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Author	A.E. Alangara Napoleon

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Initiator (University)	Prof. dr. ir. G. Lodewijks
Initiator (Company)	Ir. J. Ruijgrok (ESI Eurosilo B.V)
Supervisor:	Dr. ir. D.L. Schott(Internal) & Ir. R. Spargaaren(External)
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Supervisor:	Dr. ir. Dingena Schott	Report number:	2016.TEL.8078
Initiator (ESI)	Ir. J. Ruijgrok	Confidential:	Yes
Supervisor (ESI)	Ir. R. Spaargaren	Specialization:	TEL
		Creditpoints (EC):	35

Subject: **Improving the chute design for handling coal in Eurosilo system**

ESI Eurosilo B.V is a leading engineering and contracting company providing storage solutions for a wide range of non-free flowing bulk solids. The enclosed storage system offered by ESI Eurosilo has proven to meet the requirements of many customers throughout the power, chemical and agricultural industries. Every product is handled by unique system configurations.

The Eurosilo system configuration handling coal consists of a transfer chute which failed due to wear in a few instances.

Your assignment is to create an improved (or new) design for the chute inside the Eurosilo system which has a lesser wear with no compromises on ensuring the flow of materials inside the system.

The report should comply with the guidelines of the section. Details can be found on the website.

The professor,

Prof. dr. ir. G. Lodewijks

Preface

This report has been submitted in fulfillment of the requirements for the award of Master of Science Degree in the faculty of Mechanical, Maritime and Materials (3mE) Engineering, specialization Transport Engineering and Logistics at Technical University of Delft. The research has been conducted for ESI Eurosilo B.V., Netherlands, a leading engineering and subcontracting company proving storage solutions for bulk materials.

The purpose of this research is to create a new or an improved chute design for use in the Eurosilo system. This research has helped me to get a deeper understanding of the benefits and opportunities that Discrete Element Modelling provides to Bulk material Handling design and evaluation. I learnt that the development of a good design doesn't only involve following methodical steps but also applying common sense with a basis of engineering concepts.

I would like to thank Prof. dr. ir. G. Lodewijks (TU Delft) and Mr. J.P.J. Ruijgrok (ESI Eurosilo B.V) jointly for giving me the opportunity to work on this assignment. I would also like to thank my supervisors Dr. ir. D. L. Schott (TU Delft), Ir. R. Spaargaren (ESI Eurosilo B.V) and Ir. Chris Geijs(ESI Eurosilo B.V) for all their help, immense support and guidance to complete my research assignment.

Furthermore, I am very grateful to Mr. Henri de Boer (ESI Eurosilo B.V), for his efforts in helping me, providing information and answering my questions patiently.

A.E. Alangara Napoleon, Delft, 17-11-2016.

Summary

ESI Eurosilo B.V., Netherlands, a leading engineering and subcontracting company, provides storage solutions for bulk materials throughout a wide range of industries ranging from power till chemical and agriculture. Foreseeing the need of enclosed storage systems for coal in thermal powerplants in order to satisfy stringent environmental norms, a high demand for Eurosilo system in the market is expected. To sustain in the market and earn the goodwill of the customers, the transfer chute, which failed due to wear in coal silos in some instances, has been examined.

The objective of the research is to improve the transfer chute design for handling coal in the Eurosilo system. Since the capacity of this research is very vast, the scope was only limited only to the design of improved chutes, analysis of new designs with respect to wear, which is the primary problem, and analysis of the chutes with respect to flowability. Experiments were not conducted to determine the parameters used in the study, they were chosen based on previous research papers or assumed.

As a first step, the researches related to chute design, bulk solid flow modelling and wear were studied. It was found that there are no methodologies for designing chutes for a high velocity transfer application. However, there are some preliminary guidelines for designing a chute which form the basis for developing improved chute designs considering the limitations with respect to the Eurosilo application. Based on the wide number of researches done, it was evident that Discrete Element Methods(DEM) has been widely accepted as a tool for modelling and simulating bulk particle flow. The software, EDEM, developed by DEM Solutions U.K, has been chosen for modelling the bulk particle flow in Eurosilo application and analyzing the performance of the improved chutes with respect to wear and flowability. The inbuilt contact models in EDEM such as Hertz-Mindlin with Archard wear and Hertz-Mindlin with JKR model were found to be very efficient in modelling and analyzing the performance of the chute with respect to wear and handling cohesive materials respectively. On literature study, it was found that the wear rate is proportional to energy dissipation, so simulations for analyzing wear were conducted in a scenario where the bulk particles have highest energy, i.e at expanded position of telescopic chute. In case of flow, it was found that flow is restricted when the body forces in the bulk solid cannot overcome the forces opposing the flow. Hence to evaluate the flow performance of the chutes, the simulations were conducted when the particles are at their lowest energy, i.e retracted chute.

Simulations were conducted with the current chute design to identify the key point indicator and evaluation parameters for the improved chute designs. The maximum wear depth at the end of the simulation was identified to be the basis of analysis. Three different chute designs were developed based on the outcome of the initial simulation, classic design guidelines and taking into account the restrictions specific to the Eurosilo application. The three improved chute designs were chute with a central opening, chute with modified wear plate (with ribs) and the chute with multiple rockboxes. Simulations were conducted in a similar fashion as done for the current chute design. It was found that the chute with modified wear plate and the chute with multiple rockboxes showed reduction in wear depth in the range of 87%, 68% at the maximum and 16% at the minimum respectively when compared to the current chute design. The chute with multiple rockboxes has a reduction in wear depth by

dissipating energy over a wide surface area while in the chute with modified wear plate, the reduction was due to the particle on particle impact by virtue of particle bed formation between the ribs.

To evaluate the flow performance, it was assumed that the particle buildup after flow inside the chute is equivalent to particle agglomeration that would happen over time due to the amount of fines and moisture in the bulk material. Since there was not enough research related to modelling cohesive bulk solid flow in chutes, a qualitative calibration was conducted. Hertz-Mindlin with JKR model was used to provide surface energy density to resemble the moisture content within the particles. Based on trial and error method, bulk solid particles with the surface energy about 25 and 35 J/m^2 were found to be highly cohesive at a poured angle of repose of about 60 deg. Existing particles in the built up area were given inordinately high values of surface energy density to resemble agglomerates while a new particle was defined to imitate the particle flow. The simulations were conducted at a retracted position and it was found that for chute with modified wear plate, the bulk solid flow was not deterred inspite of the reduced cross-sectional area of flow and the low energy of particles. However, in case of chute with multiple rockboxes, plugging happened because of the wall above the outlet. The chute was redesigned, simulated again and result similar to modified wear plate was achieved with the revised design.

Even though, the simulations have not been experimentally validated, DEM provides predictive results for evaluating chutes with respect to wear and flow. Since the evaluation with respect wear was a comparative analysis, it can be concluded that the chute with modified wear plate is the best choice for installing in the Eurosilo system. Further research is recommended to identify the actual life of the chute in terms of wear and assessment of the chute for flow based on experimental validation with respect to the bulk material handled. There has been no models developed to predict particle agglomeration and DEM could be an useful tool to predict the flow performance in worst case scenarios. There are still a lot of challenges prevailing in modelling cohesive bulk solid flow and modelling a wide range of particle sizes, which are expected to be overcome in the near future.

Contents

1. Introduction

1.1 Background

Storage and handling of bulk materials in any logistic chain requires immense care and effort. Mammoth silos, by ESI Eurosilo BV, provide a complete solution for the storage of bulk solids in various industries in a very economical and environmental friendly manner. The application of Eurosilos varies over a variety of industries from potato starch, fertilizers till coal in power plants.

With increasing need for the reduction of pollution due to coal fired power plants, coal handling and storage inside power plant has become prime importance for stake holders in recent times. Even though there are numerous options for covered storage, Eurosilo proves to be the best amongst the prevalent closed storage solutions for bulk materials. The mammoth silo offers a completely controlled and enclosed environment for a bulk material storage.

The silo structure is made up of a concrete foundation and cylindrical wall with a structural roof enclosure. There is a central slewing piece which is hanging from the roof of the silo which has the slewing platform. The slewing/rotating bridges are mounted on the central structure and supported on either end (silo wall) by means of rails to facilitate rotation. There are different configurations of machinery inside the silo engineered to handle different materials in a very efficient manner such as core flow with or without the central column, slotted columns for handling hygroscopic materials and shutter column system for handling products which tend to fluidize during the filling process. For coal, the core flow without the central column is followed. Coal is fed into the silo by means of infeed conveyors on the top of the silo (the direction of coal flow is shown in figure 1 with red arrows). The conveyors transfer the coal on to a transfer chute, after which the coal passes down through a telescopic chute and is stacked by means of the screw augers. The screw auger frame is hanging from the slewing bridges by means of wire ropes and winch system and houses two screw conveyors which would stack and reclaim the bulk material. The screw auger frame can be lifted or lowered by means of the winch system, also could be rotated by rotating the swiveling bridges.

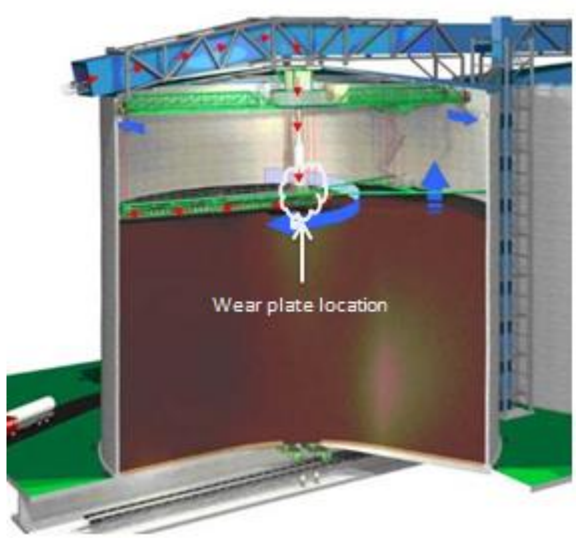


Figure 1 Location of the wear plate

The transfer between the telescopic chute and the screw conveyor is achieved by means of a wearing plate inside a stone box chute, which changes the direction of the coal towards the screw auger. The location of the wear plate has been highlighted in figure 1. In coal silos with such an arrangement, it has been found that the wear plate fails sooner with the formation of holes. There were two cases with such an issue, one was the Helsinki power plant where the plate wore off in a very short period of time while in case of Lunen, the wear plate wore off almost at the end of 2 years of operation. Better design of this wearing plate would eradicate the downtimes due to replacement of the plate, increase the performance of the machinery inside the silo and gain good will of the customer.

The challenge is to improve the design of the wearing plate/transfer chute to have a better operational period with no compromises on the flowability and the space available. In order to do that, the interaction between the material and the wearing plate has to be understood and analyzed. This is where simulation plays a pivotal role. Simulation enables to mimic the material properties and environment in which the interaction between the bulk material and the equipment takes place. The parameter influencing the interaction could be modelled and the effect could be studied thereby enabling us to develop a better design, which would take a lot of time, effort and money otherwise.

1.2 Objectives

The objective of this study is to improve the design of the wear plate/stone box chute that facilitates the transfer of coal from the telescopic chute to the screw auger. To achieve this, a virtual environment is developed to simulate the interaction between the coal particles and the wear plate. The chute model is based on the wear plate designed for Lunen case. Finally, the improved design of the wear plate is finalized and simulations are carried out to understand its performance in different scenarios.

1.3 Research Questions

In the due course of achieving the above objective, a few chute designs are developed and the following research question will be answered with the help of the simulation results:

1. What is the best improved chute solution with respect to wear and flowability for Eurosilo application?

While modelling and simulating the material flow to analyse the performance of the chutes, the following questions will be addressed as well.

- To what extent literature could be of use to develop new designs for Eurosilo case?
- What are the available theories and models based on which the new chutes could be evaluated for wear?
- How should the modelling and simulation environment be defined to effectively evaluate the performance of the developed chute designs?
- What are the parameters to be taken into consideration while designing a wear plate/chute for Eurosilo application?

1.4 Scope and limitations

The scope of this study is enormous. For the sake of clarity and focus on the objective, the scope and limitations of the listed below:

1. The scope of the analysis is restricted to the transfer point between the telescopic chute and the screw auger.
2. The material under consideration is coal.
3. In virtue of the main focus of the study, particle breakage/degradation is not taken into consideration.
4. The work will only cover the concepts of chute design, wear and extreme flow conditions in Eurosilo application.
5. Specific analytical flow model for the improved chute designs have not been developed or reviewed.
6. Experiments have not been conducted for determining the parameters used in the study. All the parameters have been chosen based on existing research papers or assumed, in case there is no research paper available.

1.5 Thesis Structure

The thesis is based on the specifications of coal handling system in a thermal power plant at Lunen, Germany. However, this study is intended to be generic in nature, making it a basis of designing chute box/transfer equipment for such a transfer application. The fundamentals of the theories, the assumptions and approach for this research have been described in the report in Chapter 2 and the choice of simulation method is made. Firstly, the model has been set up to replicate the current situation and the wear pattern. The results are analysed and the key performance indicators for the analysis of the improved design are determined in Chapter 3. Few chute models, which could probably ensure a lower wear during operation, have been conceptualized based on the available theories and the limitations related to the Eurosilo application. Simulations are conducted to derive the KPIs for the improved chute designs and the performance of the chute design with respect to wear are analysed in Chapter 4. The worst possible flow condition scenario for the analyzing chute performance is conceptualized and the same is made to model the same qualitatively and analyse the chute performance with respect to flowability in Chapter 5. Finally conclusions have been drawn with answers to the research questions and recommendations for future research have been addressed.

2. Literature review

In order to achieve the objective and the answers to the research questions, the theoretical aspects of the system need to be reviewed and practical aspects of the system should be understood. Our main objective is to improve the design of the chute for the coal transfer inside Eurosilo system and assess the performance of the chute by simulation. This chapter delves into the theoretical background of the areas of interest in order to make a platform for the analysis and discussions in the upcoming chapters.

2.1 Description of the process and the problem

Chutes are used in the transfer of bulk material between bulk material handling equipments, primarily conveyors. When the discharging and the receiving points are stationary, then the chute is a fixed and static structure. When any one of the equipment, discharging or receiving, is movable vertically, then telescopic chute is used for the transfer. Telescopic chutes finds its use in a variety of applications, such as stockpiling, ship or barge loading, truck loading. It can also be noted that the telescopic chutes are imperative, where dust control is of prime importance.

In a coal silo, the discharge from the conveyor occurs at the top of the silo and the coal has to be stacked in layers from the bottom, gradually to the top. Typically, for a 100,000 m^3 coal silo in case of Lunen powerplant, the filling height is about 42.5 m. Hence the telescopic chute is used to convey the coal onto the screw conveyor. A typical construction of the telescopic chute in the coal silo is shown below.

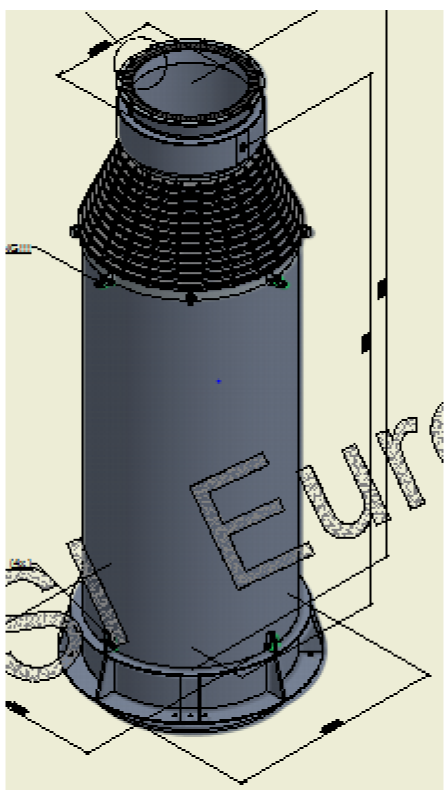


Figure 2 Telescopic chute - retracted position (Source: ESI Eurosilo B.V)

The telescopic chute can be expanded or retracted to any length, thereby facilitating the fall of coal to that particular height. The chute is made up of concentric tubes of fixed length and could slide over each other. The expansion or retraction of the telescopic chute is usually achieved by means of wire rope and winch in many applications. In a coal silo, the expansion and the retraction of the telescopic chute doesn't involve a drive mechanism. The top flange of the innermost tube in a telescopic chute is fixed to the transfer chute of the feeding conveyor while the bottom flange of the outermost tube is connected to the chute box on top of the screw conveyor.

The axis of the telescopic chute coincides with the axis of the silo and expands by gravity when the screw auger frame is lowered and retracts when the screw auger frame is lifted to a higher position. The connection of the telescopic chute with the chute box is shown in the figure below.

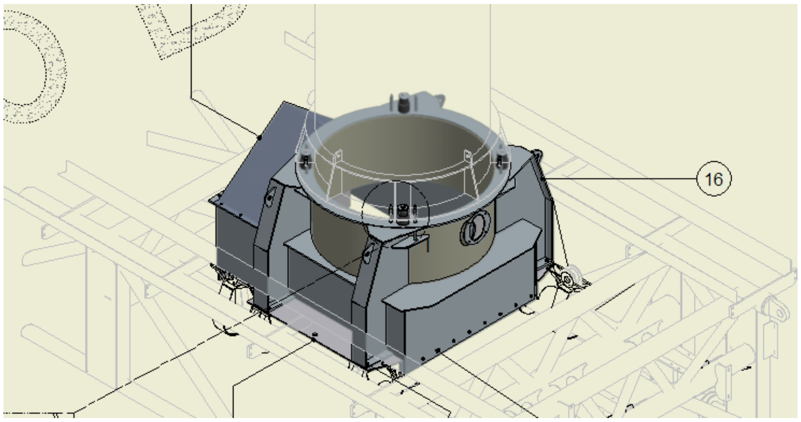


Figure 3 Chute box arrangement beneath the telescopic chute (Source: ESI Eurosilo B.V)

The chute assembly beneath the telescopic chute is also depicted in the figure 3. The chute assembly consists of a box like structure made up of welded construction and fastened to a wear plate on which the coal impacts and deviates towards the screw conveyor. The wear plate is made of creusabro liners while the chute assembly is made up of steel. The design of the wear plate on which the material impacts is depicted below.

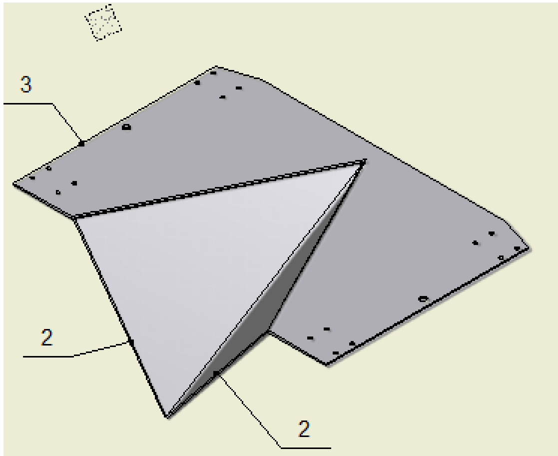


Figure 4 Wear plate (Source: ESI Eurosilo B.V)

The wear plate is found to fail after a period of operation inside the coal silo and a picture of the worn out plate from the installation at Lunen has been shown below.

Figure 5 Wear plate failure at Lunen power plant (Source: ESI Eurosilo BV)

The coal impacts on the wear plate and forms a bed on the horizontal part. This forms a protective layer to reduce the interaction between coal and the wear plate. On the first impact with the wear plate, the velocity of the coal particles is reduced. The V-shaped spout like section of the chute facilitates the flow of the coal in the direction of the screw auger.

To gain insights on the failure of the wear plate, the literature behind the design of chutes, wear mechanisms have been studied. This would enable to clarify the design guidelines to help in designing a better transfer point.

2.2 Design of chutes

As per Oxford dictionary, a chute is defined as “a sloping channel or slide for conveying things to a lower level”. This channel could be a mere plate or a structure with any type of cross section, configuration depending on the application. When large bulk materials are handled, chutes are employed to direct the flow of material from the outlet of a machine or process or a storage device to the inlet of the next equipment (Wensrich, 2003). In majority of the scenarios in bulk handling systems, chutes are used to transfer bulk material from a conveyor to another. Depending on the application, chutes are mainly classified as feed chutes (velocity around 0.3 m/s), or transfer chutes (velocity of 1m/s and above) (Roberts, 2003). There are various types of chutes employed in the bulk material transfer such as, inline transfer chutes, rockbox transfer chutes, hood and spoon design, combined rockbox and chute, cascade chutes, telescopic chutes (Kruse, 2013). Each type of chute finds its place depending on the bulk material characteristics and the material transfer configurations.

The first step to design a chute is to understand the properties of the material handled and the application for which the chute is designed. Typically for a conveyor transfer, the design of the chute should be such that it ensures efficient transfer of bulk material without spillage, blockages with minimum chute and belt wear (Roberts, 2003) (Frittella & Smit, 2015).

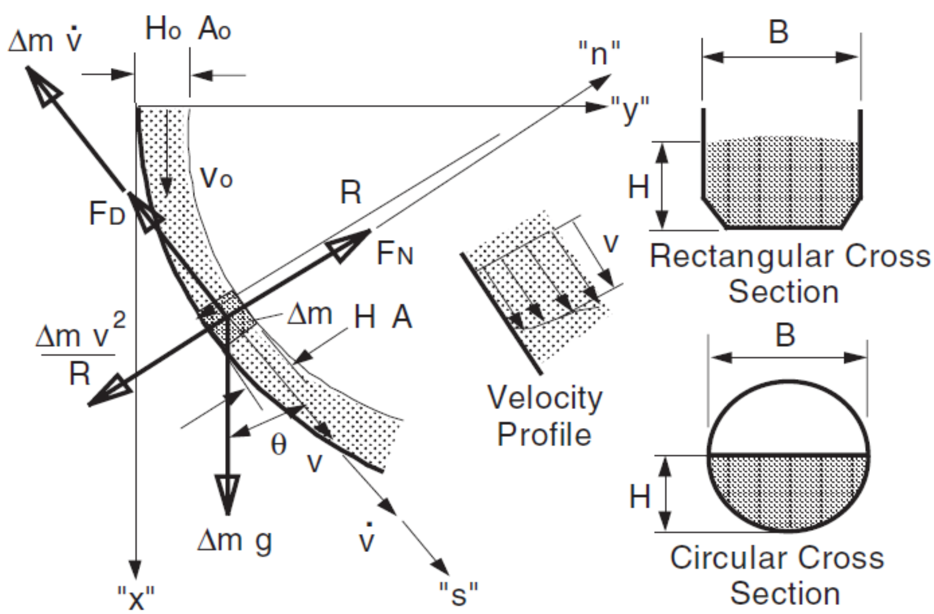


Figure 6 Chute flow model (Roberts, 2003)

2.2.1 Chute design guidelines

Conventional chute designs are mainly performed with the considerations of accelerated flow assuming that the material is always in contact with the chute bottom and side walls (Stuart Dick & Royal, 1992). Continnuum approach has been used to model the flow of bulk particles within the coal and bulk solid motions are described by a lumped parameter model as in figure 6 (Roberts, 2001). Before delving into the conventional chute design for transfer for bulk materials under gravity, we need to understand the basic design principles to be considered while designing a chute (Stuart Dick & Royal, 1992).

a. Prevent plugging at impact points
   This is dependent on the angle of impact/impingement of the bulk solid stream on to the chute surface and the wall friction angle between the bulk solid and the chute wall. The wall friction angle could be defined as the inclination angle of the wall at which the material will slip and start sliding across the wall. The smoother the chute surface, the lower the wall friction angle. If the angle of impact is too high, the effect of wall friction angle on the flowing stream is negligible.
b. Ensure that the bulk material accelerates or decelerates sufficiently to match the receiving equipment's speed
   The bulk material will accelerate or decelerate based on the angle of chute surface at that instantaneous position and the wall friction angle. The cross section of the bulk stream increases when it decelerates and reduces when it accelerates. Hence the idea is to have the chute cross

section sufficient enough to ensure flow even when the bulk stream is at the point of minimum velocity.

c. Control stream of particles
The direction of the flow of particles should be regulated to ensure that there is no spillage during transfer. Chute with a curved cross section concentrates the load to the centre which will enable the chute to self-clean. Chutes with square or rectangular cross sections often results in concentration of loads in the corners and material buildup causing plugging. Controlling the stream of particles towards the centre and having a desired exit velocity would ensure less spillage and less wear on the receiving equipment.

d. Minimizing abrasive wear on the chute surface.
The sudden changes in the direction of flow of the material and the free fall height could lead to chute surface wear by virtue of high impact pressure. Wear is minimized by reducing the impact angle of the bulk stream when it enters the chute to a minimum thereby reducing the impact pressure and ensuring the momentum of the flowing material. For highly abrasive materials rockboxes are preferred. This would minimize the amount of chute surface in contact with the material at the impact points.

e. Control generation of dust
To avoid dust generation, the design must ensure the material to be in contact with the chute surface, concentrate the material stream and keep impact angles small and the velocity of the chute as near constant as possible.

