial plots to observe the influence of each factor in terms of the mass flow and the deviation. By maximizing the mass flow and minimizing the standard deviation the configuration was set. The contour plots are shown in figures 6.3 and 6.4. It can be seen in these plots that a configuration for all levels set at zero is close to the optimum. The optimisation plot in appendix **??** shows the ideal configuration as a result of the attached polynomials of the mass flow and the deviation. The optimal configuration is found at **—**° hopper angle, **—**° outlet angle and **—**° feeder angle. However, the chosen configuration was set on the levels zero. This was done because these points were actually simulated, the results were close to the optimal results, a configuration at the optimum was not in line with the desired configuration as mentioned in section 5.1 and generating a new configuration would cost time.

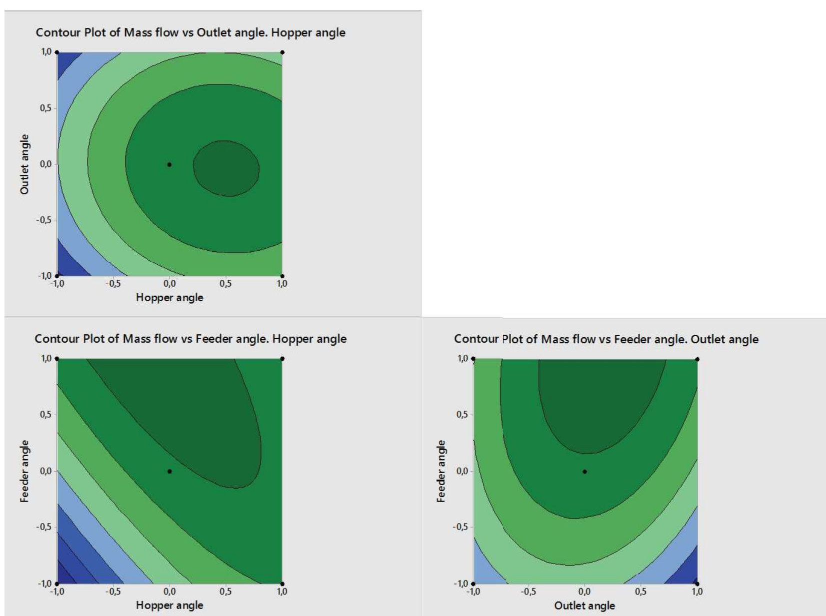

Figure 6.3: Contour plots of the mass flow per interaction of the factors

The influence of the feeder angle shows a large impact on the mass flow, the capacity increases when decreasing the feeder angle. This effect is known and is called the inclination factor, introduced in subsection 3.7.5 and used in equation 3.6. For this investigated configuration of minus and plus 5 degrees on the base case of 17 degrees, this means minus and plus 6% of the capacity. Per one

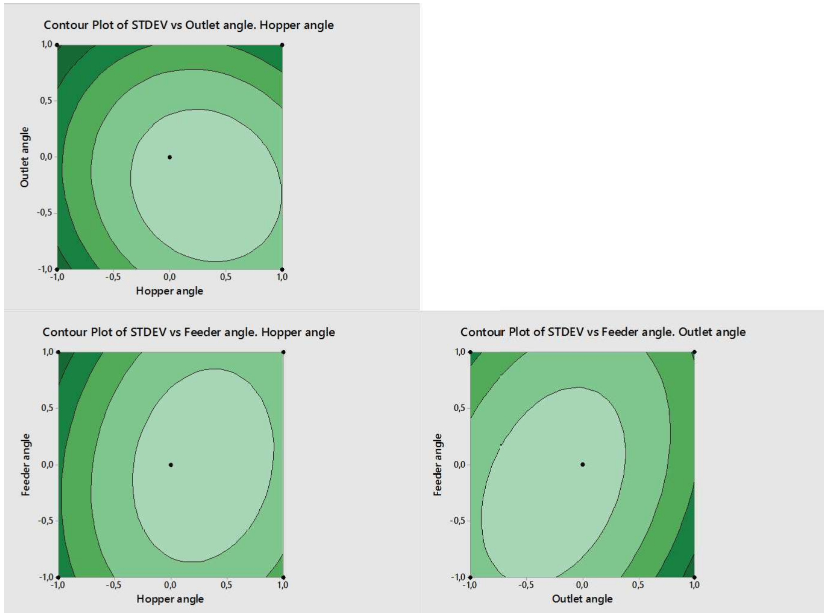

Figure 6.4: Contour plots of the standard deviation per interaction of the factors

degrees of angle increase the capacity drops 1.2%. The difference in mass flow due to the feeder angle is in line with this expectation. For the hopper, it can be seen that at the lower level of 30 degrees, the capacity reaches the bottom value. It was observed that material will not slide down the hopper and this might cause a reduction in mass flow or rocks rocks staying behind in the hopper.