2.2.2 Mathematical model for curved chute design

As mentioned in previous section 2.2.1, continuum method has been conventionally used for defining the granular flow through chutes and mathematical models for chute flows have been developed by Roberts after a wide range of studies (Roberts, 2001). In these models, the fixed volume elements, assigned with appropriate properties, are used to define the chute space. The volume element changes its characteristics as it flows under the influence of gravitational forces, surface interactions and internal forces. Hence the primary importance is given to the identification of the flow properties and the friction characteristics of the material and the wall (McILVENNA & Mossad, 2003).

For the mathematical model, the particle is generally assumed to fall a vertical height h(fig 7), before making contact with the curved chute. The curved chute is assumed to have a rectangular cross-section.

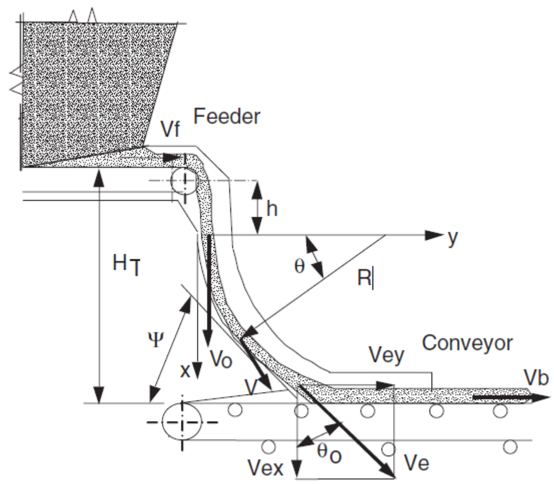


Figure 7 Typical curved chute model (Roberts, 2003)

For the free fall section, the velocity v_i can be estimated from,

$$v_i = \sqrt{v_{f_o}^2 + 2gh} \tag{1}$$

The above eqn neglects air resistance, which is likely to be small in a chute. However considering air resistance into account, the relationship between velocity $v_i$and the height is given by,

$$h = \frac{v_\infty^2}{g} \, log_e \frac{(1 - \frac{v_{fo}}{v_\infty})}{(1 - \frac{v_i}{v_\infty})} - \frac{v_i - v_o}{g} v_\infty \tag{2}$$

where v_∞ = terminal velocity
v_{fo} = vertical component of bulk solid discharging from the feeder.
v_i = velocity corresponding to the drop height ‘h’ at point of impact with chute.
The material strikes the chute and velocity of the material changes after impact.

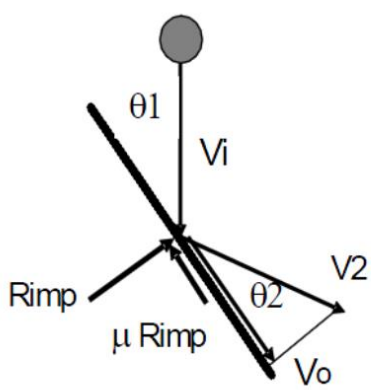


Figure 8 Impact model (Roberts, 2003)

The impact model of the material is given in the figure 8. When the material strikes the chute at an angle of θ_1 and a velocity of v_i , the velocity after impact is given by,

$$\frac{v_o}{v_i} = cos\,\theta_1 - \mu(1+e)\,sin\,\theta_1 \tag{3}$$

Where e = restitution factor, $0 < e < 1$

μ = kinetic friction, which is lower than the equivalent friction used in chute.

The material flow around the curved chute is depicted by the chute flow model as given in figure 6. The drag force experienced by the material is given by,

$$F_D = \mu_e F_N \tag{4}$$

Where, μ_e = equivalent friction which takes into account the actual friction coefficient between the bulk solid and the chute surface, stream cross section and the internal shear of the bulk solid.

F_N = normal force component.

Studies performed by Roberts (1969) (1971) (2001) (2003), showed that under thin stream accelerated flow through chutes, approximately 82% of the energy dissipation is due to the material sliding on the chute bottom, about 9% losses due to sliding against the side walls and with the remaining 9% due to intergranular friction.

Considering a chute of rectangular cross-section as shown in Figure 6 & 9, μ_e can be approximated as,

$$\mu_e = \mu[1 + K_v \frac{H}{B}] \tag{5}$$

Where μ = actual friction coefficient for bulk solid in contact with chute surface.

K_v = pressure ratio, normally K_v = 0.4 to 0.6

. H = depth of the flowing stream as shown in figure 9.

B = width of the chute as shown in figure 9.

The equivalent friction for chutes of varying width as shown in figure 9 could be given by

$$\mu_e = \mu\left[1 + K_v\left(\frac{H}{B-2s\tan\lambda}\right)\left(1 + \frac{\tan\lambda}{\mu}\right)\right] \tag{6}$$

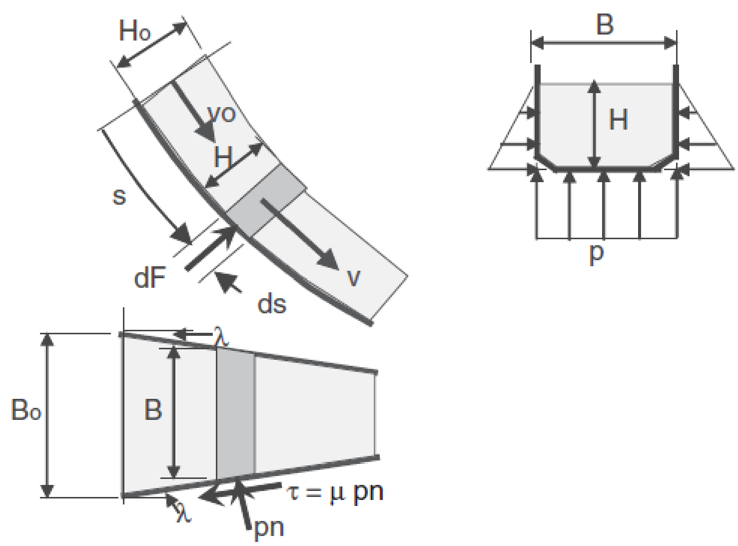


Figure 9 Chute flow model (Roberts, 2003)

To incorporate the varying equivalent friction at different sections along the chute, the following equations could be used.

For a chute with uniform cross-section,

$$\boldsymbol{\mu_e = \mu \left[1 + \frac{C_1}{V}\right]} \tag{7}$$

Where $C_1 = K_v \frac{v_o H_o}{H}$

v_o = initial velocity

H_o = initial stream thickness

For a converging chute,

$$\boldsymbol{\mu_e = \mu \left[1 + \frac{C_2}{vB^2}\right]} \tag{8}$$

Where $C_2 = K_v B_o H_o v_o \left(1 + \frac{\tan\lambda}{\mu}\right)$

$B = B_o - 2s\tan\lambda$

B_o = initial chute width

Based on lumped parameter approach, a chute model, as shown in figure 6, having mass element Δm moving along the chute bottom is analyzed based on dynamic equilibrium conditions with respect to tangential and normal components moving coordinates. Calculating the normal and tangential forces at any instant θ and substituting in equation $F_D = \mu_e F_N$ gives rise to the following differential equation,

$$\frac{dv}{dt} = g\cos\theta - \mu_e\left(\frac{v^2}{R} + g\sin\theta\right) \tag{9}$$

Where θ changes with position,

μ_e is a function of velocity as defined earlier

R is the radius of curvature and not necessarily a constant.

Considering a curved section of the chute of radius R and μ_e assumed constant at an average value for the stream, solving the above equation will give the equation find the velocity of the stream at any value of θ.

$$v = \sqrt{\frac{2gR}{1+4\mu_e^2}\left[(1-2\mu_e^2)\sin\theta + 3\mu_e\cos\theta\right] + Ke^{-2\mu_e\theta}} \tag{10}$$

When $v = v_o$ and $\theta = 0$, $K = v_o^2 - \frac{6\mu_e gR}{1+4\mu_e^2}$

This gives an approximate solution of the velocity of the particle at a position θ. To get a more exact solution, the variation of μ_e as described earlier should be taken into account. It is evident that the friction characteristics between the wall and the material play a vital role in determining the flow of bulk material in a chute. This is further discussed in detail in the next section.

2.2.3 Parameters for conventional chute design

For a conventional chute design, typically a curved chute is used for transfer between two conveyors, where the bulk material flows by gravity and is constantly in contact with the chute, the wall friction angle is the predominant factor to be measured. The wall friction angle depends on the properties of both bulk solids and the wall material along with some external factors. The parameters that influence the wall friction angles are stated below (Roberts, Ooms, & Wiche, 1991).

1. Bulk Solid Parameters

- Particle size and size distribution
- Particle shape
- Particle hardness
- Moisture content
- Particle density
- Bulk density
- Surface chemistry characteristics
- Temperature

2. Wall Surface Characteristics

- Roughness and roughness spectrum
- Hardness
- Chemical composition
- Temperature

3. Loading and Environmental Factors

- Normal pressure
- Relative rubbing or sliding velocity
- Temperature and humidity or moisture conditions
- Wall vibrations

For measuring the wall friction between bulk material and the wall material in applications where materials undergo higher compressive stresses such as silos, bins, hoppers, Jenike's shear tester was originally used. The same has been modified as an inverted shear tester to measure the shear stress under lower compressive stress, enabling the design of chutes (Roberts, 2001). Using this shear tester, the shear force under which the material fails at varying normal force is determined and the wall yield locus, shear stress versus normal stress is plotted.

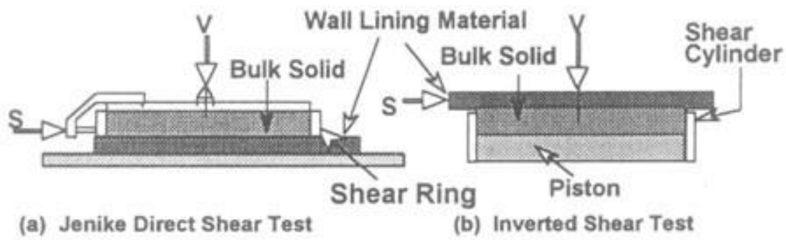


Figure 10 Jenike's direct shear tester and inverted shear tester (Roberts, Ooms, & Wiche, 1991)

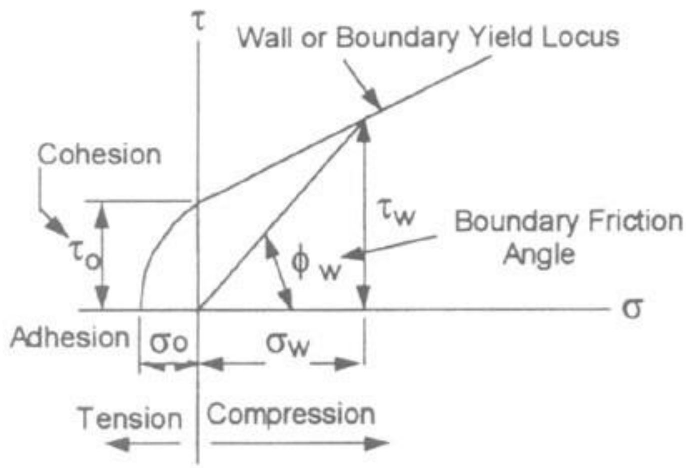


Figure 11 Wall yield locus and boundary characteristics (Roberts, Ooms, & Wiche, 1991)

Figure 11 illustrates a typical wall yield locus for cohesive material. The wall friction angle $\emptyset_w$ is given by:

$$\emptyset_w = \frac{\tau_w}{\sigma_w} \qquad (11)$$

where τ_w is shear stress at the wall, σ_w is the pressure acting normal to the wall.

The disadvantage of the direct shear tester is the inability to determine the wall or boundary yield locus in the low pressure and tensile stress zones. This difficulty was overcome in the inverted shear tester, Figure 10(b) and the cohesion and adhesion values could be determined by extrapolating the yield locus as shown in figure 8 (Roberts, Ooms, & Wiche, 1991) (Roberts, 2001).

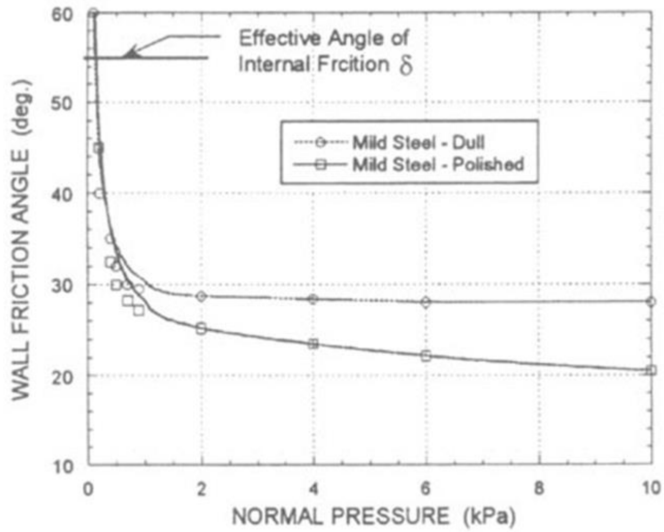


Figure 12 Wall friction angle vs Normal pressure (Roberts, Ooms, & Wiche, 1991)

From experiments, it is observed that the wall friction angle decreases with increasing pressure on the bulk solid material as shown in the figure 12. However, wall friction angle is usually less compared to the angle of internal friction, which forms an upper bound limit. At lower pressure, the bulk solid tends to fail more by internal shear, rather than by boundary shear (Roberts, 2001). The moisture content and the amount of fines also influence the values of wall friction angle and the angle of internal friction of the bulk solid. Both can cause building up of coal material on the wall surface and could lead to plugging of chutes. Hence chutes need to be designed considering the maximum moisture content and the percentage of fines in the coal into account.

In general the bulk material fails when the body forces in the bulk mass are able to overcome the forces that resist the flow. The resisting forces are usually due to shear (in case of free flowing materials) and and a combination of shear and adhesive, cohesive forces (inherently coherent materials, materials with high moisture content and fine powders) as shown in the figure 13. In a dynamic system such as bulk transfer, the body forces are normally influenced by the bulk density and the velocity of discharge of the bulk material.

Roberts, Ooms & Wiche (1991) also described the different conditions due to which a cohesive bulk solid may fail. In general case as shown in figure 14, the failure envelope of a cohesive bulk solid is always greater than the failure envelope at the boundary(wall). Hence the bulk solid fails at the wall surface rather than internally. In a special case (figure 15), where the cohesive bulk solid develops lower strength at lower consolidation pressure when compared to the corresponding strength at the boundary, the bulk solid shears internally leaving a layer of solid adhering to the chute surface.

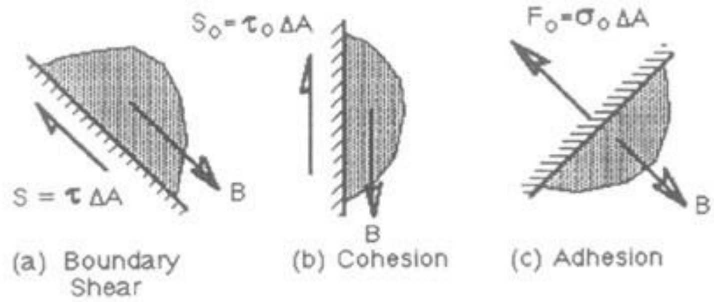


Figure 13 Bulk material failure conditions (Roberts, Ooms, & Wiche, 1991)

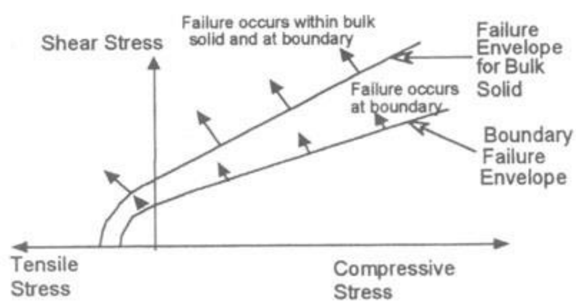


Figure 14 Failure Envelope - general case (Roberts, Ooms, & Wiche, 1991)

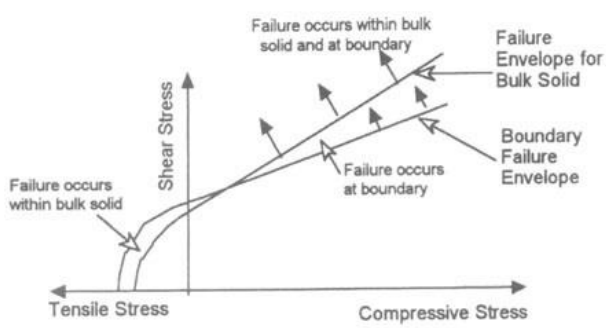


Figure 15 Failure envelope - special case (Roberts, Ooms, & Wiche, 1991)

Hence for the failure to occur, the shear stress versus normal stress state within the bulk solid should always be higher than the failure envelope of the boundary (wall).

2.3 Wear mechanisms

In general, wear is defined as the removal of material from a solid surface as a result of mechanical action. (Rabinowicz, 1976). As per DIN 20320, this progressive loss of substance could be caused by any mechanical action on a solid surface such as contact and relative motion with a solid, liquid or gaseous counter-body. When two surfaces come together, they come into contact at the tips of their asperities and there is a very small area of contact subjected to a load, normal or shear (ARCHARD, 1953). When there is further motion amongst one of the surfaces, the total area of the singular contact varies and the surfaces fail at the vicinity of contact due to various phenomena. The wear theories explaining such phenomena are described below.

2.3.1 Wear theories

2.3.1.1 Adhesive wear

Adhesive wear occurs as a result of momentary adherence of two sliding surfaces and when shear occurs, it takes place at some point other than the original interface (Rabinowicz, 1976). The particle that adheres to the other surface comes loose at a later stage, thereby showcasing wear. Adhesive wear is considered to be the most occurring wear, which is always present.

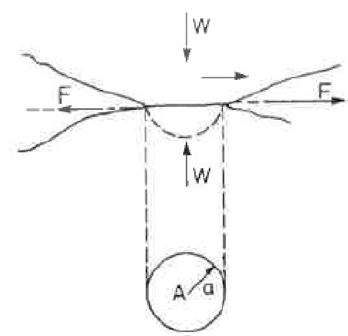


Figure 16 Adhesive wear model

As depicted in the figure 16, there is a true area of contact that is formed by the asperities in contact. It is so small that the contact pressure had an upper limiting value set by the hardness, H of the softer of the two contact bodies.

Considering the total load support and the total area of contact, it is derived that the total wear rate is given by (Archard, 1980),

$$\boldsymbol{\frac{V}{L} = \frac{1}{3} \cdot \frac{K_1 W}{H_s}} \tag{12}$$

where V is the volume of material removed, L is the sliding distance, K_1 is the proportionality constant, W is the load and H_s, hardness of the softer of the two contacting bodies. If K= K_1/3, then the equation becomes,

$$\frac{V}{L} = K.\frac{W}{H_s} \tag{13}$$

where K is the wear coefficient between the sliding surfaces.

2.3.1.2 Abrasive wear

In this type of wear, it is assumed that the abrasive elements are so sharp to indent the opposing surface. Assuming that the abrasive particle is of a conical shape with a semicone angle of θ, and the load W, hardness H, sliding by a distance L, the wear rate is given by (Archard, 1980)

$$\frac{V}{L} = K_2 \left[\frac{2\cot\theta}{\pi}\right].\frac{W}{H_S} \tag{14}$$

where cot θ is the average value of all abrasive particles. This can be re-written once again in the generalized form of the wear equation (12) as given above.

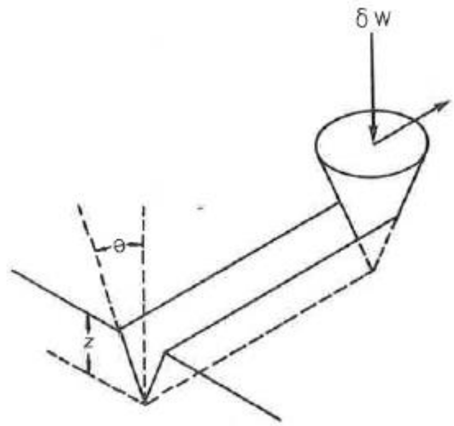


Figure 17 Abrasive Wear Model

2.3.1.3 Corrosive wear

When a material surface wears off due to corrosion, it is classified as corrosive wear. In this process, corrosion of a surface occurs, sliding happens and removes the corrosive product to expose new surface to undergo corrosion and so on.

Considering two surfaces in contact as described in section 2.3.1.1 and a reactive environment which produces a slow growth of films upon the contacting surfaces (like rusting) .These films remain undamaged until they reach a critical thickness λ, beyond which the films are liable to be removed by rubbing. The total wear rate in this case is given by,

$$\frac{V}{L} = \left[\frac{K_3\lambda}{2a}\right].\frac{W}{H_S} \tag{15}$$

where K_3 represents the proportion of events contributing to the wear volume. This equation can be rewritten to the generalized form of wear equation (12) replacing (K_3 λ/2a) by K, the wear coefficient. The wear rate increases based on the increase in the chemical reactivity in the environment and the wear surfaces and the temperature.