6.3. Validation

The resulting mass flow of this concept is shown in figure 6.5. Within this figure, the mean values of the resulting mass flow and its coefficient of variance is shown. The calculated values as shown in table 5.3 in section 5.2 are shown in the figure by the plus shaped figures. The resulting mass flow is projected for shear heights a, b and c meter. The coloured points refer to the velocity of the feeder during the run. The different shapes refer to the different gradings used in the simulations.

Take in mind that within the simulations a specific shape with a LT-ratio of 2.27 and PSD was used. For the theoretical values, it is not known what material, particle shape and PSD was used. According to Beverloo [1], it can be assumed that the mass flow through a circular and a square outlet with the same area is equal. Therefore, the translation between the used square outlet to a circular outlet, is done by comparing the area.

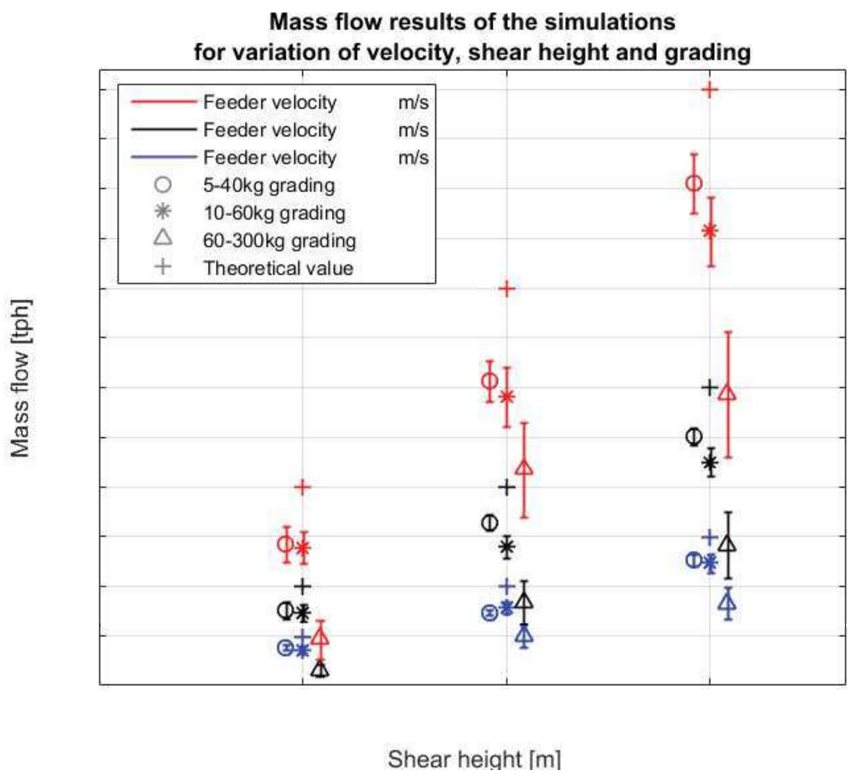

Figure 6.5: Mass flow per outlet area, feeder velocity and grading

Figure 6.6: The resulting simulated mass flow as a percentage of the calculated mass flow

6.3.1. Mass flow accuracy

The resulting data extracted from the mass flow is normal distributed. It can be said that 95% of the flow is within twice the standard deviation. Since the maximum fluctuation must be within two sigma of the mean mass flow rate, the coefficient of variance is used as twice the standard deviation divided by the mean. With this value, the fluctuation around the mean mass flow rate is studied. The percentages shown in figure 6.7 represent twice the coefficient of variance. The four coloured columns represent the tested gradings, increasing towards the right side. At the left side of the figure the outlet diameter is shown, but also a 'no shear' row is added. Simulations without a shear bar were performed as well to know the effect, especially for the 10-60kg and 60-300kg grading. It can be seen in the red coloured right corner, that the fluctuation is between –% and –%. This is within the expectations since the right bottom corner represents the 60-300kg grading transported through the smallest outlet tested. On the other hand, in the left top corner, coloured in green, it is the smallest particles moving through the largest outlet tested. Figure 6.8 shows high fluctuation of the mass flow at various shear heights for the 60-300kg grading.

It can be seen that the system can not generate an accurate and precise mass flow for the 60-300kg grading as desired. Therefore, simulations were done without a shear bar. This resulted in fluctuation just below –% of the corresponding mass flow. The use of a chain curtain is desirable to prevent rocks for rolling onto the extracted feed.

Because of an increase in accuracy of the flow for the 60-300 kg grading, this was also done for the smaller gradings. However, an improvement in the accuracy was not found. Another disadvantage of not using a shear bar at the smaller grading is the increase of the rock bed level. This means more resistance and wear on the skirt plates.

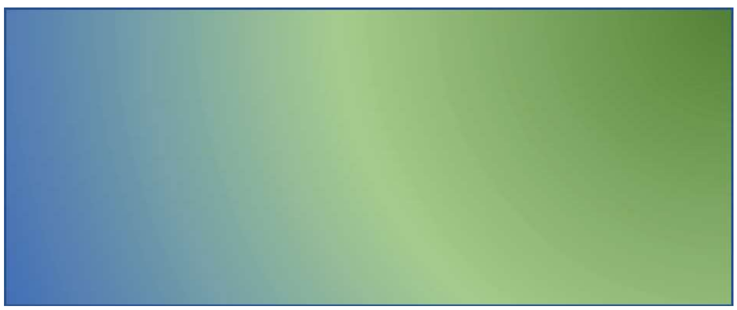

Figure 6.7: The accuracy of the mass flow calculated as twice the coefficient of variation

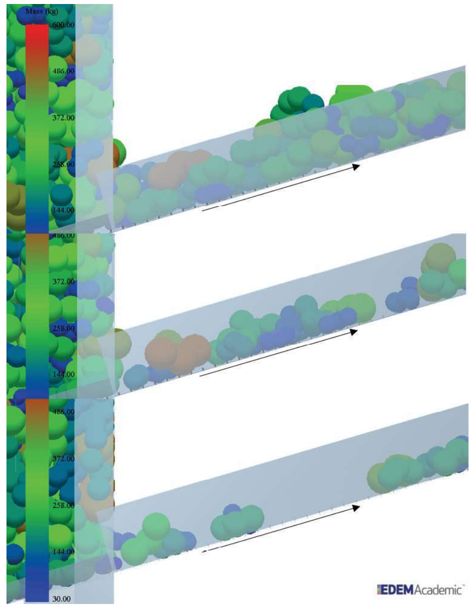

Figure 6.8: Mass flow for 60-300 kg grading at different shear heights: c meter (top), b meter (middle), a meter (bottom)

6.3.2. Outlet diameter and maximum particle diameter

The relation between the outlet area and the grading was mentioned in section 3.7. It was pointed out that a ratio between the outlet area and the maximum particle diameter greater than 6 is advised. The ratio between outlet diameter and particle diameter can be extracted from the results for this work too. The result is represented in figure 6.10, with the average mass flow and the standard deviation per ratio.

The larger the ratio, the less blockage will occur. The blockage caused by arching due to the increase of particle size can be shown when the simulation is clipped and the middle of the hopper is exposed. This is done in figure 6.9. One certain value for this ratio to avoid a blockage or mass flow stop can not be pointed out. However, for ratios around 6 and higher, the mass flow improves in terms of production and accuracy. This might be caused by the simulated dynamic translation of the feeder, forcing the particles through the outlet. Compared to Beverloo's setup, the hopper outlet is not centred below the hopper but on the side. Beside that, the particles are forces by not only gravity but also by the apron feeder.