2.3.1.4 Fatigue wear

Fatigue wear occurs in continuous process which includes contact in the form of pitting and rolling. This type of wear is so severe and plays a major role in the failure of the contacting surfaces. The number of stress cycles to cause failure of a surface decrease with the increase stress. The depth of material removed corresponds to the position of the maximum shear stress. The mathematical model for calculating the wear rate is similar to the adhesive wear model, however K represents the proportion of all contacts which contribute worn particles. In other words,

$$\frac{\boldsymbol{1}}{\boldsymbol{K}} = \boldsymbol{number\ of\ stress\ cycles\ to\ failure}. \quad (16)$$

Based on the above theories, it could be easy to identify what form of wear occurs in a particular application. However, there has not been much research in identifying the wear constants and its variations under different circumstances. This has been identified due to the statistical scatter in the experimental results of wear testing (Rabinowicz, 1976). This leads to some problems in the models used. In case of adhesive wear, the reason is accounted to the process of wear itself, which is implausible (Rabinowicz, 1976). It is due to the fact that during adhesive wear, even though it is assumed that the weaker material with lesser hardness tends to wear and shears, it is also possible that the surfaces with greater mechanical strength shears every once in a while. Abrasive wear is considered to be the most studied and understood form of wear however there is no comprehensive model to inculcate the application of polished surfaces. Similarly corrosive wear is qualitatively understood well however the process is governed by so many factors and has not been comprehensively studied. Surface topography and the role of environment are important factors that influence contact stresses in every wear phenomenon which are nearly impossible to be accounted for in the models.

2.3.2 Wear in chutes

Based on various experiments, wear occurring in the chutes due to bulk solid flow have been identified to be a combination of abrasive and impact wear (Roberts, 2003). Considering a curved chute of rectangular cross section, the abrasive factor for the wear of chute bottom surface is given by

$$\boldsymbol{W_c} = \frac{\boldsymbol{Q_m K_c} \tan \emptyset_{\boldsymbol{w}}}{\boldsymbol{B}} \boldsymbol{N_{WR}} \quad (17)$$

where, W_c is the abrasive wear factor (N/ms),

N_{WR} is a non-dimensional abrasive wear number and is given by $N_{WR} = (v^2/R) + gsin\theta$.

Q_m is the mass flow rate (kg/s),

$K_c = V_s/V$

V = average stream velocity at section considered

V_s = rubbing velocity for bulk solid on chute bottom-surface

$\emptyset_w$ = friction angle for bulk solid on chute surface

B = chute width

R = radius of curvature

θ = chute slope angle measured from the vertical.

It is assumed that the side wall pressure increases from zero at the stream surface to a maximum value at the bottom of the stream and the average wear on side walls is estimated as

$$W_{csw} = \frac{W_c K_v}{2K_c} \quad (18)$$

where, W_{csw} = abrasive wear factor on the chute side wall (N/ms)

K_v = pressure ratio, (0.4 to 0.6)

Impact wear in chutes are considered to occur at the points of first impact or sudden change in direction. For chutes made of ductile material, highest wear is when the impingement angles are low in the order of 15^o to 30^o, while for the hard brittle materials, the greatest impact wear is at steep impingement angles (Roberts, 2003).

2.4 Choice of simulation method

Design of transfer chutes using lumped parameter model, as developed by Roberts (A.W.Roberts, 1969) (Roberts & Arnold, 1971) (Roberts & Scott, 1981) (Roberts, 2003) has been widely followed all over the world in different case scenarios. Based on the same concepts, simulation of bulk solid flows have been performed is softwares like Fluent using Eulerian model (McILVENNA & Mossad, 2003). Modelling the particle stream using a continuum approach is more on a macroscopic scale in steady state, which makes it difficult for the engineers to conceptualize or visualize complex situations. The material properties and the bulk properties of the material to be handled are studied extensively to understand the criteria for flow and used in these models. However, these models provide only a 2D analysis of the systems, which makes it difficult to analyze the design for situations such as cohesion, wear, handling multiple commodities etc. The properties of bulk solids tend to vary throughout the process hence defining very general continuum models applicable for many situations is tedious (Orlando & Maynard, 2016).

In recent times, Discrete Element Method (DEM) has gained popularity and has become a widely accepted technique for addressing engineering problems related to the flow of bulk solid materials. The limitation of continuum methods to account for local variation in particle concentration and localized flow behaviour can potentially be modeled using DEM (Grima A. P., 2011). There are a vast number of researchers who have recommended and used DEM for optimizing and improving design of bulk material handling equipments (Grima A. P., 2011, pp. 14,15). The concept of discrete element modeling and the simulation technique based on the same has been described in the section below.

2.4.1 Discrete Element Method

DEM is a numerical method for computing the motion, displacement and collisions (or interactions) between particles at discrete time events known as time steps. This means the motion of the bulk material is analyzed particle by particle and the particle interaction is monitored for every contact. DEM employs a large number of variables or properties, hence enabling us to model the particle interaction at a microscopic level and helps us to understand the bulk behaviour of the materials. DEM has become widely acceptable as an effective method to address engineering problems in granular flows, powder mechanics and rock mechanics (Weerasekara, et al., 2013).

The interaction between the particles is controlled by means of contact models, based on which the forces acting on every particle, position, inertia and energy of particles are calculated and determined for a time step. The time step is so small that the velocities and accelerations of particles are assumed to be constant over the time step. Based on the works of P.A. Cundall and O.D.L.Strack (1979) where in Newton's second law of motion and the force displacement law are applied, the new positions of the particles are determined for every time step thereby providing the capability to simulate the flow of particle and the particle-machine interaction in any system.

2.4.2 Contact models

The software that has been chosen to simulate the particle flow based on DEM is EDEM from DEM Solutions Ltd., UK. The particles or equipments can be modeled by importing CAD geometry. Database for modeling materials are also readily available in software like EDEM.

EDEM comes with a set of built in contact models, the main one being the Hertz-Mindlin contact model(Fig 18) which is the basis for many other models in EDEM software (DEM Solutions Ltd, 2016). This contact model incorporates normal forces based on Hertzian contact theory, tangential forces based on Mindlin- Deresiewicz (Mindlin, 1949) (Mindlin & Deresiewicz, 1953)and the damping coefficients based on the coefficient of restitution as modeled by Tsuji, Tanaka, & Ishida (1992). The tangential friction forces are based on the works of Cundall and Strack (1979) and the rolling friction model based on the works of Sakaguchi, Ozaki, & Igarashi (1993).

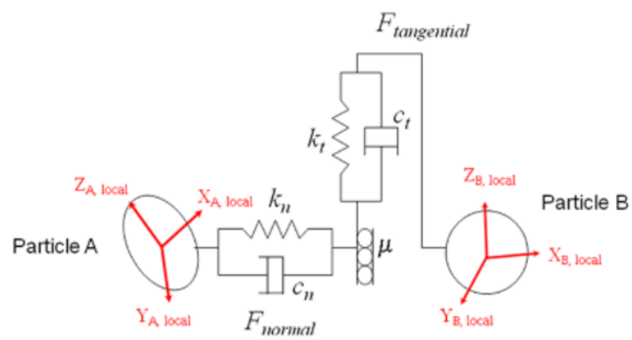


Figure 18 Pictorial representation of Hertz-Mindlin contact model

The normal force F_n is calculated as a function of normal overlap δ_n and is given by the

$$F_n = \frac{4}{3} E^* \sqrt{R^*}\, \delta_n^{\frac{3}{2}} \qquad (19)$$

Where E^* and R^* are equivalent Young's modulus and equivalent radius at contact and are defined as

$$\frac{1}{E^*} = \frac{(1-v_i^2)}{E_i} + \frac{(1-v_j^2)}{E_j} \qquad (20)$$

$$\frac{1}{R^*} = \frac{1}{R_i} + \frac{1}{R_j} \qquad (21)$$

Where E_i, v_i, R_i and E_j, v_j, R_j being the Young's Modulus, Poisson ratio and radius of each sphere in contact. Additional to the normal force, there is a damping force F_n^d, given by

$$F_n^d = -2\sqrt{\frac{5}{6}}\, \beta \sqrt{k_n m^*} v_n^{\overline{rel}} \qquad (22)$$

Where $m^* = (\frac{1}{m_i} + \frac{1}{m_j})^{-1}$ is the equivalent mass, $v_n^{\overline{rel}}$ is the normal component of the relative velocity and β (damping ratio) and k_n(the normal stiffness) are given by

$$\beta = \frac{\ln e}{\sqrt{\ln^2 e + \pi^2}} \tag{23}$$

$$k_n = 2E^* \sqrt{R^* \delta_n} \tag{24}$$

Where e is the coefficient of restitution. The tangential force F_t depends on the tangential overlap δ_t and the tangential stiffness k_t.

$$F_t = -k_t \delta_t \tag{25}$$

$$k_t = 8G^* \sqrt{R^* \delta_n} \tag{26}$$

Here $G^*$is the equivalent shear modulus. Additionally, tangential damping F_t^d is given by:

$$F_t^d = -2\sqrt{\frac{5}{6}}\, \beta \sqrt{k_t m^*} v_t^{\overline{rel}} \tag{27}$$

Where $v_t^{\overline{rel}}$ is the relative tangential velocity. The tangential force is limited by Coulumb friction $\mu_s F_n$ where μ_s is the coefficient of static friction.

For simulations in which rolling friction is important, this is accounted for by applying a torque τ_i to the contacting surfaces.

$$\tau_i = -\mu_r\, F_n R_i\, \omega_i \tag{28}$$

With μ_r the coefficient of rolling friction, R_i the distance of the contact point from the centre of the mass and ω_i the unit angular velocity vector of the object at the contact point.

2.4.3 Modelling wear

The standard Hertz-Mindlin in-built model in EDEM has been extended to incorporate the general equation of wear developed by John F Archard as described in the section 2.2.1 (DEM Solutions Ltd, 2016). The model is based on the idea that the amount of material removed from the surface will be proportional to the frictional work done by the particles moving over the surface. The equation for the model is given by:

$$Q = W_i F_n d_t \tag{29}$$

Where Q is the volume of material removed, d_t is the tangential distance moved and W_i is the wear constant originally given by,

$$W_i = \frac{K}{H_s} \tag{30}$$

Where K is the dimensionless constant and H_s is the hardness measure of the softest surface. The eqn (29) is rearranged to give the depth of material removed per element from the calculated volume of material removed.

$$Wear\ depth = \frac{Q}{A} \qquad (31)$$

For better understanding of the model, a literature survey was done to find the research done so far on use of EDEM to study wear. Ashrafizadeh and Ashrafizadeh (2012) performed a DEM simulation to understand the behaviour of a jet of particles on a flat plate for different impact angles, velocities and particle concentrations. Impact energies were considered as the attribute to study wear and it was confirmed that shear impact energy plays a major role in the wear rate of the surfaces. The shear impact energy was the highest at a collision angle of 30^o while for normal impact energy it was 80^o. Moreover, higher the impact velocities and particle concentrations, higher were the shear and normal impact energies at $20\text{-}30^o$ and $60\text{-}80^o$ respectively.

A thermo-mechanical discrete element model of rock cutting process was simulated by Jerzy Rojek (Rojek, 2014). This model was a combination of a classic Archard model for wear taking the change in hardness of the tool material with temperature into account. This model provided qualitative results matching the theoretical and practical observations. For a quantitatively correct result, it was recommended to model based on experimentally measured parameter and three dimensional geometry.

Another DEM study (Kalala & Moys, 2004), that was done to understand the load behaviour and milling performance in tumbling mills, is based on a model that takes into account the sum of abrasion and impact wear based on the abrasive and impact energies dissipated on the surface. This paper provides insight on the contribution of impact energies on the wear of the liner and the effect of variation of the liner profile on the load behaviour.

Wear being a relatively slow process, there have been a very few simulation work done for prediction of wear based on the Discrete Element Method. This could be attributed to the fact that it is very difficult to accurately predict the forces and energies involved in the collision of particles and liners (Kalala & Moys, 2004).

The paper reviewing the concepts of friction and wear (Amiri & Khonsari, 2010) from a thermodynamic point of view gives a very good understanding on the prevailing models about the subject. The paper reviews the works done by various researchers on modelling the friction and wear from an energetic approach. The motion between the two bodies due to which friction might occur is either a sliding or a non-sliding contact. The resultant wear due to the sliding and non-sliding contact is mainly due to the frictional energy dissipated, which is mainly proportional to the applied load and the velocity in case of non-sliding contact and the applied load and sliding distance in case of a sliding contact. The material characteristics, relative velocity, size and shape of the materials also influence the distribution and the dissipation of energy leading to wear. The works of Mindlin and Deresiewicz (1953) provided a major advancement in the study of energy dissipation under non-sliding contact. Many researches were done to experimentally confirm Mindlin and Deresiewicz’s theory of surface damage due to energy dissipation. It was concluded that the wear volume varied linearly with the energy dissipation during a non-sliding contact(fig 19).

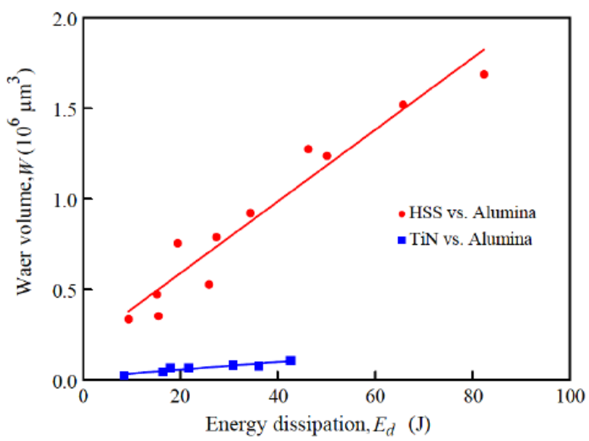


Figure 19 Wear volume as a function of cumulative dissipated energy (Fouvry, Kapsa, Zahouani, & Vincent, 1997)

For sliding contact, a similar energetic approach to wear established the correlation between energy dissipated by friction force and the wear volume. The experimental results as shown in fig 20 (Ramalho & Miranda, 2006) , which were based on the extension of Archard's wear theory, stated the rate of change of wear is linearly related to the dissipated energy and the slope of the line in the graph between wear volume and the dissipated energy gives the estimation of the wear coefficient.

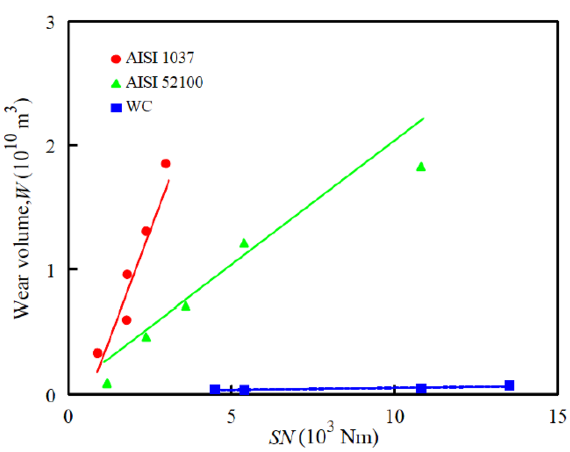


Figure 20 Wear volume as a function of work done by sliding force (Ramalho & Miranda, 2006)

EDEM involves both the concepts of Mindlin and Deresjewicz and Archard and records the energy dissipation at the surface and the wear depth. This proves vital in this research as the wear happens due to both sliding and non-sliding contact. The experimental results, as cited in the above reviewed paper, confirms the relation between wear rate and the energy dissipated. Hence the built-in DEM models would prove to be satisfying in assessing the performance of the wear in chutes.

2.4.4 Modelling cohesive flow conditions

A good chute design must ensure the flow of the bulk material at any condition. The extreme condition in any bulk material handling equipment for transfer is when the bulk solid has a high moisture content and higher proportion of fines (Grima A. P., 2011). During the flow of bulk solid with mixed particle sizes, the larger particles move bodily while the material shears across the fines and the yield strength of the bulk solids is dependent on the fines (Jenike, 1985). Hence, the flowability of bulk solids is typically governed by powders and fine materials (Schulze, 2007). The cohesive and adhesive properties of bulk materials could be due to a variety of mechanisms such as solid bridges, liquid bridges, chemical bonding, Van der Waals forces and electrostatic forces. The significant mechanisms that govern the cohesive and adhesive properties due to the presence of moisture content and fines are liquid bridges and Van der Waal's forces. Both forces are proportional to particle size (Schulze, 2007). Wet bulk solids exhibit greater cohesive strength and the forces which oppose the flow can exceed the forces promoting the flow (Grima A. P., 2011).

In EDEM, there are preset contact models to model the mechanisms between cohesive materials so that the flow behaviour of wet cohesive models could be understood and simulated. The following are the contact models available (DEM Solutions Ltd, 2016):

1. Linear Cohesion Model
2. Hertz-Mindlin Model with JKR

Linear Cohesion model modifies the basic Hertz-Mindlin contact model by adding a normal Cohesion force, given by

$$F_{coh} = kA_{coh} \tag{32}$$

where A_{coh} is the contact area and k is a cohesion energy density in J/m^3.This force added to the traditional Hertz-Mindlin normal force. No tangential force is added in this model however the magnitude of the non-cohesive normal force is increased beyond Hertz-Mindlin model. Therefore a stronger frictional force can be withstood before slippage.

Hertz-Mindlin JKR model accounts for the influence of Van der Waals forces within the contact zone and allows the user to model strongly adhesive systems such as dry powders or wet materials and is based on the works of Johnson, Kendall, & Roberts (1971). The contact model calculates all the forces except the normal elastic force as per the Hertz-Mindlin(no-slip) contact model. The JKR normal elastic force is calculated based on the overlap and the surface energy as follows,

$$\mathrm{F_{JKR}} = -4\sqrt{\pi\gamma E^*}a^{\frac{3}{2}} + \frac{4E^*}{3R^*}a^3 \tag{33}$$

and

$$\delta = \frac{a^2}{R^*} - \sqrt{\frac{4\pi\gamma a}{E^*}} \tag{34}$$

where γ is the surface energy per unit area of contact in J/m^2 and a is the contact radius.

For γ=0, the JKR normal force turns into Hertz-Mindlin normal force,

$$F = \frac{4}{3}E^*\sqrt{R^*}\delta^{\frac{3}{2}} \tag{35}$$

This model provides attractive cohesive forces even if the particles are not in physical contact. The figure below shows normal force as a function of normal overlap for different contact models in EDEM.

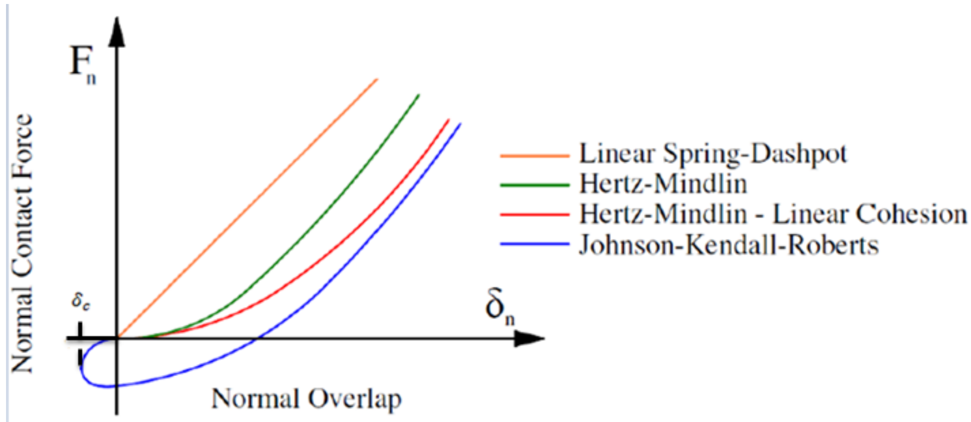


Figure 21 Normal force as a function of Normal overlap (Grima A. P., 2011)

In the curve representing JKR model, negative overlap denotes the gap between two separated particles and there exists negative normal force or adhesion force for values of negative overlap till some value of positive normal overlap. Thus there are attractive forces even if the particles are not in physical contact. The maximum gap between particles with non-zero force is given by,

$$\delta_c = \sqrt{\frac{4\pi\gamma a_c}{E^*} + \frac{a_c^2}{R^*}} \tag{36}$$

For $\delta < \delta_c$, the model returns zero force. The maximum value of the cohesion force occurs when the particles are not in physical contact. For small normal overlaps, the total force is still negative (adhesive) and becomes positive for larger normal overlaps or contact area radii as shown in the figure above. The critical pull off force or the maximum value of cohesion force is given by,

$$F_{pulloff} = -\frac{3}{2}\pi\gamma R^* \tag{37}$$

This model could also be used to model wet particles by virtue of the force required to separate two particles under liquid surface tension γ_s and wetting angle θ.

$$F_{pulloff} = 2\pi\gamma_s \cos\theta \sqrt{R_i R_j} \tag{38}$$

Equating the above force to JKR max force, $F_{pulloff} = -\frac{3}{2}\pi\gamma R^*$ allows JKR surface energy parameter estimation if the EDEM particle is not scaled.

It is evident from the above that the Hertz-Mindlin with JKR model helps to simulate cohesive material flow better than the linear cohesion model where there is no cohesive force at lower values of normal overlap and zero overlap.

Most of the studies in DEM have been focused on dry granular media and cohesive dry powders. Despite all the recent advances in understanding the free flowing and cohesive granular materials, there is still plenty of research required to understand and model the effects of cohesion (Li & McCarthy, 2006). The only attempt found in calibrating a cohesive material flow for coal was by Andrew P. Grima (2011) based on Linear Cohesion model on a trial and error basis. There have been quite a few researches involving Hertz Mindlin with JKR model (Subero, Ning, Ghadiri, & Thornton, 1999) (Mishra & Thornton, 2001) (Lee, Kang, & Kwon, 2008) (Bierwisch, T.Kraft, H.Riedel, & M.Moseler, 2009) however it has always been difficult to model realistic cohesive granular flow for an industrial application using DEM due to the limitations in the number of particles, particle size and the processing time (Grima A. P., 2011). For the Eurosilo application, Hertz Mindlin with JKR model would help in efficient modeling the cohesive flow through a transfer chute, especially when the materials form a rockbox.

2.5 Chute design improvement

The current transfer chute design in Eurosilo is a rockbox chute wherein the material forms a bed of particles with a slope and the material starts sliding beyond the slope. The rockbox chute is preferred when the material is very abrasive or for transfers with high rate of discharge when the chute material is expected to wear off quicker. The highest velocity for which any transfer chute has been designed is 15 m/s (Pheonix Conveyor Belt Systems GmbH). In the Eurosilo application the velocity of the materials varies between 15 m/s to 34 m/s at the retracted and expanded position respectively.

Currently there aren't any literature on rock box design however a few design principles discussed by the experts in bulk handling industry in an online forum are given below.(The Powder/Bulk Portal - Forum, 2008).

1. The bulk material product size, shape, moisture properties, drop height, details of the stream pressure and the buildup of the product affect the design of rockboxes.
2. The slope of the surface created is equal to the angle of repose at lower pressures. However the formed surface undergoes constant impact and shear at higher pressures. New surfaces are expected to constantly build up at lower pressures.
3. The surface of the slope is not always planar and is expected to form a multiple curved concave surface depending on the product lumps and the cohesiveness of the fines.
4. Away from the impact zone, the rock box can be expected to accumulate fines. The velocity of the particles perpendicular to the face of the wall is lost on impact.
5. The space needed to create a static bed to deal with the expansion and the change in the direction of the flow stream is of primary importance when compared to the inclination of the geometrical surface.

The above points along with the basic design guidelines for a chute provides good framework for the rockbox chute design. Apart from the above discussed, the following points need to be considered for the design of chute specific to the Eurosilo application.

i. Chute angle and the energy dissipated:

For an improved chute design, it has to be made sure that the angle of the chute is just enough to ensure the flow of the bulk solid in case of both material on material and material on chute contact regions. It can be seen from the literature reviewed that the wear on the chute surface is proportional to the energy dissipated. Hence wear on the wall surface would be higher if the energy is dissipated on the wall. Wear on material is acceptable since that would aid the material flow. It is preferred to have a material on material contact. Hence a dead zone is preferred for the first impact of the material.