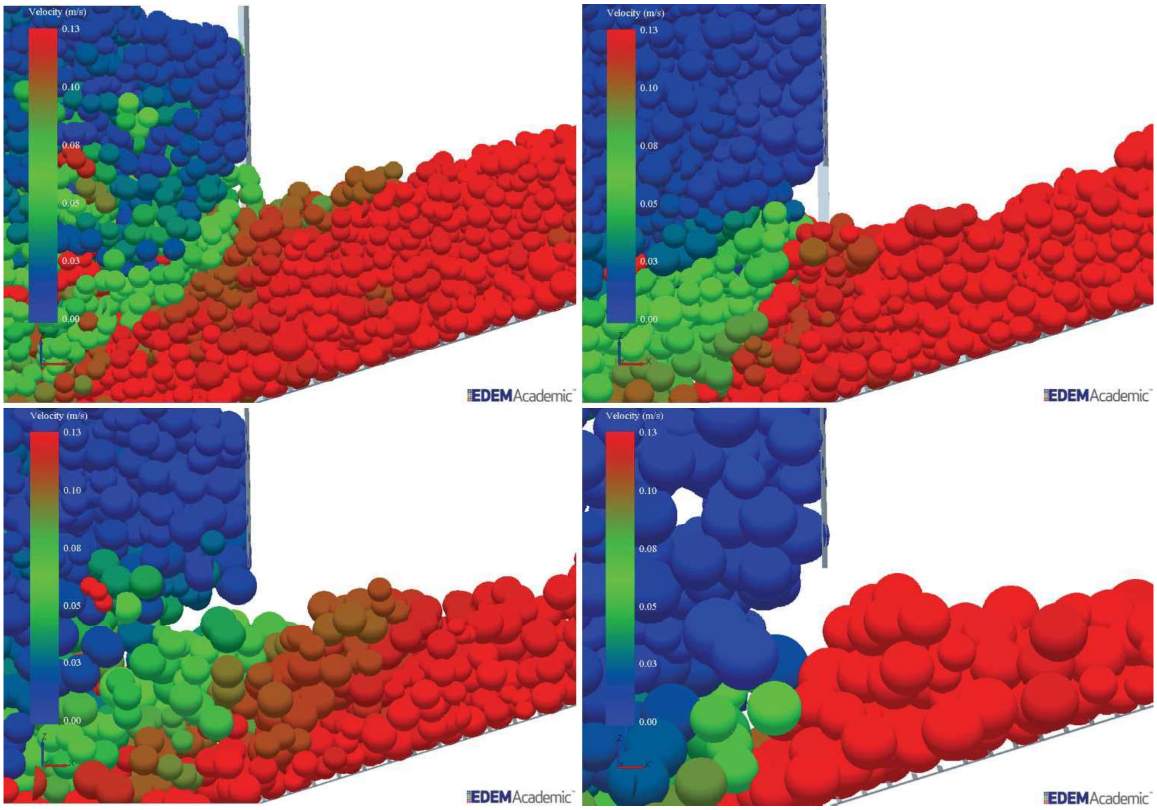

Figure 6.9: Arching occurring per grading. CP63/180 (top left), 5-40 kg (right top), 10-60 kg (left bottom) and 60-300 kg (right bottom)

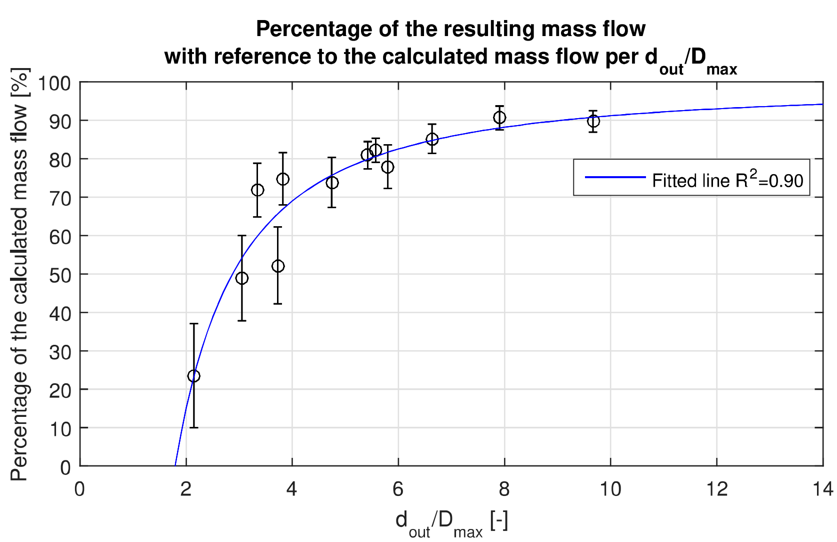

Figure 6.10: The resulting mass flow percentage of the expected values at different ratios d_{out} and D_{max}

6.3.3. Extraction efficiency factor

An extraction efficiency factor on the outlet area of 0.75 was introduced in various literature [27][9]. It is not known what the exact input of the empirical theory is. Different material, particle size distribution and the ratio between d_{out} and D_{max} can all have an effect on this factor. In figure 6.10, the ratio between outlet diameter and particle diameter shows the inequality between the empirical theory and the simulations. Comparing the resulting capacity with the empirical theory without the extraction efficiency factor, is shown in figure 6.11. The fitted line shows an asymptote towards an extraction efficiency factor of 0.71. A check was done by comparing the cross section of the rock bed with the outlet area, resulting in similar factors. This curve could be used to determine the value of the extraction efficiency factor. Take in mind that this is only applicable for the particular shape, particle size distribution, material used in the simulations. The value of 0.75 suits the empirical theory for that certain input, but for these simulations other input parameters were used. For the use of armourstone, with the particle size distribution according to Rosin-Rammler, the uniform shape and the simulation configuration, the extraction factor needs to be adjusted when using the equations obtained by Das and Primo.

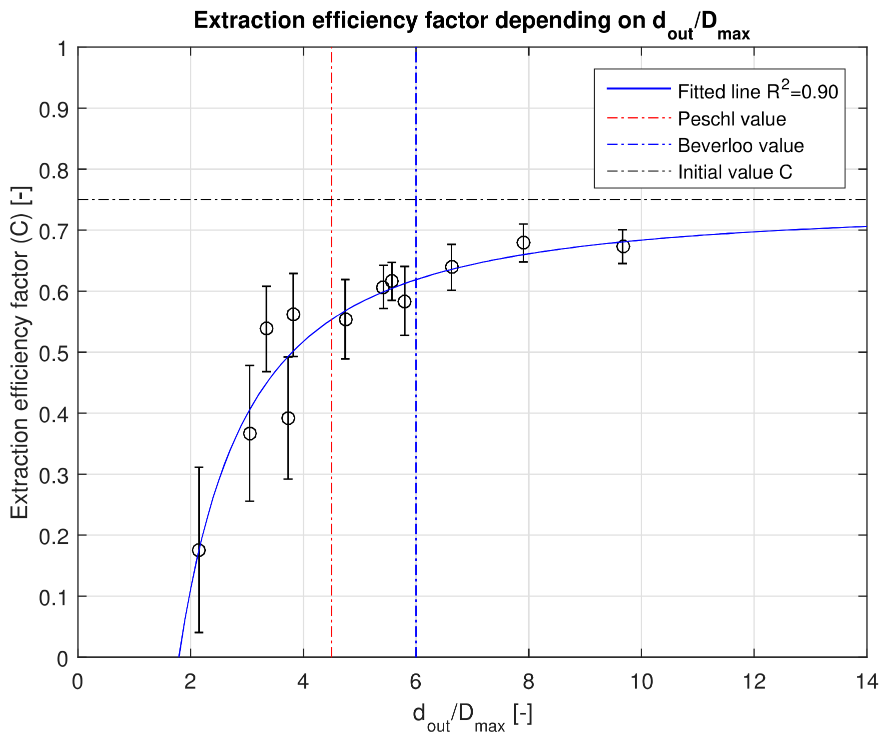

Figure 6.11: Value of C depending on the ratio d_{out} and D_{max} with an asymptote towards 0.71

6.3.4. Mass flow accuracy

The same ratio was used whilst looking at the accuracy of the mass flow. In figure 6.7 and figure 6.10 it was introduced that the standard deviation of the mass flow increases for smaller ratios of d_{out}/D_{max}. In figure 6.12, the accuracy per ratio is shown. According to this figure, the outlet diameter must be 6 times larger than the maximum particle diameter to generate an accuracy below 10% of its mass flow capacity. This is also a reason to design the outlet area with a ratio of 6 with respect to the maximum particle diameter used in the application of the apron feeder.

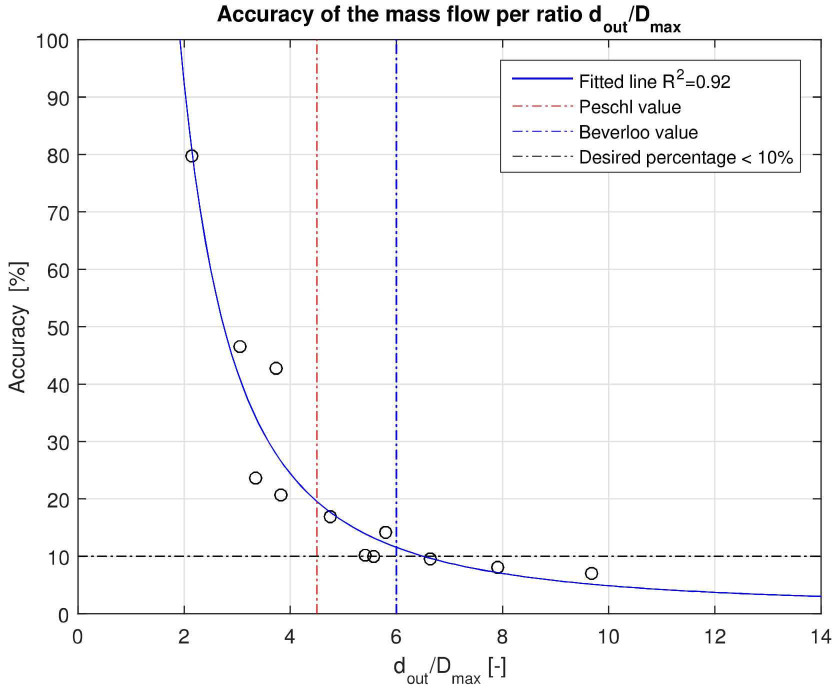

Figure 6.12: Accuracy of the mass flow depending on the ratio d_{out} and D_{max}