In practice, curved chutes are designed to be self-cleaning, hence there would be more material-wall interaction, which would mean higher wear on the wall surface. It has also been proven from experiments that the wear is higher at impact angles of 10-30 deg (Roberts, 2003). If the angle of the chute is reduced to a minimum sufficient enough to reduce wear and material flow inspite of material build up, it becomes rockbox/stone box chute.

ii. Space available

The restriction on the height and width of the chute available should be taken into consideration when making a new design for this application. The below pictures give the current dimensional space available in the transfer point between the telescopic chute and the screw auger in the end of the auger frame.

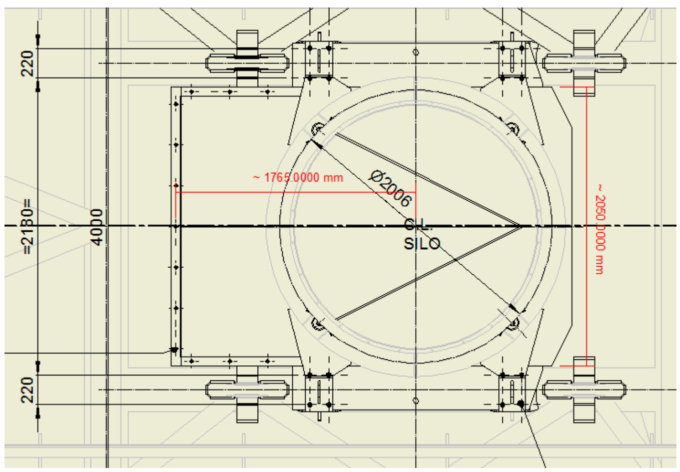


Figure 22 Top view of the chute box

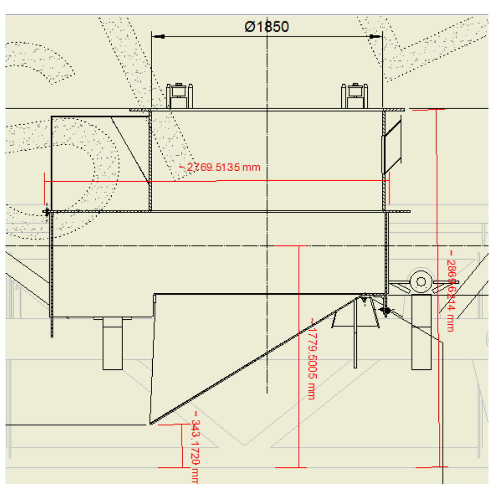


Figure 23 Side view of the chute box

The height and the breadth available are approximately 2540 mm each while the width available is around 2000 mm. There is no provision to extend the chute in the upper half or in the lower half.

iii. Height of the chute

The height of the chute cannot be more than 2540 mm because the telescopic chute connected to the chute is optimized for the height of the silo and any change in the height of the chute would result in lesser capacity inside the silo.

iv. Centralized material flow to create a material dead zone between the screw augers

The material flow needs to be controlled and directed to flow towards the zone between the screw augers. The reason is that the screw augers acting over a free surface needs a dead zone of material (indicated by shaded lines in figure below) between them to propel the material (indicated in large dots) for stacking.

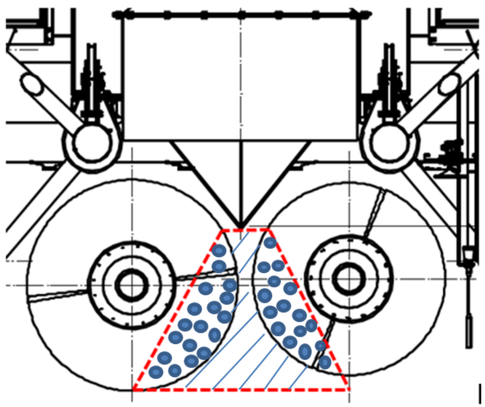


Figure 24 Material zone between screw augers

2.6 Conclusions from Literature review

It is evident from the section 2.5 that that curved chutes are not suitable for the Eurosilo application and there is no methodology available for stone box chute design. The analytical model developed for the curved chute design is not applicable and there is no established methodology or analytical model for designing a transfer chute for the Eurosilo application. The chute design guidelines along with a few design principles for stonebox chute could be used as a framework to develop better chute designs for the Eurosilo application.

As mentioned in section 2.4, simulation based on DEM gives a better overview for the evaluation of chute design rather than the conventional approach based on continuum mechanics. DEM has the capability to analyse complex situations such as wear and could enable the user to understand the state of the system even in transient condition. DEM has been utilized and recommended by various researchers as an effective tool to model bulk solid flow.

The wear model developed by Roberts is limited to curved chutes of radius R and rectangular, square or circular cross section. However, in theory, it gives the nature of relationship between the wear rate and the parameters like flow rate and wall friction angle. The built-in Archard wear model in EDEM provides the depth of element removed on the chute surface. The depth of the element removed is proportional to the volume of wear which depends on the wear constant, normal force between the particle and the element and the tangential distance moved by the particle on the element. It has also been proved that the rate of wear volume of the material is proportional to the energy dissipated at the chute surface. Hence it can be concluded that the progress of wear depth is proportional to the energy dissipation and both attributes would give a good insight on the surface wear due to particle impact, sliding. Also the impact energy profiles on the surface of the wear plate would provide an overlook on the energy dissipated at the surface. For analyzing the wear performance, the particle flow shall be governed only by the forces due to gravity and the interaction between the particle and material. Hence the material is assumed to be free-flowing and only Hertz-Mindlin with no-slip and Hertz-Mindlin with Archard Wear should be considered.

Modelling an extreme case of bulk solid flow considering the particles to have a high amount of moisture content is possible with the Hertz Mindlin with JKR model. For force calculations, this model incorporates the surface energy per unit area, which could be calibrated to include the effect of moisture content and Van der Waals forces in case of fines. However as concluded in the above literature reviewed, for obtaining quantitatively correct (or atleast close to accurate) data, the parameters should be experimentally measured and modeled.

It can be summed up that in the absence of specific models for chute design and evaluation for Eurosilo application,the discrete element modeling would provide a better and comprehensive approach to evaluate the chute design for the application under study. Computations based on the discrete element models built into EDEM such as Hertz-Mindlin with no-slip, Hertz-Mindlin with Archard wear and Hertz-Mindlin with JKR would provide the basis for analyzing the bulk solid behaviour and the performance of the chute with respect to wear and flow.

3. Analysis of the current design

In this chapter, the description of the modeling and analysis of the current chute design installed is discussed. The simulation is set up and run based on the Lunen design and the outcome is analysed qualitatively with respect to the literature reviewed earlier.

3.1 Model setup

In DEM, to model a process, the following needs to be done: the modeling of the particle, the modeling of the geometry involved and the modeling of the particle-particle interaction and particle geometry interaction.

3.1.1 Particle modeling

In the simulation, the particle should be modeled to have an approximate resemblance to real case. The characterization of particles based on their size, shape, density and mass are done in this step. Here the particle considered is coal. When the coal is stored, it is recommended that the particles have a maximum size of (-) 50 mm. Hence the particles are characterized based on equivalent sphere with 50 mm diameter. The properties of coal have been given in EDEM as follows (Hose, 2011)

Particle properties in DEM(Coal)		
Poisson's ratio	:	0.23
Shear Modulus	:	2 GPa
Density	:	1357 kg/m^3

3.1.2 Modelling of the geometry

As explained in section 2.1, the coal is discharged from a conveyor to a telescopic chute, which has a chute box and a wear plate attached at its bottom to deviate the coal towards the screw auger. The equipments under consideration are only chute box and the wear plate. However to replicate the particle flow on the top of the chutebox and wear plate, the entire assembly has been modeled. The following are the boundary conditions considered for the discharge of the belt conveyor.

Coal discharge specifications		
Discharge capacity	:	1600 TPH
		444.44 kg/s
Speed of discharge	:	2.6 m/s
Bulk Density	:	800 kg/m^3

Assuming that the belt conveyor width is 1600 mm, for the above conditions, the area of discharge of the bulk material is approximated to a rectangle of width 1.1935 m and height 0.2685 m. The telescopic chute, chute box, wear plate geometry in EDEM is based on the construction drawings of the chute equipments available. The assembly and construction of the equipments inside the silo is such that the axis of the silo coincides with the axis of the telescopic chute. The models have been created to replicate the same. The below figures depict how the representative model looks like in EDEM.

3.1.3 Modelling the particle-particle interaction and particle-geometry interaction

The discrete element modelling calculates the positions, forces, velocities and acceleration of the particles in the simulation domain based on the properties of the particles, material of the geometry and the interaction properties of the particles and the material of construction of the geometry. The particle properties of coal have been described already. For geometry, the material of construction used in Lunen is AISI 304/SS 304. The properties given in EDEM are as follows (ASM Aerospace Specification Metals Inc.).

Material properties in DEM(AISI 304)		
Poisson's ratio	:	0.29
Shear Modulus	:	86 GPa
Density	:	8000 kg/m^3

The interaction properties to be defined are the coefficients of restitution, static friction and rolling friction during coal-coal and coal-steel interaction. The properties are given below (Teffo & Naudé, 2013).

		Coal-coal	**Coal-steel**
Coefficient of restitution	:	0.55	0.22
Coefficient of static friction	:	0.77	0.34
Coefficient of rolling friction	:	0.23	0.23

3.1.4 Contact models

As explained in section 2.4, the built-in contact models define the framework of interactions between the elements in the discrete element simulation. For interaction between coal on coal, the primary contact model of Hertz-Mindlin (with no slip) is used. For interaction between coal and the geometry, Hertz Mindlin with Archard wear (as mentioned in 2.4.3) is used. The wear constant for the Archard wear model has been specified only for the wear plate geometry. Wear constant is a characteristic property of the material by virtue of hardness and the application. Since this is a qualitative and comparative analysis, the wear constant specified wouldn't affect the results of this study, it is assumed to be 1.5 x 10^{-7}. This value has been assumed taking into account the number of simulations planned and the time available. For actual case scenarios, the value of K could be determined experimentally.

3.2 Simulation & discussion

The modelling of coal discharge from the conveyor is done based on the cross section of the bulk material at the discharge end of the belt conveyor. The coal stream is caught tangentially and enters the column connecting the bottom of the discharge to the topmost flange of the telescopic chute. The length of the telescopic chute is approximately 6 m in a retracted position and about 51.5 m in an extended position. The total fall height of coal inside the coal silo is about 60 m from the conveyor discharge point. The coal particles moved down due to gravity and the velocity of the particle streams vary from 2.6 m/s at the discharge end to 34 m/s at the lower end of the telescopic chute. Since the end velocity at which the particles reach the wear plate is higher at the extended state, the simulations are performed only for extended position. The whole model setup is shown in the figure 25.

Inside the telescopic chute the coal stream hits the wall of the telescopic chute at around 11 m from the discharge point at a very low angle of impact and continues to slide down as a uniform stream. Since the telescopic chute is long tubular structure, the coal stream is susceptible to the drag effect of air inside the telescopic chute. However, the effect of air drag has been neglected in this simulation.

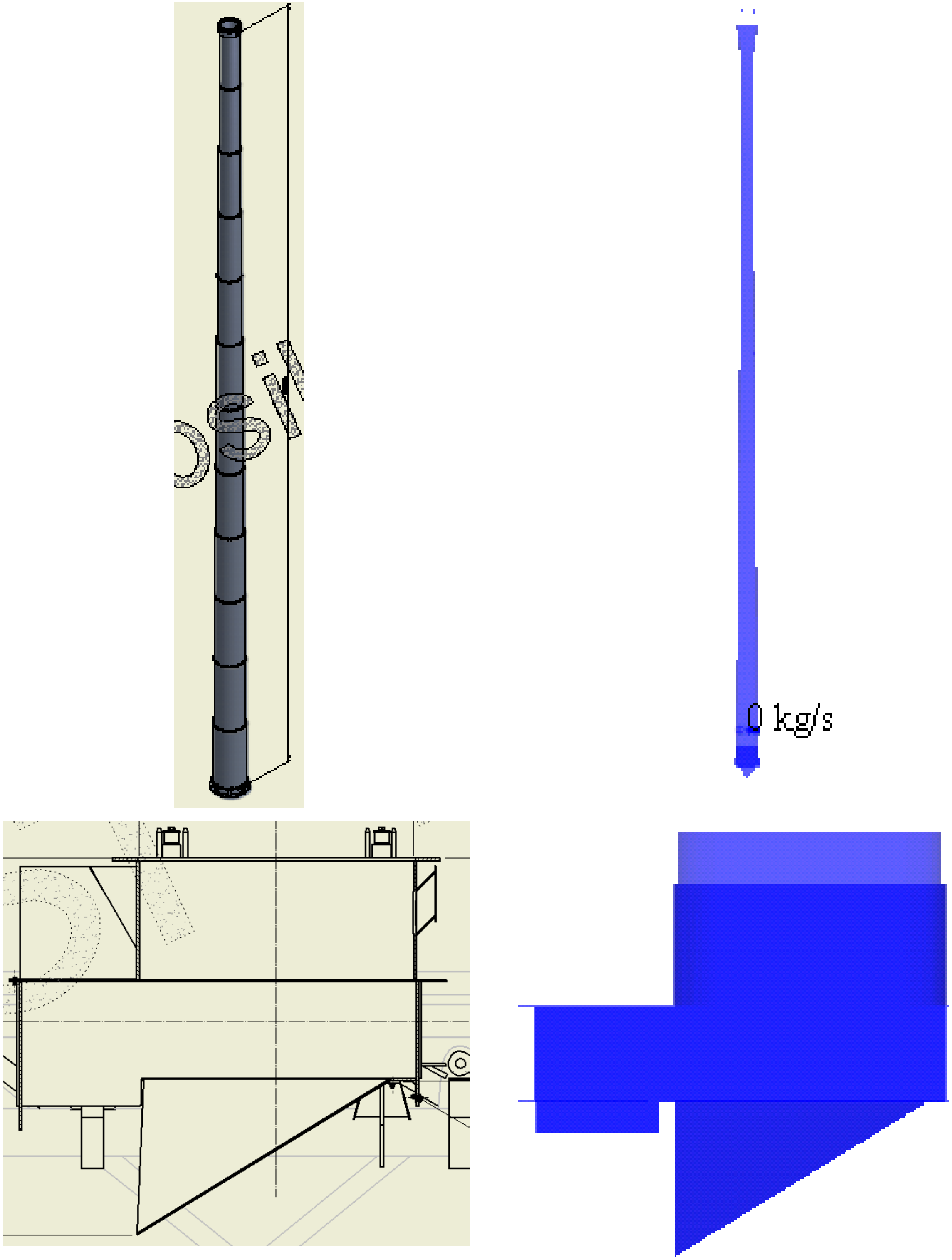


Figure 25 Geometry model for current design in EDEM

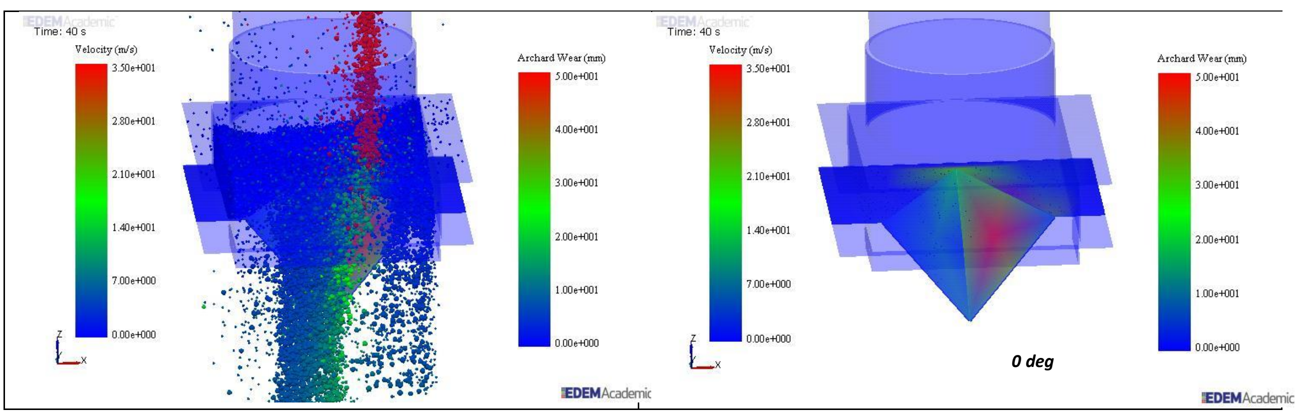
The reason is as follows. The models of the effect of air on a bulk stream is based on the assumptions that the air flow in the blanking tube moves at an average velocity and the particles of the material do not interact with other particles. Also the effect of particle interaction with the blanking tube is neglected. Therefore the models developed are not appropriate to calculate the state of the motion of particles. Also in reality, after forming a relatively stable stream, the particles in the stream interact with the air very less when compared to when they fall independently (Xiaochuan, Qili, Qi, & Yafei, 2016). The flow of coal in the current application is also such that only one side of the stream is exposed to the quiescent air within the telescopic chute while the other side is much closer to the wall. Considering the above, it can be safely assumed that the effect of air drag on the bulk particle stream is negligible.

3.2.1 Simulation of the current design

The simulation has been set up as explained above. The particle factory was set to the following specifications:

Maximum discharge rate	:	444.44 kg/s (1600 TPH)	
Speed of discharge	:	2.6 m/s	
Max particle size	:	50 mm	
Particle size distribution	:	Scale	%
		0.1	20
		0.4	5
		0.6	5
		0.8	50
		1	20

The simulations are performed for a time period of 40 s, which is just enough to understand the wear rate of the material. In reality the chute box and the wear plate rotates about its axis to spread the coal inside the silo while the particle stream remains the same with respect to the axis. Hence the simulation is done for 4 positions (0, 90, 180 and 270 deg from initial position assumed) to understand the wear pattern in the chutes at different positions. At the end of the simulation at each position, the wear pattern on the current design in the chute is as given in the figure below.



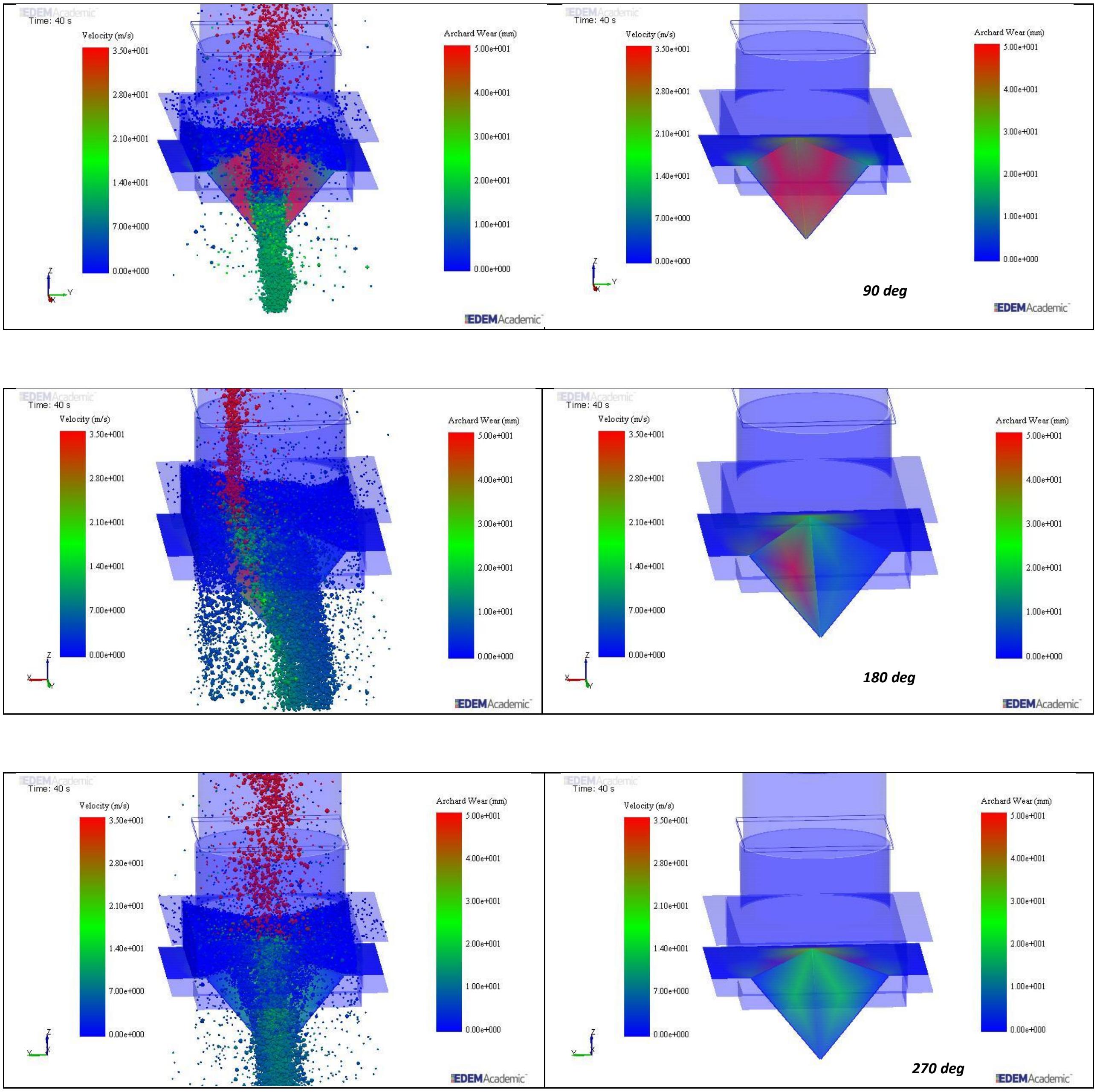


Figure 26 Wear pattern at each position - current design

The current design of the wear plate is a combination of rock box and a sliding chute, like a spout of a beaker. The rock box dissipates the high energy of the incoming particles, spreads the material along the horizontal direction to create a bed of particles. These particles shield the plate from further direct impact and the spout like arrangement ensures the discharge of material towards the screw auger. For the current design, the value of angle of slope of the plates is 53.83 deg with horizontal. The valley angle of the plates is 32 deg to the horizontal. It can be noticed that the wear pattern varies with every position of the wear plate. However, on a majority, the wear is higher on the inclined plates over which the coal slides from either side. The joint between the plates is covered by the particles while the inclined areas are continuously exposed to particles sliding. The wear pattern in each position does not resemble the actual picture of the failed wearplate. However, on overlap of the pictures of wear pattern in all positions, we get the following image(Fig 27) which shows the concentration of wear.