6.3.5. Apron feeder width

As demonstrated in the figures 6.6 and 6.7 the gradings 10-60kg and 60-300kg will not result in a mass flow with the desired accuracy. It was demonstrated in figure 6.12, that taking a larger ratio between outlet area and maximum particle diameter, will result in an increase of the accuracy. In figure 6.13 the required apron feeder width for multiple d_{out}/D_{max} ratios is shown. In case a desired mass flow for the 10-60 kg grading needs to be realised, a ratio of at least 6 is used. This results in an apron feeder width of at least — meter, or a standardised size of — meter. If the ratio of 6 is used for the 60-300kg grading, the required apron feeder width for this application is — meter, or a standardised — meter wide apron feeder.

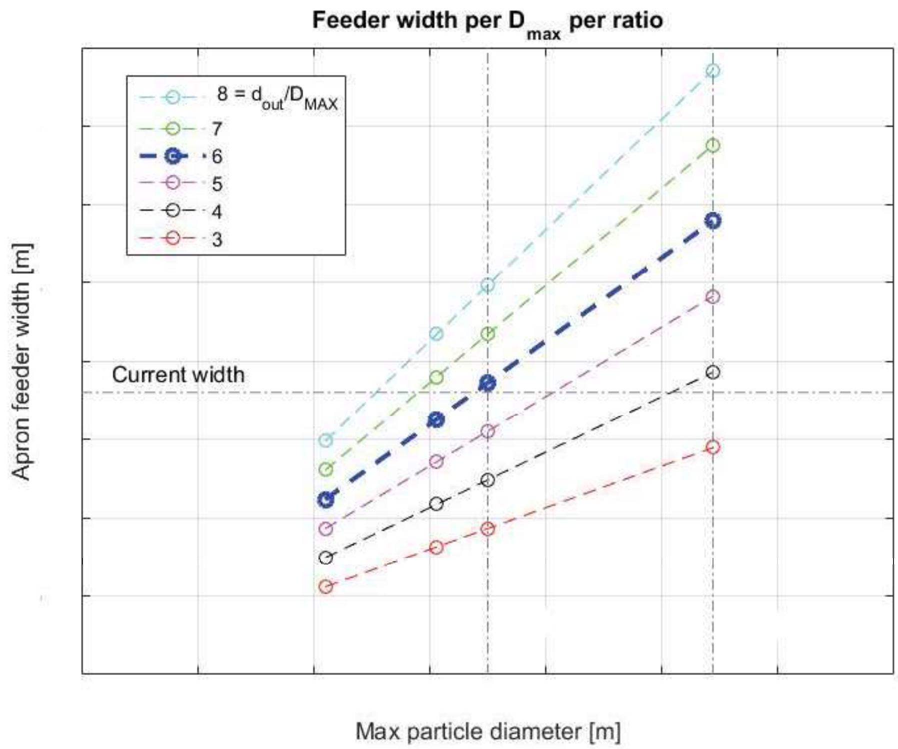

Figure 6.13: The required apron feeder width per maximum particle diameter at different ratio's of outlet diameter and maximum particle diameter

6.4. Trajectory

Observations were done at the chute and the top part of the pipe. Particles leaving the feeder show a trajectory onto the designed chute. The chute directs all the particles with different mass and velocity through the pipe. This was simulated at high and low velocity for the 10-60 kg grading and the 60-300 kg grading. Trajectory was investigated with the initial 0.2 coefficient of restitution (CoR), shown in figure 6.14. However, as mentioned in appendix **??**, put holes were noticed all over the inclined fall pipe on the fall pipe vessel the Seahorse. Therefore, an increase of the coefficient of restitution was looked into. The extreme value for rock on rock of 0.6 [4] was looked into to observe if particles still would enter the pipe. The results of the increased CoR are shown in figure 6.15. The simulations show a complete flow through the IFP. Since the rock on rock CoR can have a wide range depending on the shape [4], more investigation is needed on this value and the chute design, preferable with field experiments.