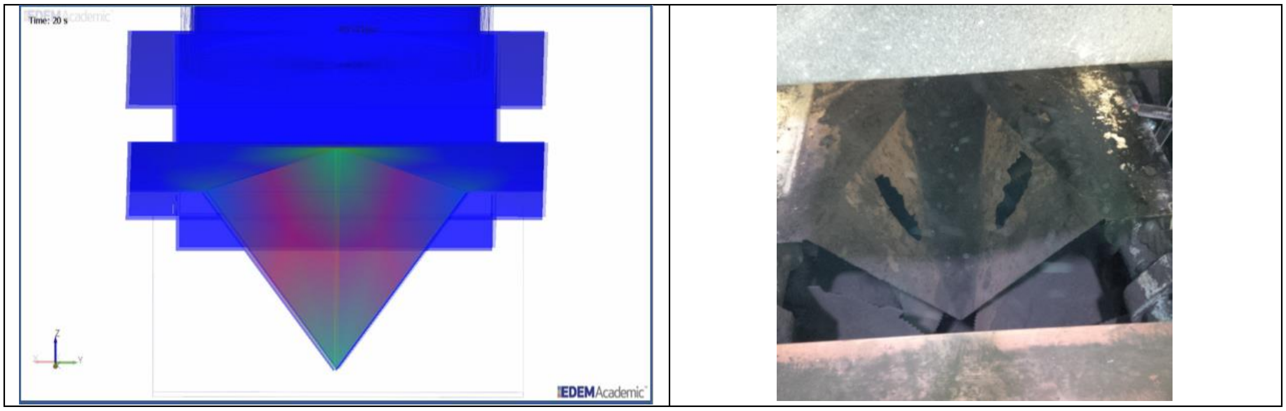


Figure 27 Result of simulation & failed wear plate

Since the model considers only free flowing bulk solid, there is an indication that wear happens at the joint between the plates, whereas in actual case there is particle buildup in the valley of the spout. However, this does not affect the results of this research, since the particle build up will only reduce the wear on the plate.

3.2.2 Discussion on results

The EDEM software provides us a variety of options to analyze the results of the simulation. The parameters/ attributes that are chosen to analyze the performance of the chute design are listed below (DEM Solutions, 2015).

Key performance indicator (KPI)

a. Archard Wear (Maximum) – This attribute provides the depth of the element removed from the surface of the geometry due to sliding/ abrasive wear and is dependent on the wear constant set for the geometry. This maximum wear depth value at the end of the each simulation would give an insight on how much the surface has worn off.

Apart from the above key performance indicator, the following parameters are also looked into to gain more insights.

I. Velocity – the average discharge velocity would be of interest to understand the impact on the receiving equipment – screw auger.
II. Normal and tangential cumulative contact energy (total): The relative wear model based on Mindlin and Deresjewicz works by the way of identifying regions of high impact (normal) and abrasive (tangential) wear on the equipment within a simulation. It is calculated based on the relative velocity and associated forces between the bulk material and the equipment. The total value of each attribute gives the amount of energy lost thereby causing impact and abrasive wear on the wear plate. From the magnitude of these values, the phenomenon which plays a dominant role in causing the wear on the surface could be identified. The total energy dissipated

at the surface of the wear plate can be calculated from these values. As per the literature reviewed in section 2.4.3, the following is the governing relation between the wear volume, Q and the total energy dissipated.

$$Q \propto E_d$$

From eqn 31, it can be seen that wear depth d is directly proportional to the wear volume Q.

This implies that the average wear depth should also have a linear relation with the total energy dissipated at the surface of the chute. The plot between the average wear depth and the total cumulative energy dissipated is made to validate this.

The graphs depicting the trend of the attributes maximum wear depth, tangential and cumulative energies dissipated is shown in the figures 28, 29 and 30.

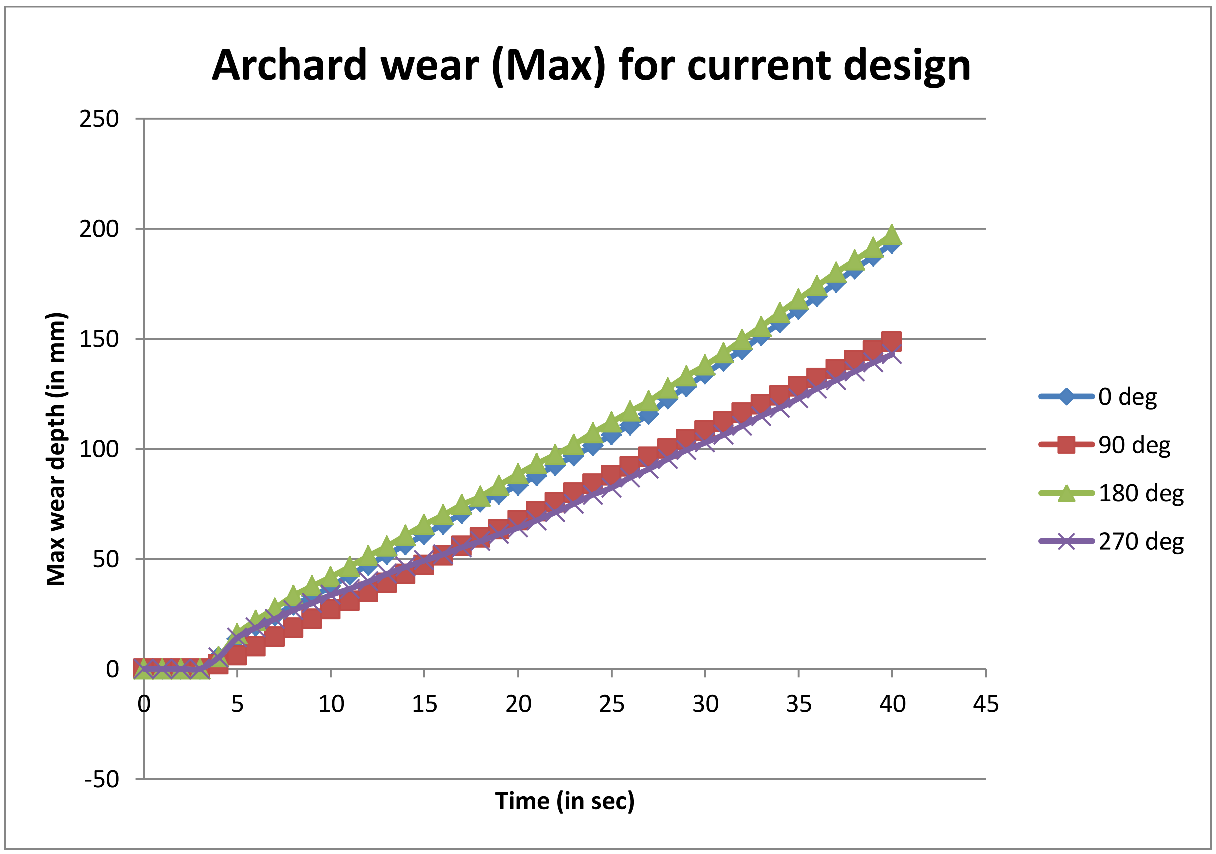


Figure 28 Archard wear (Max) for current chute box design

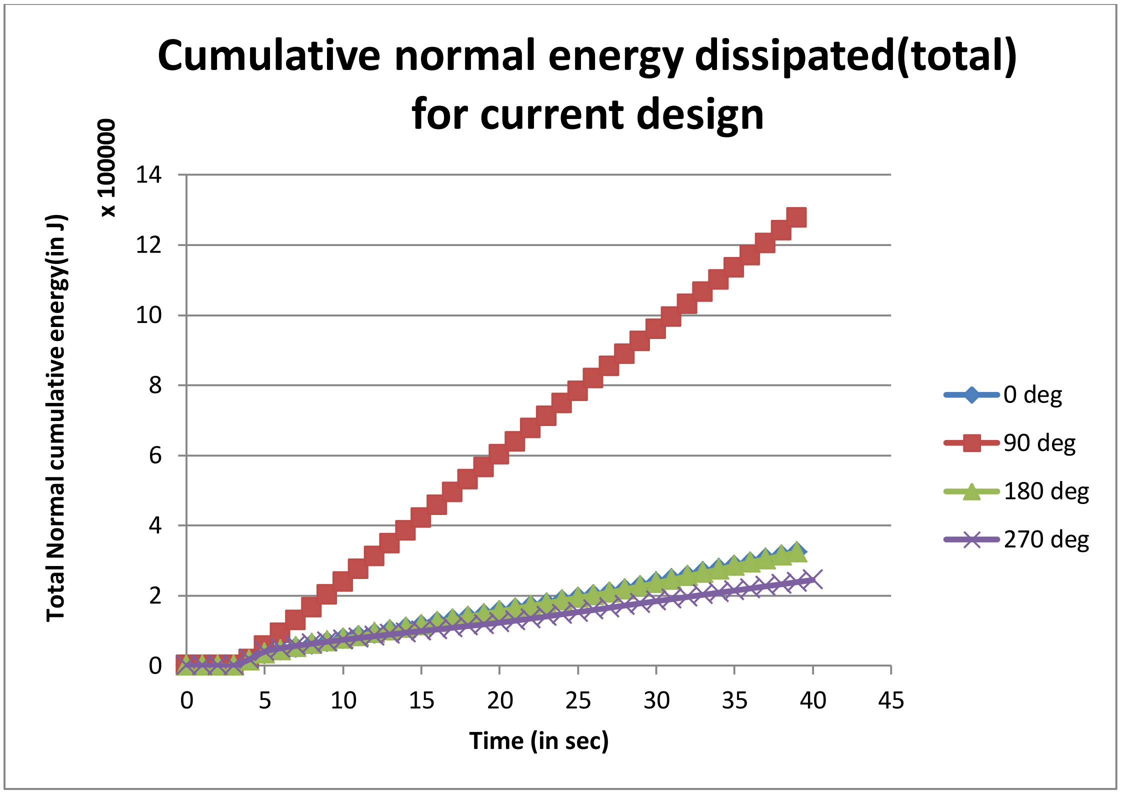


Figure 29 Cumulative normal energy dissipated (total) for the current chute box design

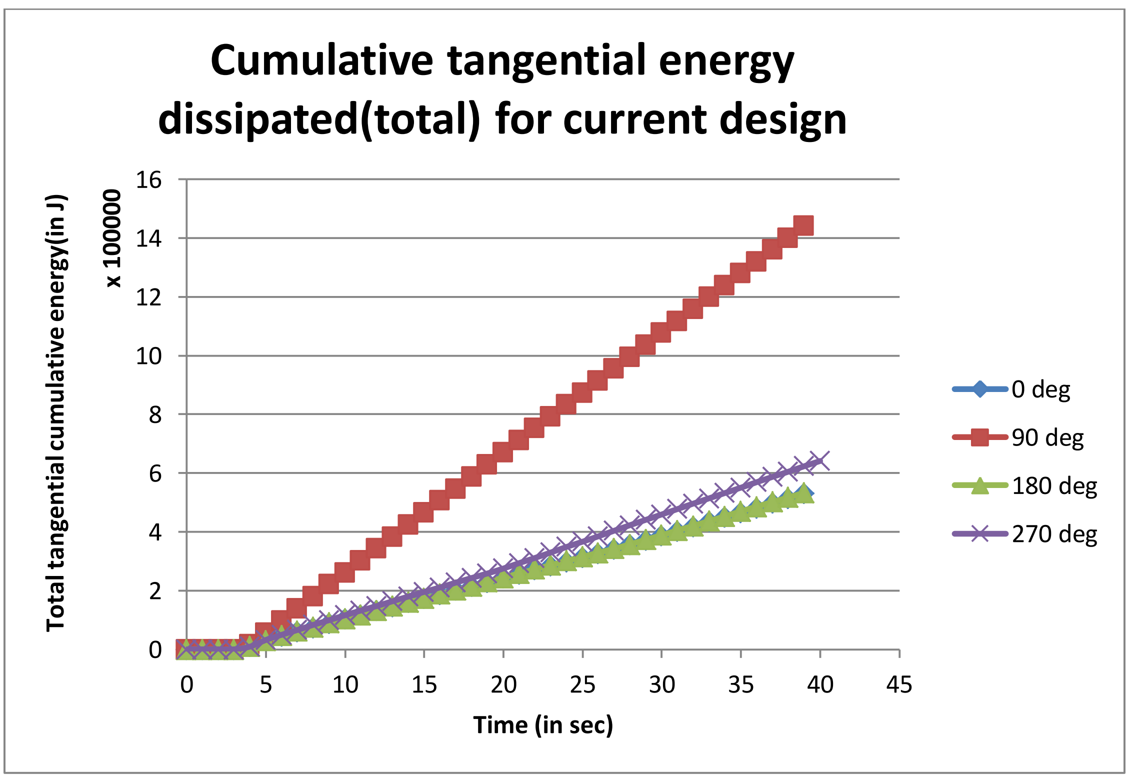


Figure 30 Cumulative tangential energy dissipated (total) for the current chute box design

The maximum wear depth at the end of simulations for every position are summarized in the table below. These would form a basis for comparison and evaluation of the improved designs.

Position (deg)	Max Wear Depth (mm)
0	193.32
90	148.41
180	197.36
270	142.84

Table 1 Max wear depth - current design

It can be observed from the figures 29 and 30 that the tangential energy dissipated at the surface is higher when compared to the normal energy dissipated, which shows that the wear is higher due to abrasion than impact.

The plot between the average wear depth and the total energy dissipated at the surface is shown in the figure 31. The relation between the values is linear proving that the wear depth is also proportional to the energy dissipated at the surface.

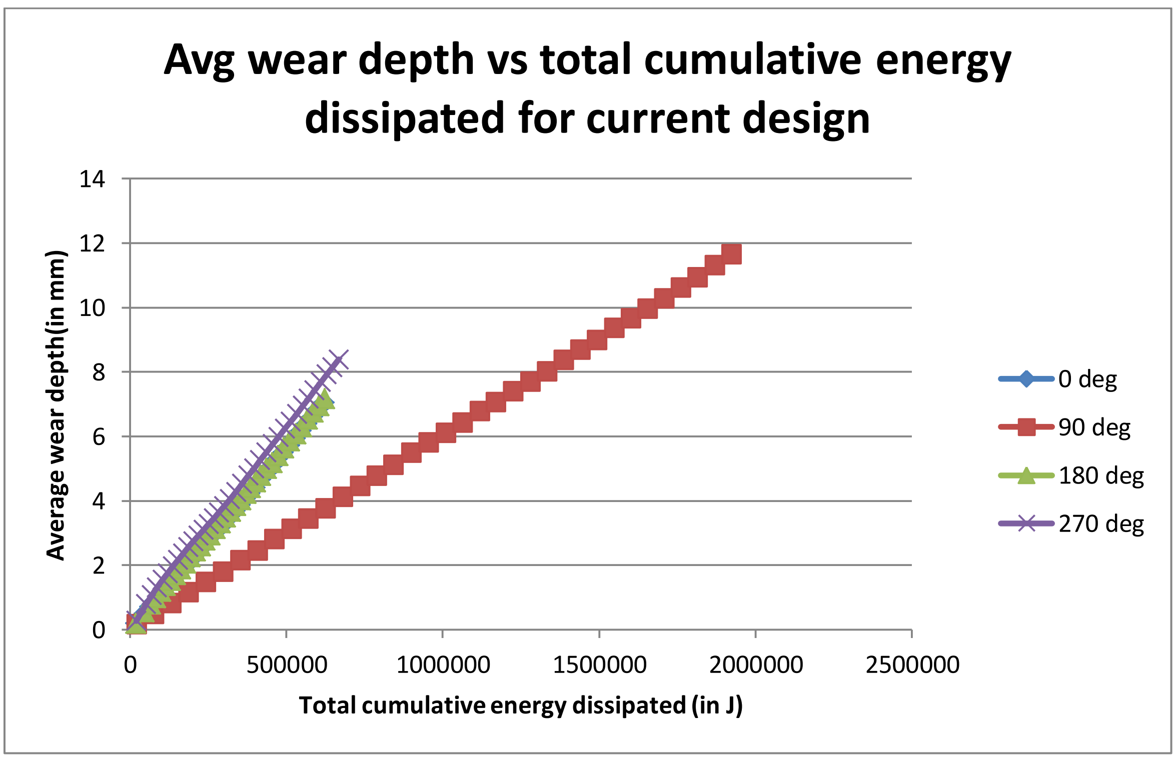


Figure 31 Avg wear depth vs total cumulative energy dissipated for current design

The graph of the discharge velocities show that the velocity of the material discharge is too high at 90 deg position. From figure 33, it can be seen that due to direct chute impacts, lesser interaction to coal particles and by virtue of proximity to the outlet of the chute before discharge when compared to other positions. The velocity is higher whereas for other positions such as 0 and 180 deg, the material on material impact is higher, hence the velocities are comparatively lower.

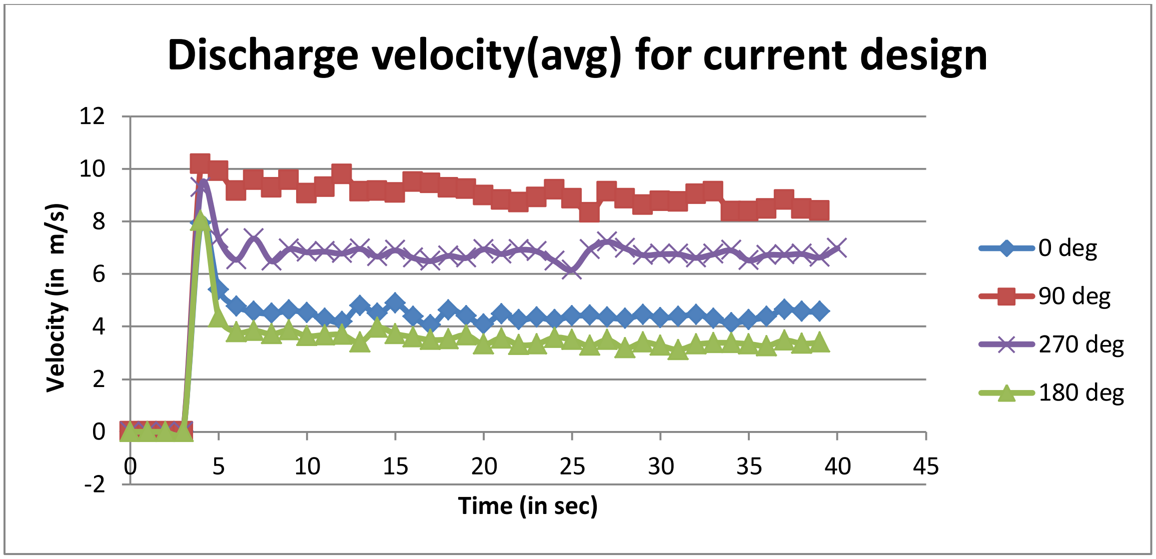


Figure 32 Average output velocity for the current chute box design

To sum up, the wear profile at the end of the simulation was found to be similar to the wear profile in the real case scenario. The maximum wear depth has been identified as the key performance indicator for evaluating chute designs. Apart from that, parameters like total energy dissipated at the surface of the chute, the discharge velocity of the material from the chute are compared to have a better insight into the performance of the chute.

4. Improved chute design and analysis

In this chapter, three different chute designs have been developed based on the classic design guidelines, design considerations for the stone box chute in general and the considerations with respect to the Eurosilo application as mentioned in chapter 2. The design of the new chutes is elaborated and the simulation results are presented.

4.1. Improved chute designs

To understand the bulk solid flow exactly at the point of entry of the chute, a grid domain was created and the particle positions, velocities were recorded. The maximum velocity of the particles was found to be 34 m/s. The positions of the particles at the end of the telescopic chute just above the chute over the course of the simulation are given below in figure 33.

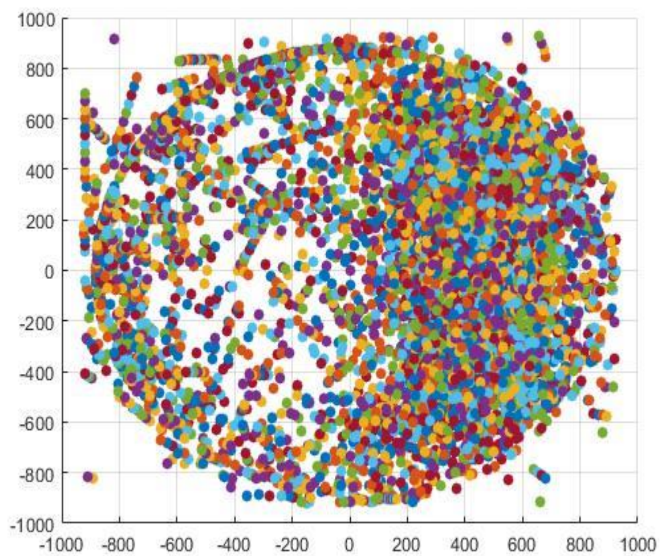
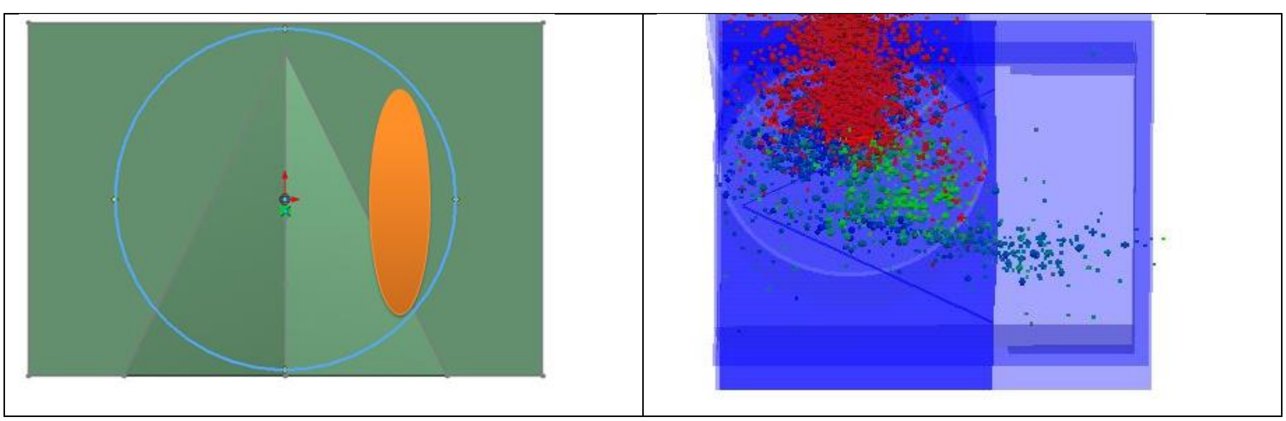


Figure 33 Particle positions at the end of the Telescopic chute

It can be noticed that the majority of the particles are concentrated on one side of the telescopic chute. Since the chute rotates about the axis of the silo, the particle concentration falls on different locations over the chute body in the entire duration of operation (refer figures 33 & 34).