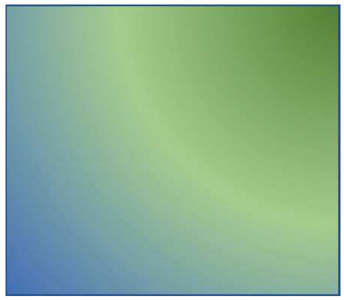

Figure 6.14: Trajectory for simulations with 0.2 coefficient of restitution

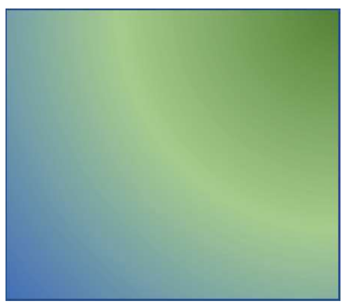

Figure 6.15: Trajectory for 10-60 kg (left) and 60-300 kg (right) with a front view (top) and side view (below) at 0.6 CoR

7

Conclusions

The goal of this work is to realise a concept design for a rock handling system to feed the inclined fall pipe system aboard of the multipurpose vessel Living Stone. This study answers the main research question, which reads as:

- `What is a feasible conceptual design for a Rock Handling System to feed the Inclined Fall Pipe System for the multipurpose vessel Living Stone?`

This work demonstrated that the inclined apron feeder out of the rock hold can handle rock gradings up to 60-300kg and mass flows up to — tonnes per hour for feeding the inclined fall pipe system. This system, as shown in figure 7.1, includes proven technology, has a great allowance in peak production and knows a strong solvability in case of blockage. Final system parameters are shown in table 7.1.

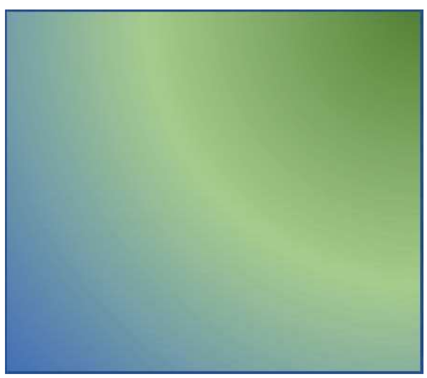

Figure 7.1: The final concept layout coloured in blue

The simulations show that arching occurs at the outlet and that the shear bar height has a great influence on the continuity of the mass flow and its accuracy. The lower the shear bar, or the smaller the outlet area, the more influence arching has on the extracted mass flow.

A ratio between the outlet area diameter and maximum particle diameter, d_{out}/D_{max}, was used to study the effect of the outlet area and the grading on the mass flow and its accuracy. It was shown that for the application of an apron feeder, a ratio of 6 is recommended in order to generate a continuous and accurate flow within 10% of its mass flow capacity. This is in line with a required outlet diameter six times the maximum particle diameter found for hoppers by Beverloo [1].

Since the ratio d_{out}/D_{max} has such an influence on the extracted rock bed and mass flow, the magnitude of the extraction efficiency factor $C_{extraction}$, used by Das and Primo, should be determined per ratio of d_{out}/D_{max}. Figure 7.2 shows the effect of d_{out}/D_{max} on the magnitude of $C_{extraction}$.

The apron feeder width for this application with a square outlet area, should be selected by taking the maximum particle diameter and the advised ratio d_{out}/D_{max} of at least 6 into account. For handling armourstone with a grading up to 10-60kg, it is advised to install a shear bar at — meters from the feeder and to control the mass flow with the velocity of the feeder. In order to generate a 60-300kg armourstone mass flow with the desired accuracy, a feeder width of — meter is required. However, it is questionable if a feed of 60-300kg requires such accuracies and if it is useful to realise a system with a — meter wide feeder. Because of that, the final feeder width of — meter is advised including a shear bar and for larger gradings to remove the shear bar.

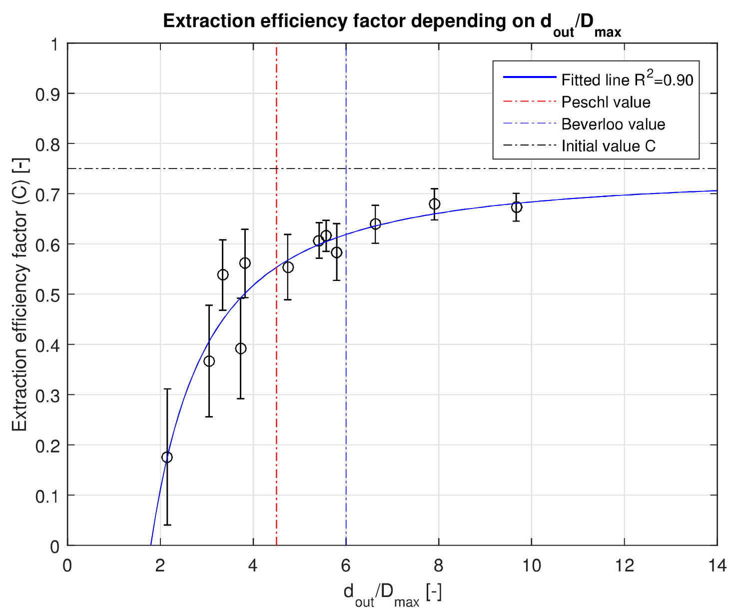

Figure 7.2: Value of C depending on the ratio d_{out} and D_{max} with an asymptote towards 0.71