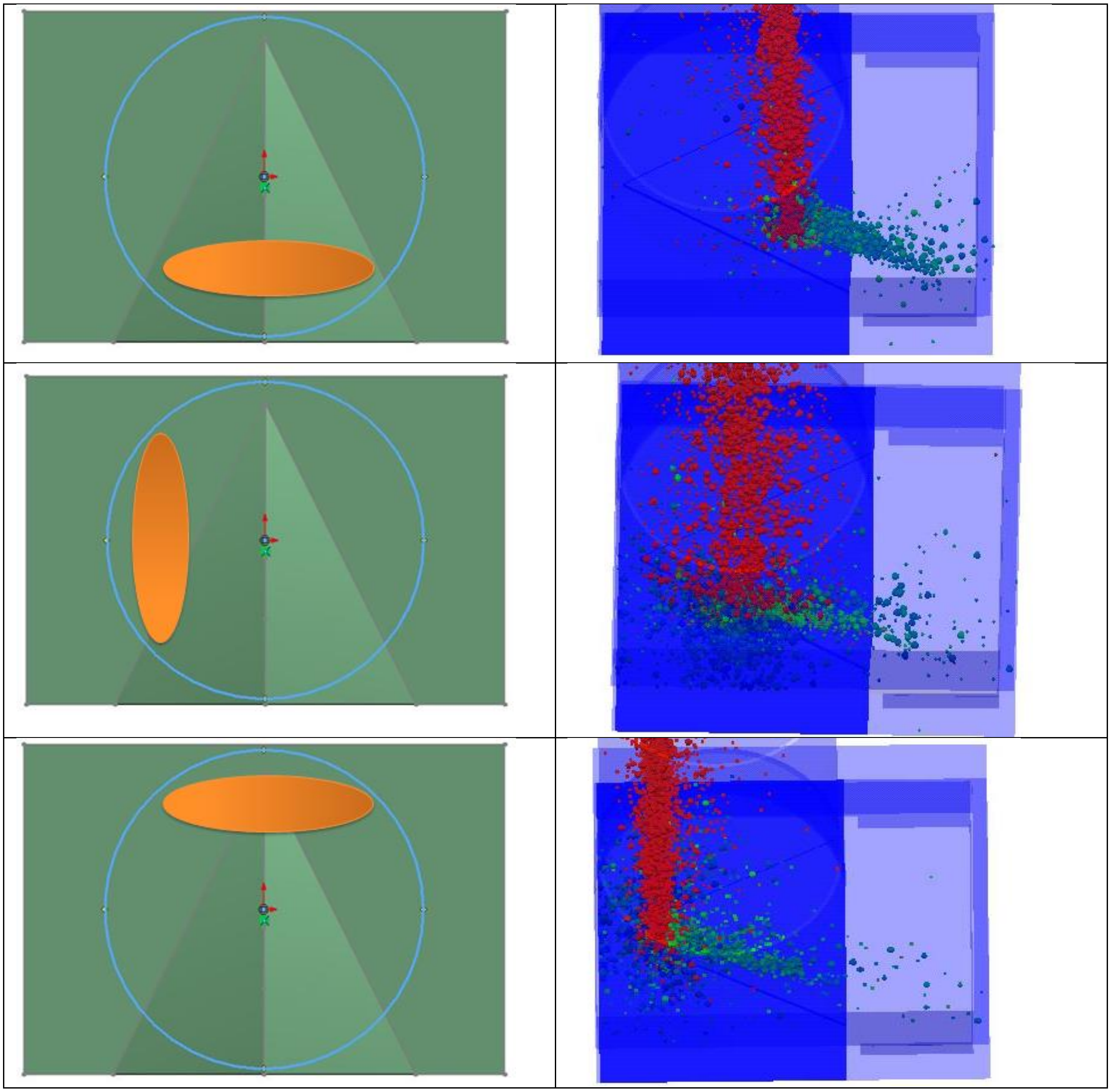


Figure 34 Impact areas on current design(extended position)

4.1.1 Chute with a central opening (CO)

In the current design the material falls partially on the flat plate and on the sliding section on the wear plate. The velocity of the particles are very high when it impacts on the plates and there is a huge wear when the chute's orientation is such that the material falls directly on the sloped plates(Figure 35 – 90 deg),unless it is protected by a material bed. In this design, it was decided to create material bed for impact in all positions of the chute, while maintaining the area required for flow.

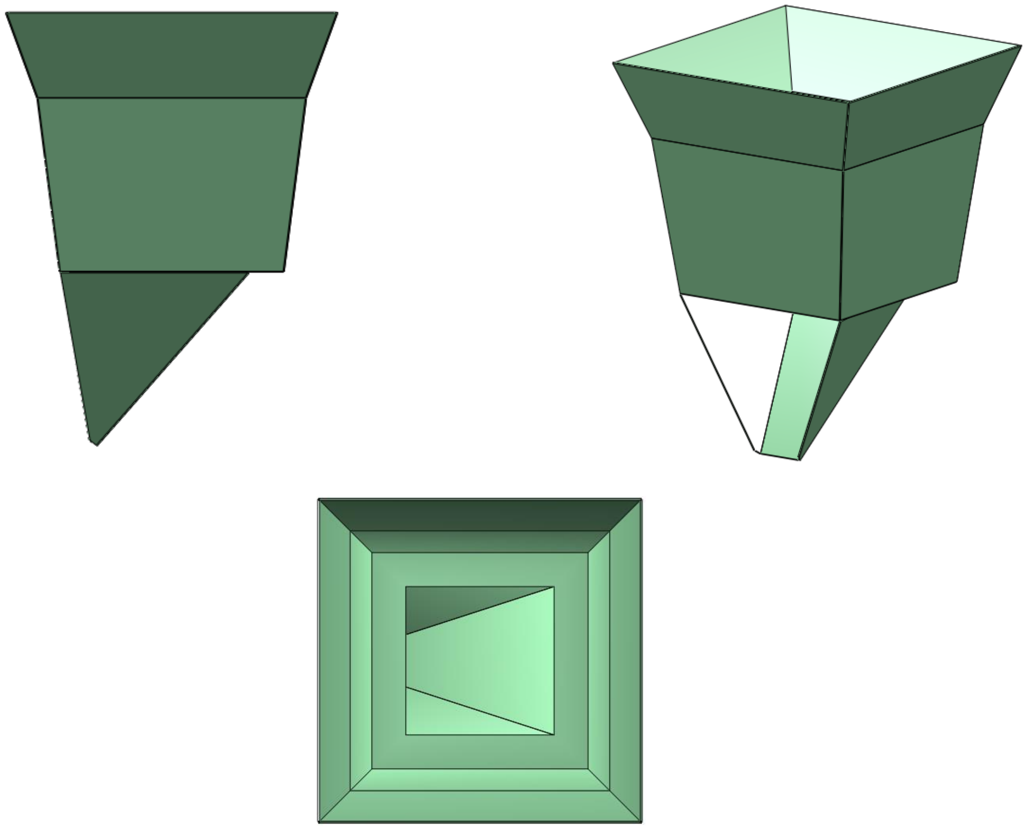


Figure 35 Side view, isometric view and top view - chute with central opening

From figure 21, it can be noticed that the majority of the particles fall between the distances of 400mm to 900 mm from the axis. Moreover the chute needs to rotate and material on material impact needs to be ensured to have low wear. After the material gets slowed down because of the rockbox, the material needs to be guided such that it flows in between the screw auger. Hence a spout like arrangement could be considered inevitable. In this form of the chute, a flat plate is provided to form a rockbox like arrangement on impact and a central opening in the form of a square to enable the flow of material down the spout like arrangement. The bottom plate of the spout is at an angle of 50 deg with the horizontal and the central opening is a square of side 820 mm.

4.1.2 Modified wear plate with ribs (MWP)

The design incorporates a well-known concept in the industry to reduce material on chute wall impact, ribs. The ribs on the chute surface should be placed in the direction of particle impact, so that when the material hits the chute, particles are captured in between the ribs and creates a bed of particles within a very short time. In the current design the particles form a bed on the flat region of the plates and the wear is very high due to sliding action on the plates. Hence the ribs are placed on the spout like plates. The design of the improved chute with ribs is shown in figures below.

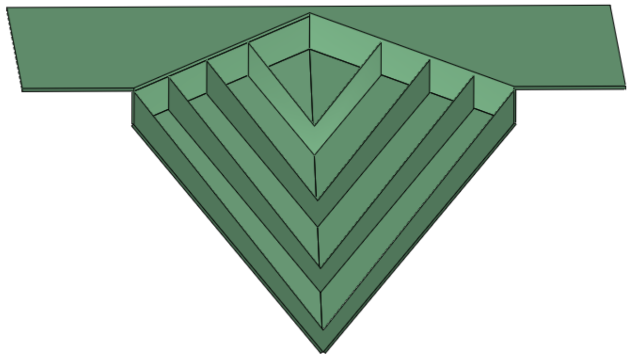


Figure 36 Modified wear plate with ribs

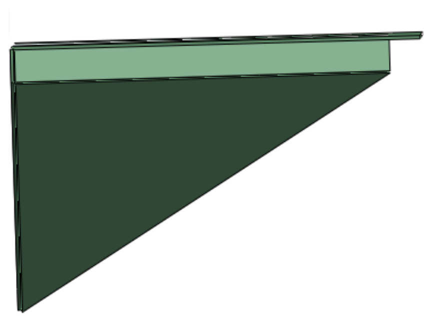


Figure 37 Side view – modified wear plate with ribs

In the current design the angle of the plates is about 53.83 deg to the horizontal and the valley angle is about 32 deg to the horizontal. In the improved design with ribs, the angle made by the edge of the ribs would be the influencing factor since the material bed would be formed in between the ribs. The angle of edge of the ribs are 52 deg to the horizontal and the valley angle is about 32 deg with the horizontal. To obtain this angle with the horizontal, the sliding plate structure is given a depth of about 150 mm at the joint as shown in the figure below.

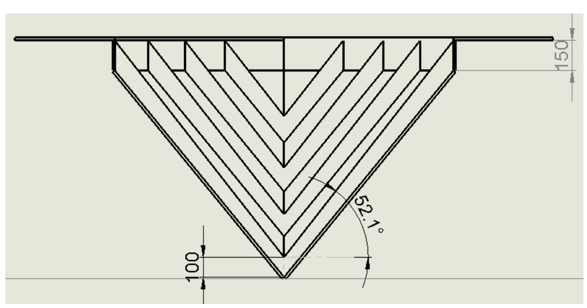


Figure 38 Modified wear plate with ribs - Front view

4.1.3 Chute with multiple rock boxes(MRB)

In the current design and the improved designs stated above, the rock box concept is utilized just once to make sure that there is material on material contact. In chute with central opening, due to the spout like arrangement concentrate the material flow to the region between the screw augers, wear is always higher. The discharge velocity is also considerably high when compared to the speed at which the screw augers operate because the slope is high enough for the material to start accelerating again. As in modified wear plate, forming a particle bed very near to another dead zone might be looked at as unfavourable for flowability. Hence a concept in which there are multiple rock boxes to dissipate energy of the materials is considered. In this type of chute, the entire slope is made up of small rock boxes. So the material slides from one rock box to another, fills up the rock boxes and reduces the chute area exposed for material impact. The height and breadth of the chute spans 2540 mm symmetrically and the width is about 2000 mm. Since the slope is 52 degrees, which is high enough to ensure flow on particle-particle contact, flowability is achievable for the conditions considered. The design of the chute with multiple rock boxes is shown in the figure below.

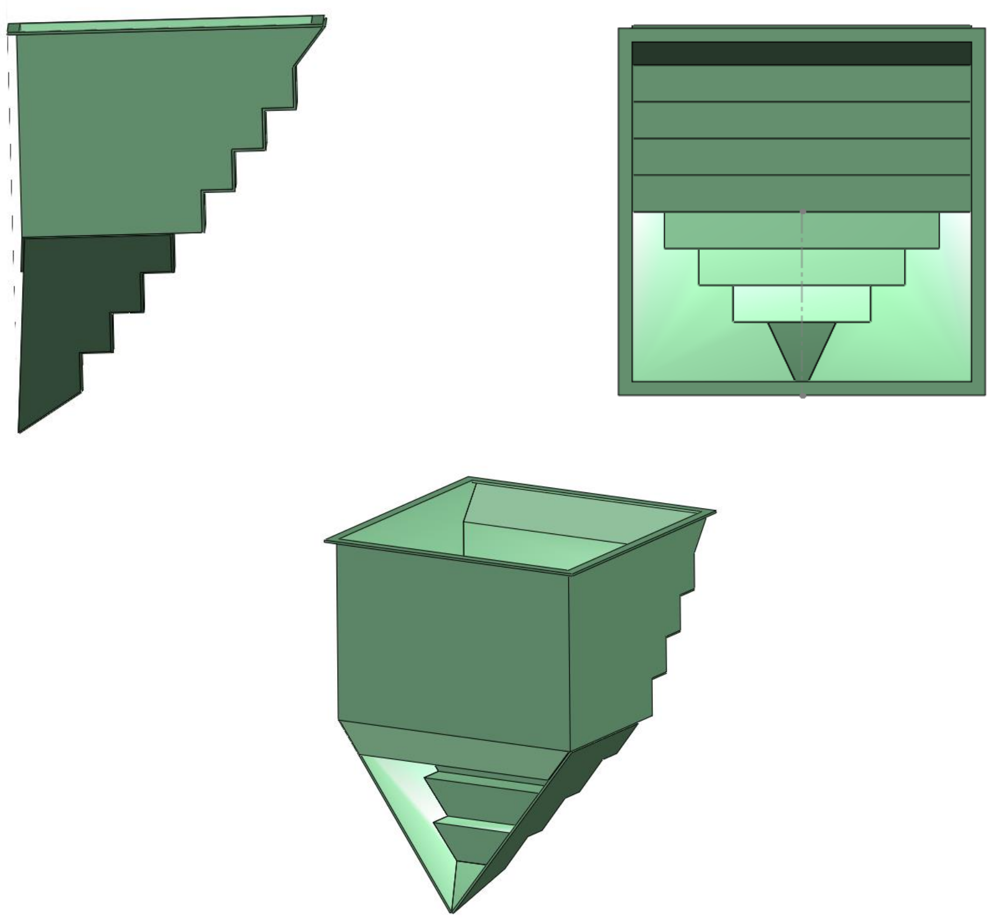


Figure 39 Side view, top view and isometric view - chute with multiple rockboxes

The spout like structure is still incorporated to concentrate the material flow but the difference is that there is a rockbox like structure even in such a zone when the material is concentrated towards the region between the screw augers. The wall opposite to the rock boxes is provided so that the material doesnot fly out immediately after impact. These kinds of chutes are widely used in high velocity transfers and transfer points for abrasive materials. However for highly wet, cohesive materials, use of this design is criticized.

4.2 Improved chutes - Dimensional aspects:

In the current design, the arrangement of the chute box and wear plate above the screw augers is shown below.

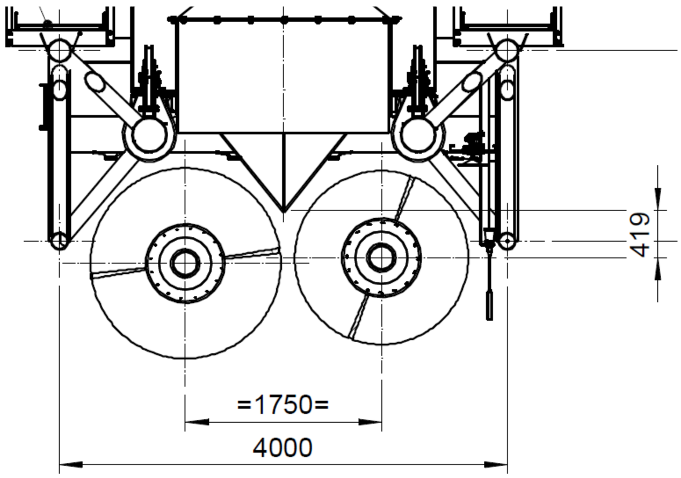


Figure 40 Chute box and wear plate arrangement - current design

The clearance prevailing in the current chute design is about 419 mm. The clearance for the proposed chute designs are given below.

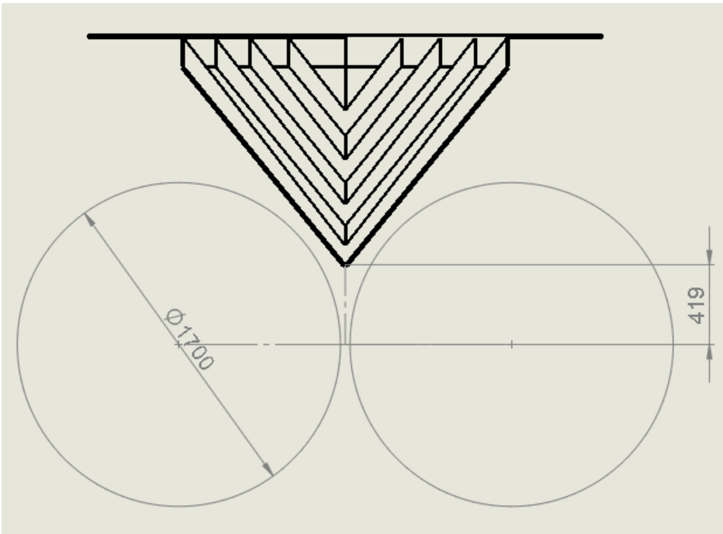


Figure 41 Clearance provision - modified wear plate

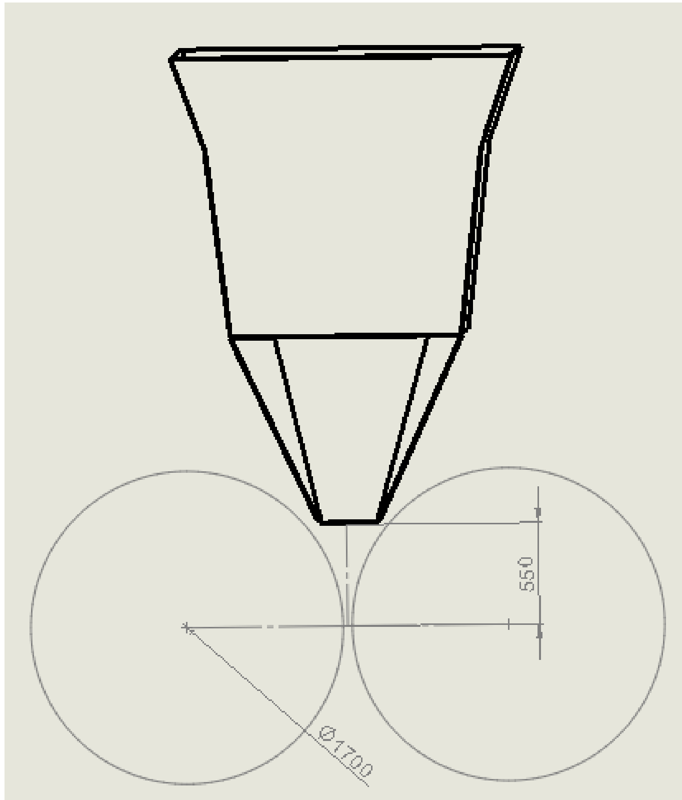


Figure 42 Clearance provision - chute with central opening

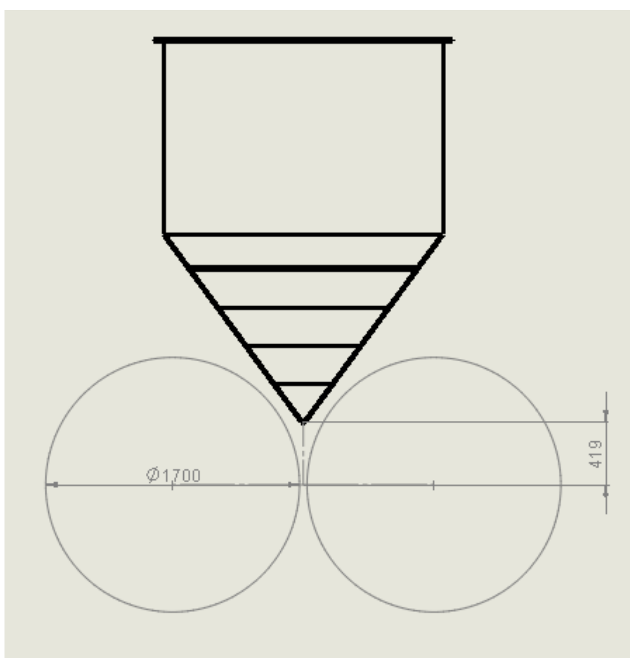


Figure 43 Clearance provision - chute with multiple rockboxes

From the figures 41,42 & 43, it could be identified that the clearance possible for the chute with modified wear plate, chute with central opening and the chute with multiple rockboxes are 419, 550 and 419 mm respectively. The modified wear plate is a bit deeper by 100 mm in construction when compared to the original design. This should be taken into account during the design of the chute box for the modified wear plate.

4.3 Simulation results and discussion

The improved chute designs are incorporated in the geometry and simulated under the similar boundary conditions as mentioned in chapter 3. The simulations are also carried out in 4 different orientations of the chute. As expected there has been considerable reduction in wear on the plates in all the chute designs since the material on material contact has been increased. The values of maximum wear depth which is considered as the key point indicator has been extracted for all chute designs at the end of all simulations. The total energy dissipated and the discharge velocity of the particles have also been extracted and compared with the trends from the current design in figures 47,48 and 49.

The figures 44,45 and 46 below show the state of the chutes at the end of the simulation with particles and the wear region on the chutes. The extracted data have been tabulated along with an indication of % increase or decrease in relation the respective value for the simulations with current chute design.