This work also demonstrated that to research the concept's dynamic bulk behaviour, discrete element modelling can be used. By simulating individual particles and their interaction, the resulting bulk behaviour can be studied. After calibration of the bulk, to make sure it behaves as in the real world, the model can be used. By measuring the mass flow during the whole simulation with a mass flow sensor located on the feeder, the average and fluctuation of the mass flow can be found. With the use of EDEM-software and the Box-Behnken design of experiment method, the optimal configuration was found for —° hopper angle, —° outlet angle and —° feeder angle.

Furthermore, for the application of generating continuous rock flows with gradings including 600 kg rocks, the solutions can be found in the mining industry. Equipment such as vibratory feeders, low profile feeder, chain conveyors and apron feeders are capable of generating mass flows up to — tph for 10-60kg rocks and — tph for 60-300kg rock. Criteria for a rock handling system aboard on the Living Stone were found and ranked from great importance to less importance as follows: Maximum solvability in case of failure or blockage, proven technology resulting in maximum robustness, maximum allowance of peak production, minimum required space for the solution and minimal costs.

It was found that the supplied batch of armourstone by the quarry can have a grading curve within a wide range on the upper and lower end. According to the standard `NEN-EN-13383`, there is no absolute lower and upper limit of the grading. However, a reasonable upper limit of the largest rock occurring in the grading is twice the extreme upper limit of that grading.

Table 7.1: Advised concept parameter values

Parameter	Value	Unit
Length of the feeder	—	[m]
Width of the feeder	—	[m]
Angle of the feeder	—	[°]
Angle of the hopper	—	[°] from the main deck
Length of the hopper	—	[m]
Height of the hopper	—	[m]
Angle of the outlet wall	—	[°]
Angle of side skirts	—	[°] from vertical
Installed required power	—	[kW]
Installed shear bar height	—	[m] for grading up to 10-60 kg

8 Recommendations

For further work on this topic, multiple recommendations are outlined below:

- Real life experiments will be useful to validate the extraction efficiency factor for lower ratios of d_{out}/D_{max} for armourstone with the used particle size distribution. Although the theory of Das[9] and Primo[27] is a result of empirical research, it is questionable if the same material, shape, particle size distribution and ratios between d_{out} and D_{max} were used.
- On the other hand, in the simulations the largest ratio between d_{out} and D_{max} used was smaller than 10. To investigate the location of the asymptote in figure 7.2, simulations need to be done with higher values of this grading. The asymptotic value of $C_{extraction}$ might be 0.75, the same value used by Das and Primo.
- During the simulations in this work the maximum allowed grading curve within the standards was used. It would be useful to know the effect on a more common particle size distribution, meaning a curve in the middle of the boundaries, or a grading curve obtained at the quarry and multiple shapes of particles.
- In terms of simulating rocks and water, the ultimate simulations done to study the rock flow from start to end is done by coupling Discrete Element Modelling with Computational Fluid Dynamics. This way the behaviour of the rock and its final position can be simulated.
- The work showed that the mass flow of armourstone entered the pipe as wanted. However, a wide range of coefficient of restitution was found in literature and other applications of armourstone though an inclined fall pipe show wear and tear through the whole pipe. Therefore, it would be useful to investigate the behaviour at the chute and in the pipe with more precision. Therefore, it is recommended to perform real life experiments of armour rock on the chute and in the pipe. This way, the behaviour of the rock in the top section of the pipe can be simulated and the location for wear plates can be determined with greater reliability.
- Besides that, it is recommended to perform simulations with real shaped particles and a real apron feeder design. In this work the apron feeder was modelled as a plate with 50 mm high cleats, where in real life the plates of the apron feeder are individual with a bit of overlay. It would be interesting if this has an effect on the production but also on the earlier mentioned trajectory onto the chute and into the pipe.
- Required power will be also depending on the ratio of outlet diameter and maximum particle diameter. Within the industry accepted power calculations, the particle size distribution is not mentioned. However, it can be expected that with arching due to large particles the shear force and so the required power increases. Therefore, it is interesting to investigate the effect of arching on the required feeder power at different ratios for d_{out}/D_{max}. Additional interesting research would be to validate the required start up power for a full system with simulations and real life experiments.

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