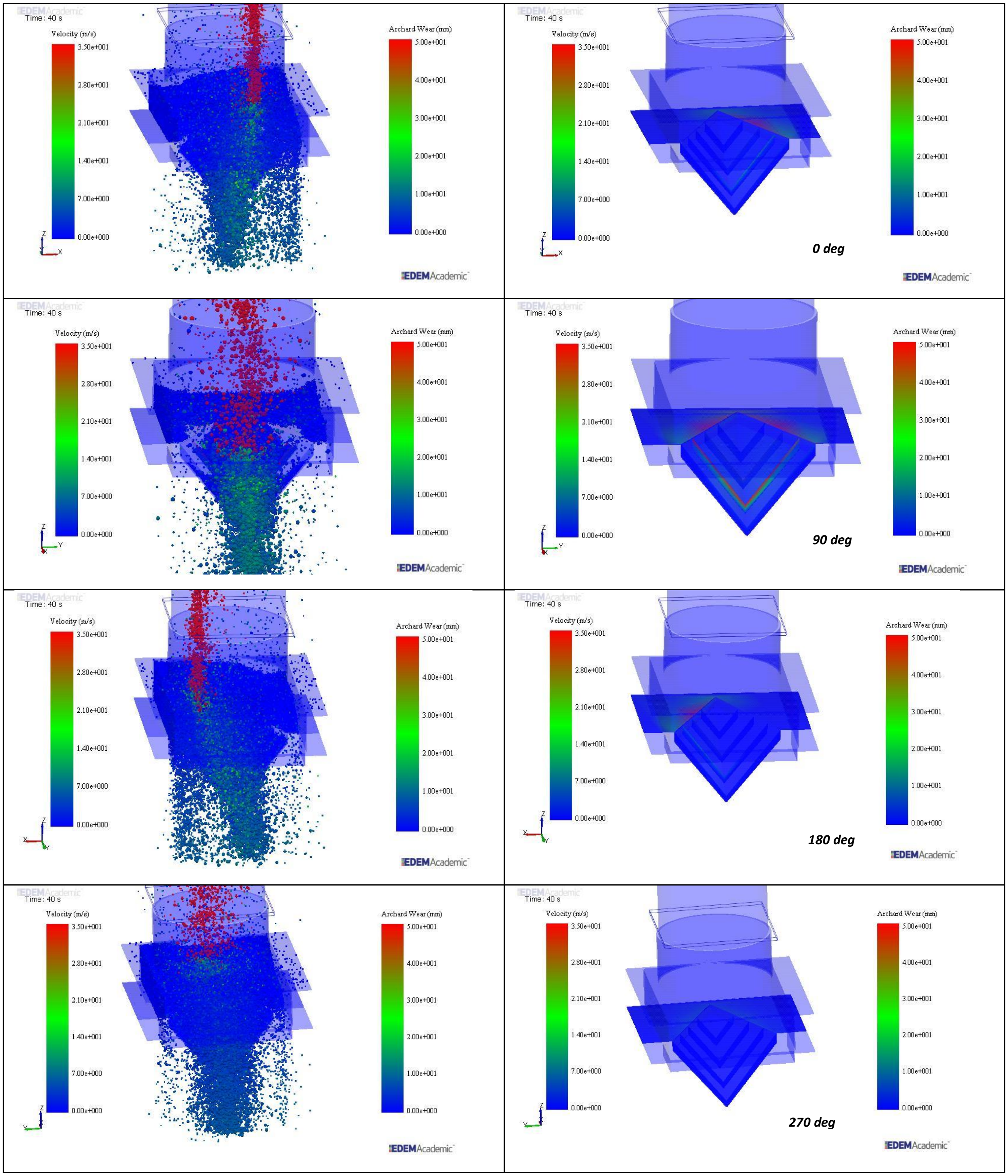


Figure 44 Flow and wear patterns – chute with modified wear plate

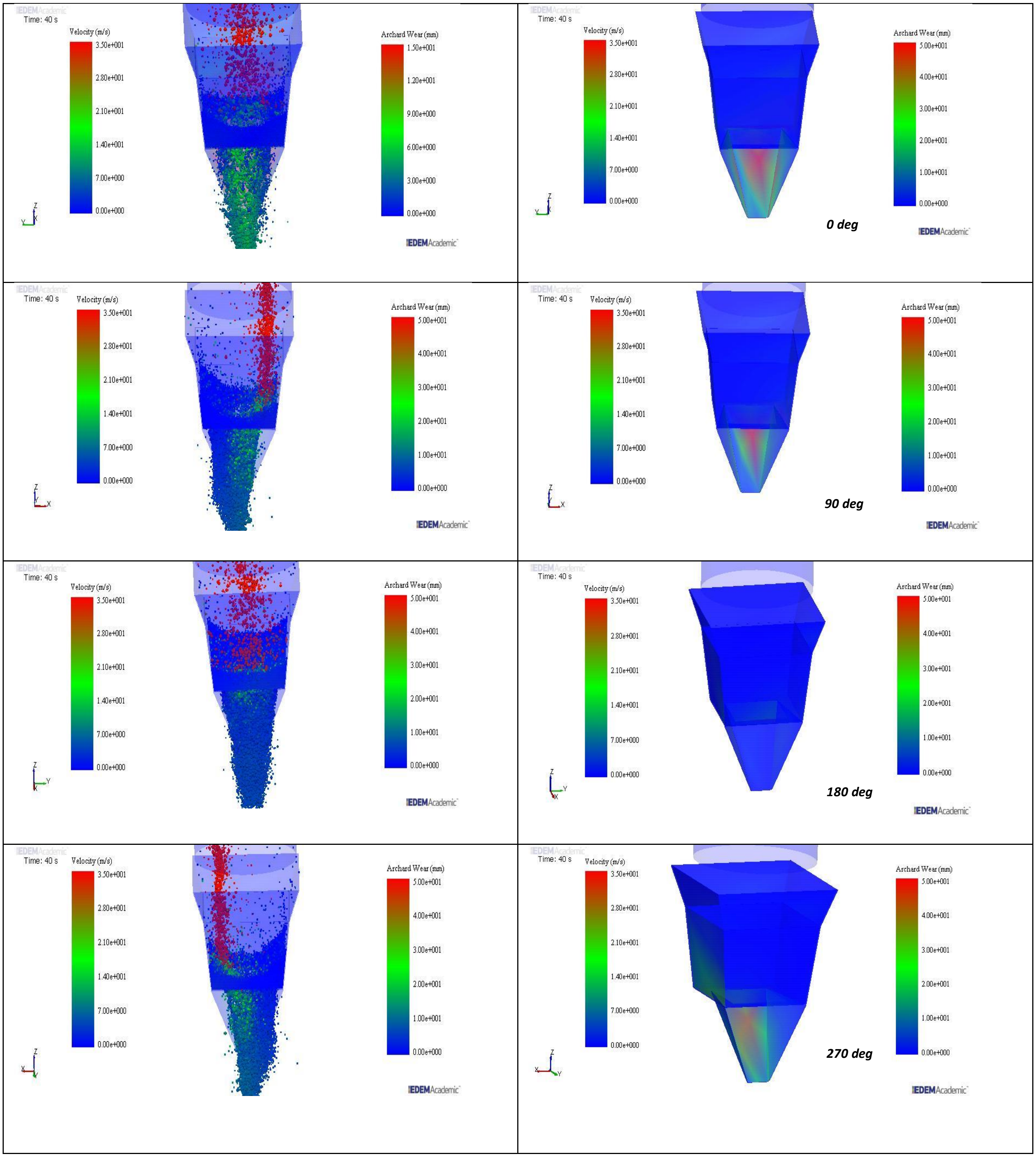


Figure 45 Simulation results - chute with central opening

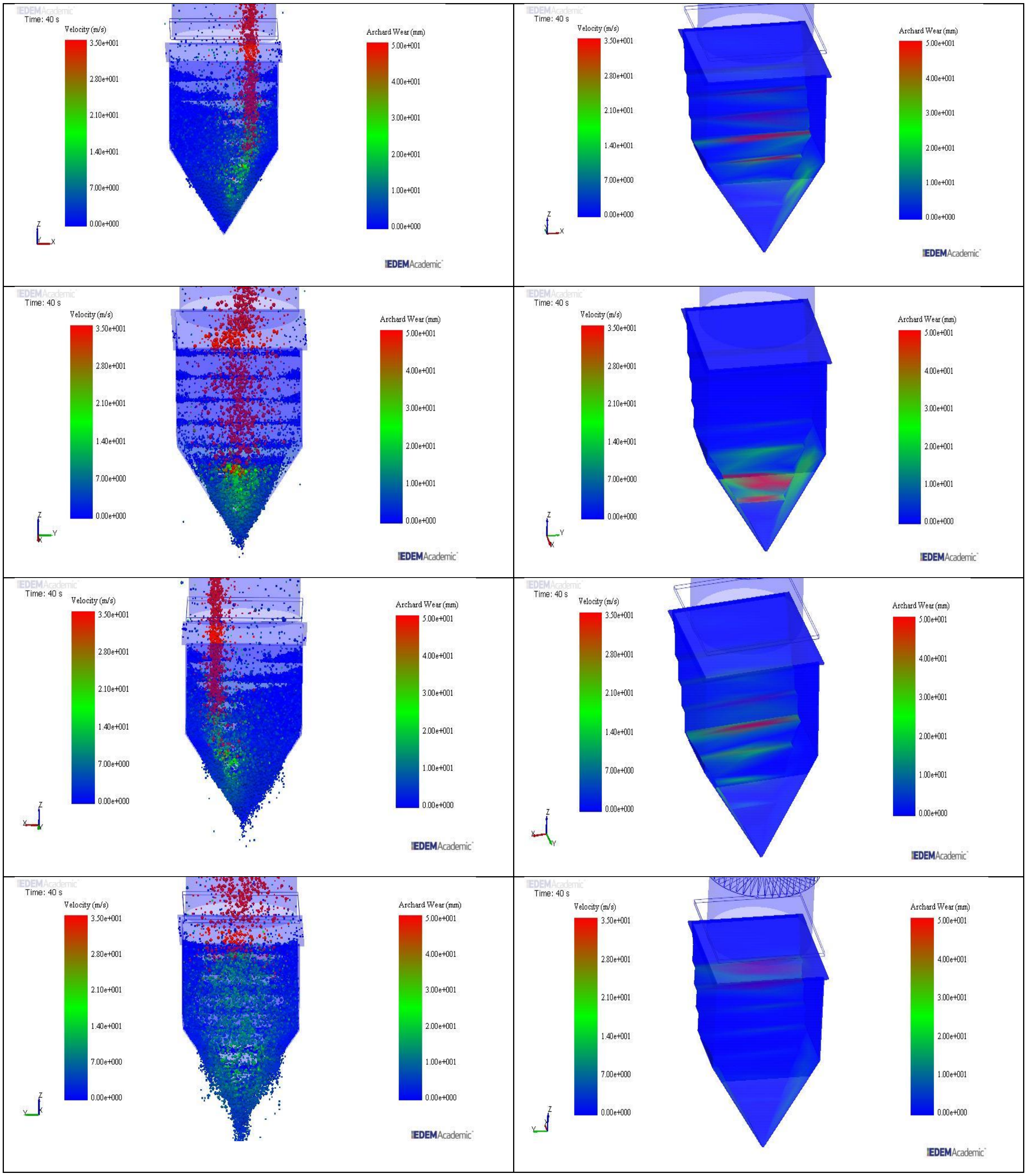


Figure 46 Simulation results - chute with multiple rockboxes

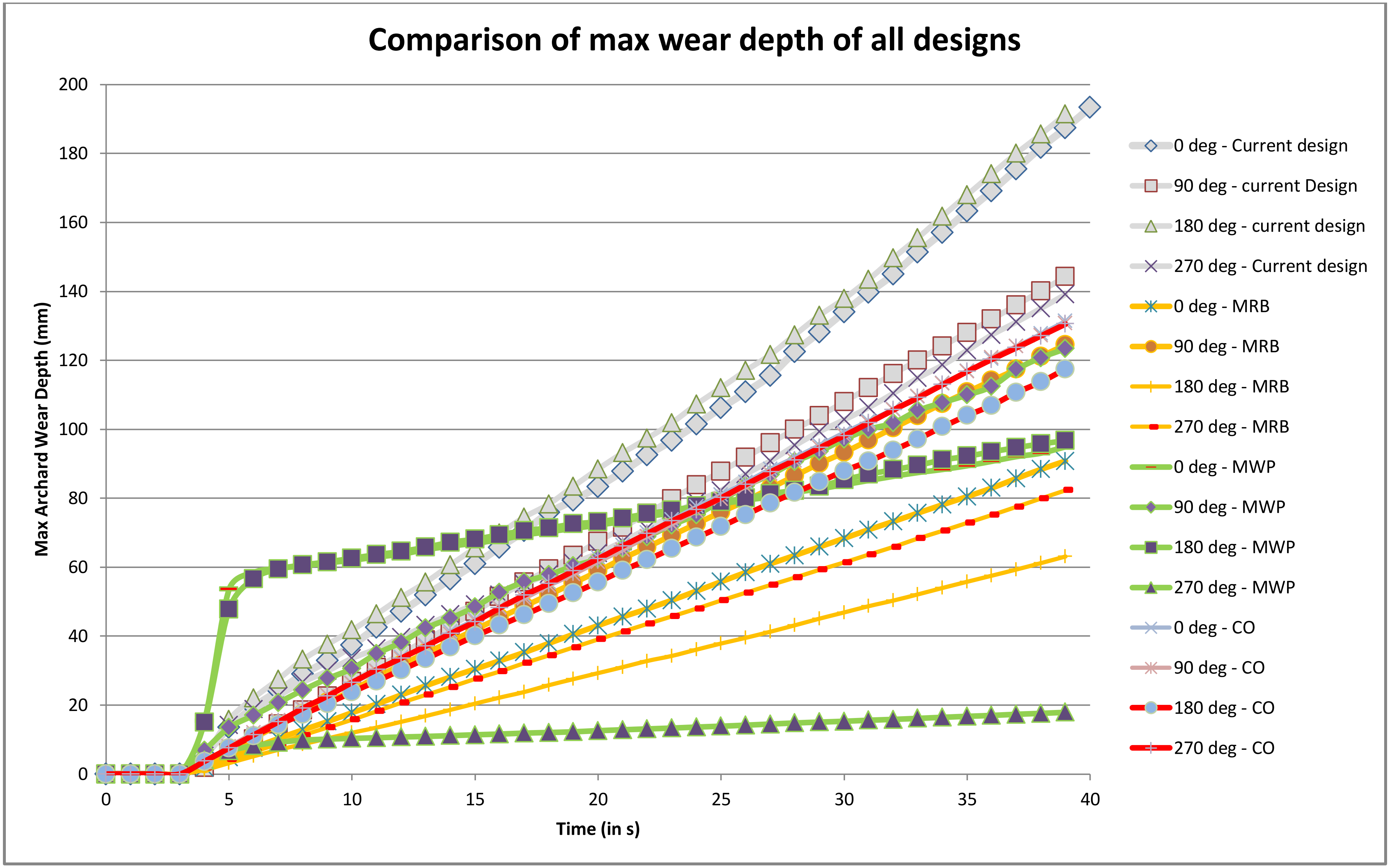


Figure 47 Comparison of max wear depth for all designs

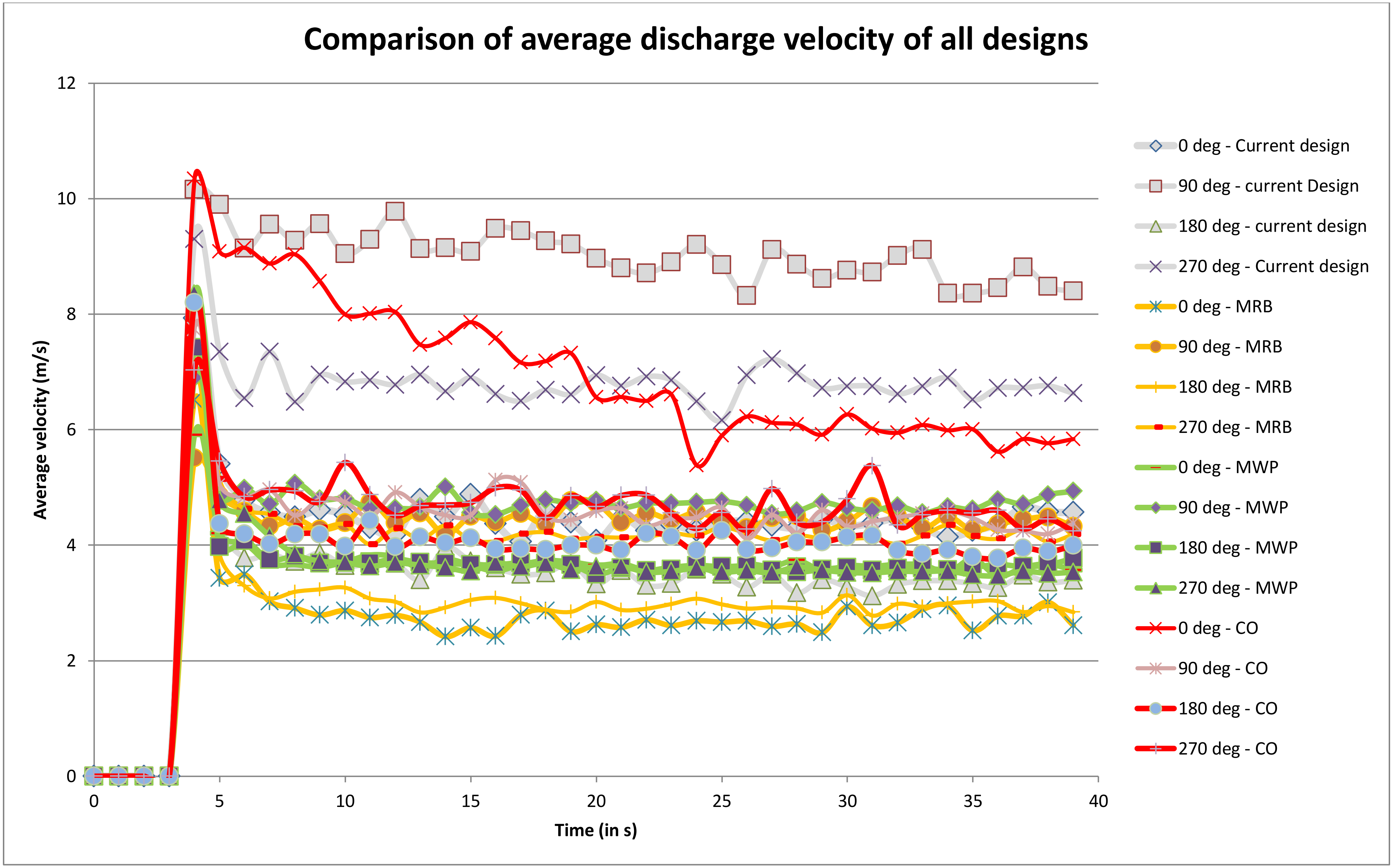


Figure 48 Comparisono of average discharge velocity of all designs

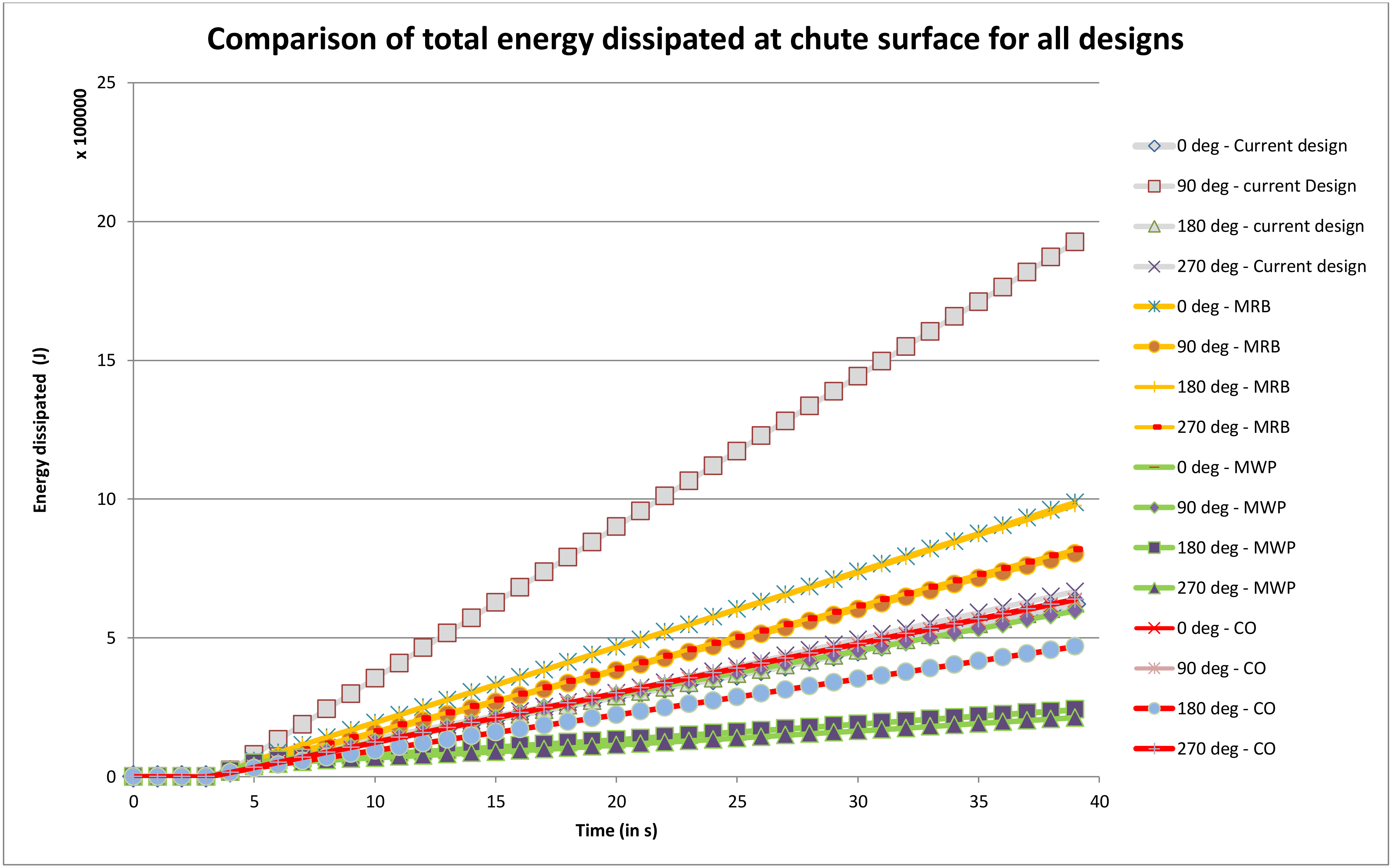


Figure 49 Comparison of total energy dissipated at chute for all designs

A summary of the key point indicators are tabulated below.

KPI	Maximum Wear depth (mm)						
Position	Current design	Modified wear plate	% inc/ % dec	Chute with central opening	% inc/ % dec	Chute with multiple rockbox	% inc/ % dec
0 deg	193.3	94.9	50.90	131.3	32.04	90.8	53.03
90 deg	148.4	123.3	16.88	130.7	11.90	124.4	16.11
180 deg	197.3	96.6	51.01	117.4	40.47	63.1	68.03
270 deg	142.8	17.8	87.47	130.5	8.62	82.3	42.39

Table 2 Summary - Max wear depth

	Total energy dissipated at the surface (x100000 J)						
Position	Current design	Modified wear plate	% inc/ % dec	Chute with central opening	% inc/ % dec	Chute with multiple rockbox	% inc/ % dec
0 deg	6.21	2.41	61.24	6.35	-2.28	9.87	-59.00
90 deg	19.25	5.97	68.99	6.37	66.89	8.04	58.25
180 deg	6.23	2.41	61.26	4.69	24.78	9.76	-56.57
270 deg	6.67	2.13	68.08	6.38	4.33	8.18	-22.56

Table 3 Summary - total energy dissipated

	Discharge velocity (m/s)						
Position	Current design	Modified wear plate	% inc/ % dec	Chute with central opening	% inc/ % dec	Chute with multiple rockbox	% inc/ % dec
0 deg	4.57	3.57	21.87	5.84	-27.87	2.61	42.80
90 deg	8.40	4.93	41.24	4.37	47.91	4.33	48.49
180 deg	3.39	3.77	-11.33	3.99	-17.75	2.84	16.21
270 deg	6.63	3.53	46.73	4.24	36.00	4.19	36.88

Table 4 Summary - Discharge velocity

From the table 2, it can be identified that all three chute designs provide lesser wear when compared to the current design. The modified wear plate and the chute with multiple rockboxes are better in terms of max wear depth amongst the three improved chute designs. With the chute with multiple rockboxes, the maximum wear depth is reduced by an extent of 68% at 180deg position and the lowest is at 16% for 90 deg position. In the chute with modified wear plate, the maximum extent of wear depth reduction is at 270 deg position at 87% while the lowest is at 16.8% at 90 deg position. At 90 deg position, the wear depth is high in all chute designs.

The total energy dissipated at the surface is considerably reduced at the modified wear plate design in all positions of discharge. This is mainly due to the formation of the particle bed between the ribs. In case of chute with central opening the total energy dissipated at the surface is not as good when compared to the results of the modified wear plate. Whereas with the chute with multiple rockboxes, the total energy dissipated is much higher than other designs. It is even higher when compared to the current design in all positions except one. However, the wear depth is lower because the energy is dissipated over a larger surface area when compared to the other positions. The amount of particle on particle impact is lesser when compared to all the designs and the energy is dissipated at the surface.

From table 5, it can be seen that the discharge velocities of modified wear plate and the chute with multiple rockboxes are also considerably lower when compared to the current design and the chute with central opening. The low velocities of the particles in the chute with mini rockboxes can be attributed to the total energy dissipated in the chute by the particles sliding horizontally after the first impact and dissipating low energies multiple times as they slide down the rockboxes for positions 0 and 180 deg while the velocities are considerably higher at 90deg and 270 deg positions because at 90 deg, the particles fall closer to the outlet of the chute while at 270 deg position there is more particle on particle interaction and the material rolls down by the slope easily owing to the lower rolling friction coefficient. In case of the modified wear plate, the velocities are normalized to a range of 3.5 m/s for 0, 180 and 270 deg positions due to the material on material impact while at 90 deg the velocity is a bit higher at 4.93 m/s owing to the proximity towards the outlet.

The wear constant considered gives a very high rate of wear as an output. To calculate the actual wear depth, it is recommended that the wear constant should be found out for this particular application by means of experiments to calibrate the model. This would also help in choosing the material of the chute and optimization of the plate thickness required for the chute to perform for a desired life time. Given the current discrete element models based on elastic contact theories, it is not possible to visualize the actual rate of wear and area of wear using EDEM. The wear area as a result of the simulation may prove to be an effective tool for analysis but doesn't portray the actual deformation on the wall material in a direction normal to the surface.

Based on the chosen KPI, the maximum wear depth, the chute with modified wear plate and the chute with multiple rockboxes are the best designs with respect to wear. Even though both designs provide a better solution against wear for the application under study, the performance of the chutes with respect to flowability in other scenarios inside the Eurosilo system needs to be investigated, which is explained in Chapter 5.

5. Simulation for flowability

In Chapter 4, the improved chute designs with respect to wear have been determined. The simulations were performed with the telescopic chute at an extended position since the energy of the particles would be the highest in that scenario, thereby becoming the worst case of wear. The particles were considered to be free flowing since that would be the best conditions to analyse the performance of the chute with respect to wear. However, one of the key aspects of chute design, to have a smooth material flow without blockage, should never be overlooked regardless of the nature of flow of bulk materials.

In the chute designs selected, the wear is reduced by promoting particle to particle interaction instead of particle to wall material of the chute. Also the particles are accumulated to form a layer over the material with the help of ribs or rockboxes. In industry, these concepts ring an alarming bell to customers, since the materials that are handled with rockboxes tend to agglomerate over time and might cause flow problems. An example of such flow problem is shown in the figure below.

Figure 50 Cohesive material buildup in a rockbox chute -Source: (Marion, 2015)

The figure 50 shows rock box chute handling very high cohesive and fine material, has particle built up on the ledges leading to plugging in the rock box chutes. Even with free flowing bulk materials, there is a possibility that the fines that are present in the mixture, tend to lodge in the corners. When they mix with moisture that is sprayed on the coal or any bulk material, for the sake of dust suppression, they stick to the wall surface and agglomerate when still in contact with the wall. When the moisture evaporates, what remains is a thick layer of solid crystal like material stuck in the corners. These solid agglomerates accumulating enable the adhesion of more fines with moisture and causes material buildup. Material buildup leads to poor flow of material in the chute and could eventually lead to plugging due to reduction in cross sectional area of flow required for the bulk material. Such a material build up could be seen in the original design of the wear plate in the Eurosilo in Figure 5.

The general industry practice is always to assume for the worst conditions of the material to be handled when designing a handling equipment but it is still not enough. A lack of understanding of the mechanics that govern the flow of cohesive materials has consistently led to the failure of processing equipments and systems (Grima A. P., 2011)

There are not many researches that could be found related to the simulation of flow of cohesive bulk solid in chutes. However an attempt is made here to evaluate the performance of the chute qualitatively based on some assumptions.

5.1 Qualitative calibration:

For JKR model, the cohesive energy as denoted by the surface energy per unit area of contact is the main input. The value of cohesive energy is in J/m^2 and shall be modeled to replicate the effect of Van der Waals forces and liquid bridges. The cohesive strength of a bulk solid mixture is dependent on a lot of factors like particle size distribution, moisture content, material properties and the wall material properties. Since there are no determined methods to calibrate the cohesive energy that could incorporate all these factors and could be translated to the flowability of bulk solids, a qualitative calibration method is followed. Depending on the poured angle of repose, a basic guide to determine the flowability of the material was developed by Hill (1987) as given in the table below.

Angle of Repose (deg)	Flowability
25-30	Very free flowing
30-38	Free flowing
38-45	Fair flowing
45-55	Cohesive
>55	Very Cohesive

Table 5 Flowability based on Angle of Repose

Since the particle size hasn't been scaled in this research, the above method could prove to provide a satisfactory calibration method for the particle size distribution as mentioned earlier. The cohesive energy values were input on trial and error basis until the material slope was high enough indicating that the material is cohesive. The material properties and the particle size distribution remain the same as per the simulation for evaluation for wear. The angle of repose for 25 J/m^2 and 35 J/m^2 was found to be greater than 60 deg which means the material is very cohesive.

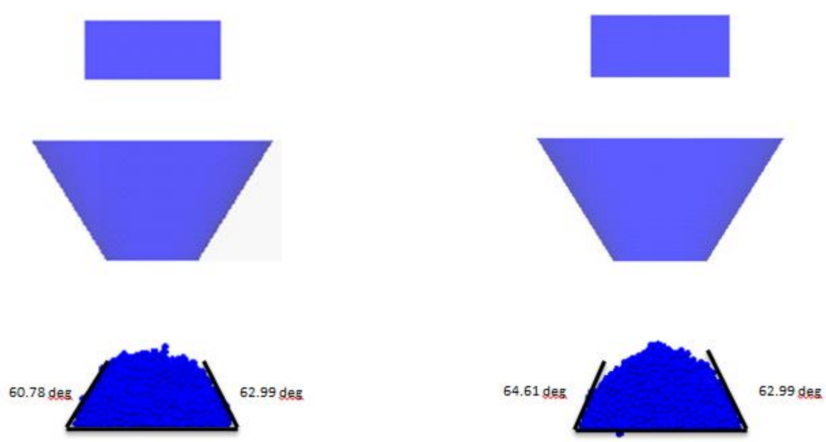


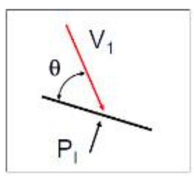
Figure 51 Poured Angle of Repose

5.2 Flow of cohesive bulk solid – considering crystallization of particle bed

5.2.1 Simulations set up

Chute plugging takes place when the bulk material at its lowest velocity does not have enough cross section area for it to flow through. The cross section area is expected to shrink when the particle builds up inside the chute. The particle build up happens at lower pressures when the strength of the cohesive material is lesser than the corresponding strength at the boundary (wall) as explained in Section 2.2.2. To determine such cohesive strength of the material and the strength at the boundary between material and the wall surface, shear tests are conducted. The pressures at which these tests are conducted are determined by the pressures that could be exerted by the bulk material on the wall material during a transfer through the chute. The impact pressure due to a bulk solid stream can be found by the formula as shown in the figure 52.

$$\text{Impact Pressure} = \frac{\gamma V_1^2 \sin^2\theta}{g}$$



γ = Bulk density
V_1 = Impact velocity
θ = Impact angle
P_I = Impact pressure
g = Acceleration (gravity)

Figure 52 Impact pressure (Frittella & Smit, 2015)

The velocities of the bulk stream within the Eurosilo system varies between 15 m/s and 34 m/s and the impact pressure due to the same are in the order of 0.18 to 0.96 MPa respectively. In the current industry, the discharge velocity of the bulk material handling system above 3-4 m/s is termed as high speed conveying. It is also known that at such high velocities which means at higher pressures, the wall friction angle tends to become very low. There are no studies that could be found explaining the effect of such high impact pressure in the range of 0.18-0.96 MPa on the friction characteristics of the material flow inside a chute. Hence it is safe to assume that the effect of wall friction angle in Eurosilo application is negligible.

Moreover, in chutes based on rockbox concepts the material on material contact is higher than the material on chute wall and the material is expected to build up. The material that is stagnant experiences the impact pressure due to the incoming bulk stream and disperses, loses strength and is expected to flow. The impact pressure is higher in the range of 0.18 to 0.96 MPa in the retracted and expanded positions of the telescopic chute. If there is a chance of particle build up, it is bound to happen in situation with lowest impact pressure. Hence the simulations with cohesive solid is performed only at the retracted position.

5.2.2 Particle bed formation

When the particle hits the chute plate, it loses energy, thereby velocity and moves by itself or is pushed by the following particle in some random direction. If the direction in which it moves is toward an open space, where it doesn't lose much energy, the particle moves. Otherwise when the particle hits an enclosed space or loses its energy and velocity becomes zero, the material becomes stagnant. The particle bed could be formed inside an empty chute at both retracted and expanded positions. The spatial orientation of the particle stream hitting the chute is shown below in figure 53. The inner circle represents the tube diameter at retracted position and the outer circle represents the telescopic tube diameter at expanded position.

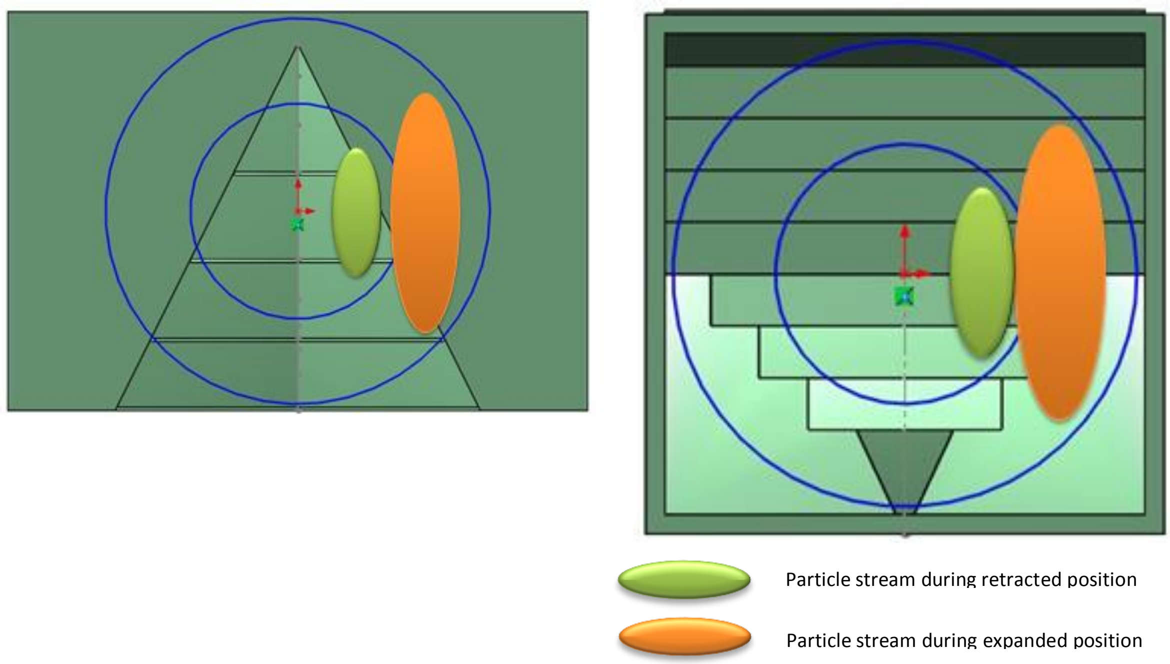


Figure 53 Particle stream concentration in telescopic chute - expanded vs retracted position

The particle stream at the expanded position has higher probability to form a stable particle bed than at retracted position. Since the pressure of the particle stream is the lowest at the retracted position at 0.18 MPa and increases till the expanded position upto 0.96 MPa and the particle stream impact area at the expanded position of telescopic chute is on a wider space, it is assumed that the particle bed/ material accumulation formed at the expanded position disturbs the particle bed formed at previous positions and is stable compared to every other position.

The particle bed formation has been achieved by simulating particle flow for a few seconds and stopping the particle flow to let the particles that could still move, flow out of the chute. This is done at 0,90,180,270 deg at the expanded position in both chute with modified wear plate and the chute with multiple rockboxes. The particle properties are the same as mentioned in the Chapter 3 except that the contact model chosen is JKR with a surface energy of 25 J/m^2 between the particles and the surface energy of 10 J/m^2 between the particle and the wall of the chute. The results are shown in the figure 54 below.

There hasn't been any research attempting to model the crystallization of bulk solid during over time in the corners of a chute. This phenomenon could depend on a lot of dynamic factors and the adhesive forces at microscopic level which form a very strong bond amongst the particles and the particles and the wall. These crystallized particles would form a profile on top of the chute wall to which more particles stick and so on and the particles might build up. The purpose of this part of the research is to evaluate if the bulk material would flow even if there is a particle build up/agglomeration within the chute since all the chutes are based on rockbox concept.

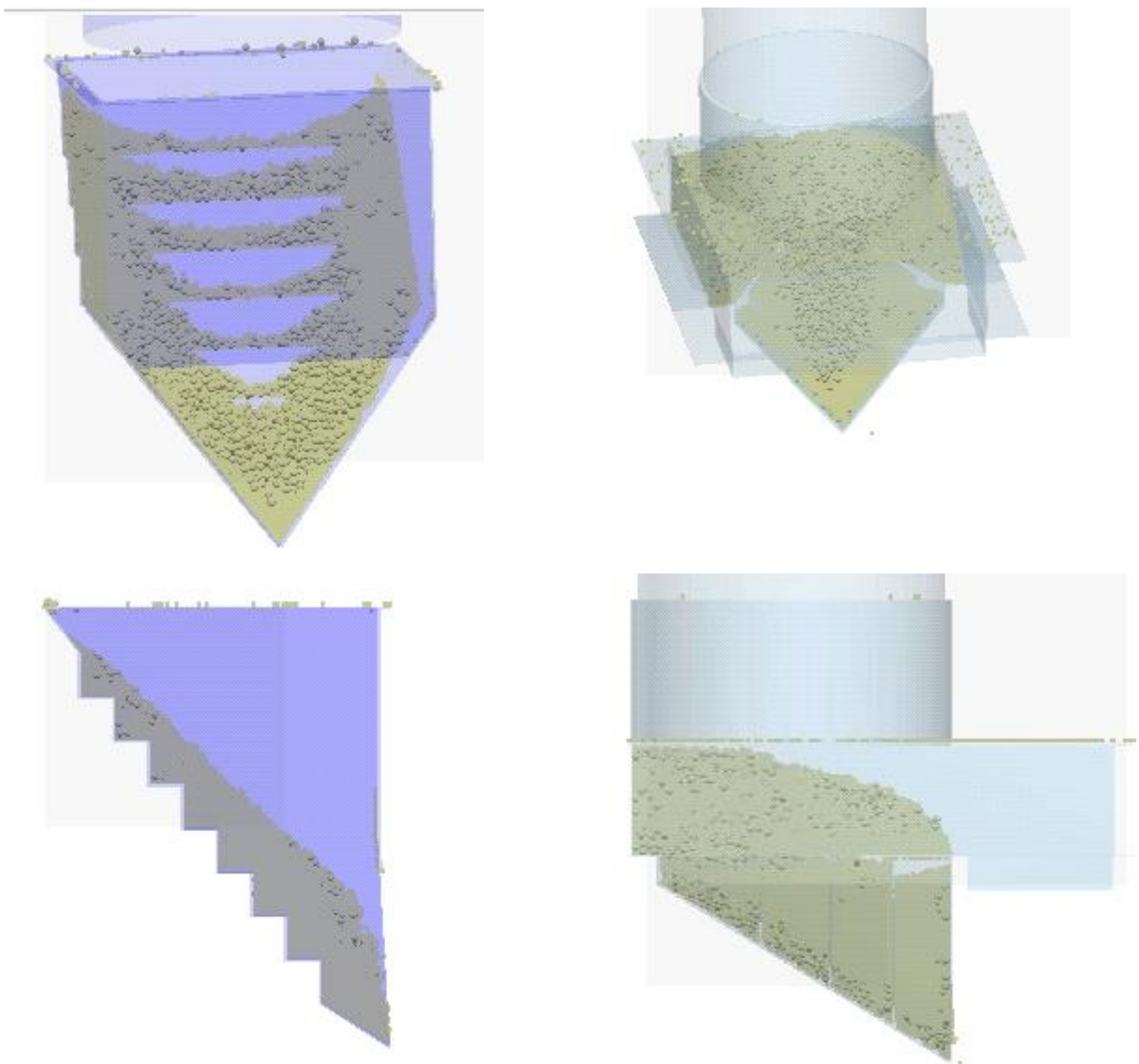


Figure 54 Particle build up in chutes with MRB & MWP

In both cases the cross section of the flow area required for the bulk material is expected to reduce. It is nearly impossible to predict the particle agglomeration and model the same in any chute as it depends on a lot of dynamic factors. However, it is widely accepted and agreed upon that the fines that are present in the material along with the moisture content play a major role in forming agglomerates at areas where the particles become stagnant.

To simplify and prove that the material flow is ensured in both cases, i.e after formation of the particle bed (loose particles) as well as the formation of agglomerates(hard solid), the particle bed obtained as a result of simulation above is assumed to be the agglomeration formed by the fine particles over time. There are two ways possible to model the above particle bed as a solid agglomerate.

1. The particle positions could be exported along with the diameter of the particles and modeled as a single solid structure and imported to EDEM.

2. A very high value of cohesive energy density could be specified to exist amongst the particles and between the particle and the wall using JKR contact model in EDEM.

The first option requires a lot of work and the current solid modelling softwares could not model 30,000+ particles in a single file to be exported into an IGS file for using it in EDEM. Hence the second option was chosen. This would also mean that when the incoming particle stream exerts a higher force good enough to break the bond between the coal particles, the agglomerate deforms, which is desired.

The model is set up for retracted position. The length of the telescopic chute is reduced to about 10 m with a diameter of 1000 mm in the EDEM model. A new particle is defined for generation from particle factory with the same properties of coal, called Coal 1. The interaction properties of Coal 1-Coal 1 and Coal1-Coal are the same as that of the interaction properties of Coal-coal defined previously in Chapter 3. The interaction properties of Coal1-steel are the same as that of the properties of Coal-steel. The JKR bond properties specified are as below.

Bond	JKR cohesive energy value(J/m^2)
Particle-particle	
Coal- Coal	500
Coal1-Coal1	35
Coal1-Coal	25
Particle-Chute	
Coal-Chute	400
Coal1-Chute	10

Table 6 JKR model parameters - cohesive flow

The model set up is shown below.

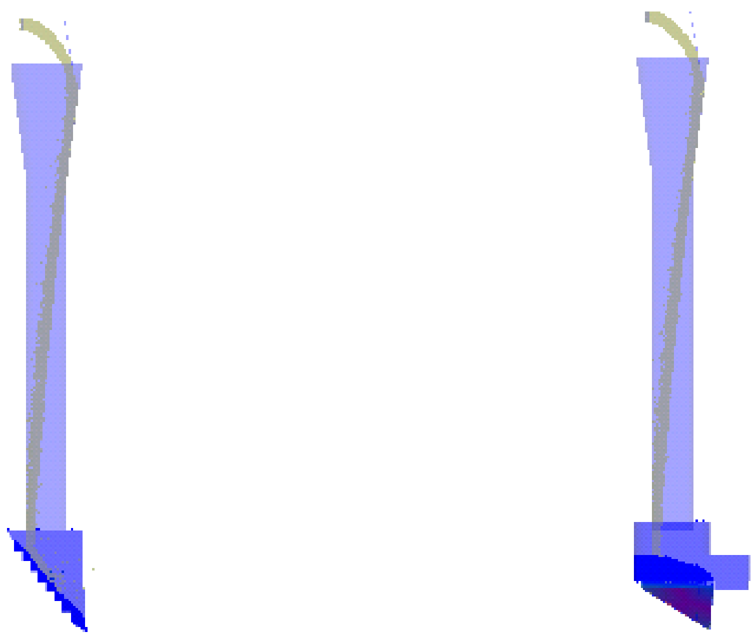


Figure 55 Model setup - bulk solid flow after formation of agglomerates

The chute is also given a rotation of 2 deg/s about the central axis to understand the behaviour of particles. On simulation with the chute with multiple rockboxes, there was particle buildup and plugging due to the fact that the cross sectional area wasn't sufficient for the material to flow out due to the wall in front of the chute as shown in the figure below.

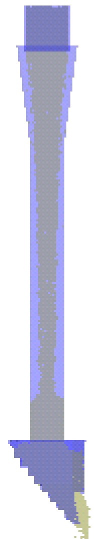


Figure 56 Plugged chute - Chute with MRB

Hence the chute was modified without the wall and the particle build up simulations were performed once again. Again the simulations were re-run for the situation with particle agglomeration. The results of the simulation are shown below.

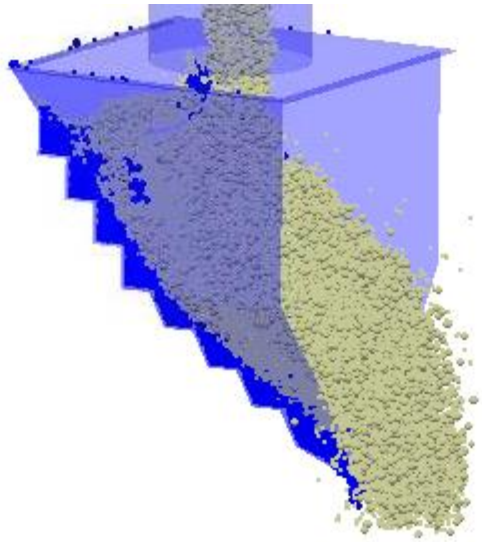


Figure 57 Cohesive material flow with agglomerated particle - Chute with MRB

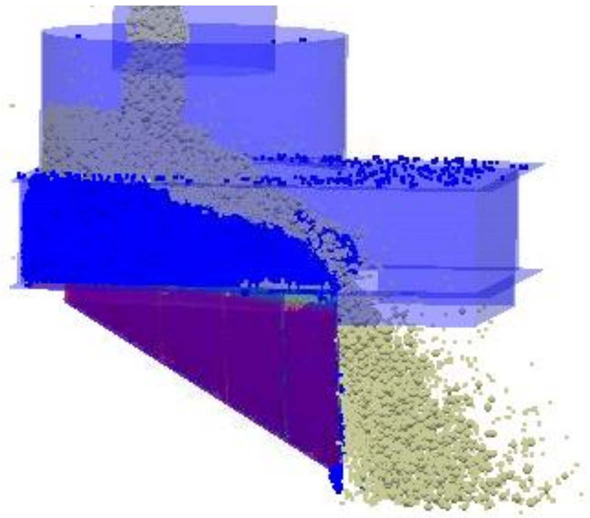


Figure 58 Cohesive material flow with agglomerated particle - Chute with MWP

From the simulations, it was seen that there were no broken bonds between Coal-Coal. However, there has been no chute blockage in both cases inspite of that.

The modelling of particle flow in the both chutes after the formation of agglomeration has given a very good insight into the performance of the chutes with cohesive bulk solid and the ability of EDEM to evaluate the chute designs for Eurosilo application. The results of this part of the study could be considered uncertain because the values input in EDEM were not based on any experiments and not based on any previous research. It was preferred to model the particle build up as a single solid model so that the number of particles in the simulation will be lesser and Hertz Mindlin with Archard wear model could be used to find out the amount of particle would wear off the agglomeration, by providing the wear constant for coal on coal impact. However, in order to get a satisfactory result, the particle agglomeration needs to be studied and modeled with different parameters.

The simulations with JKR contact model requires a lot of simulation time owing to the number of forces to be calculated and the number of particles involved in the simulation domain. It does give an insight into the particle bed formation after material flow through each position, flow of cohesive material after particle build up. However, it is expected that due to high energy dissipated at the particle bed, the agglomeration would wear off and the worn surface would be replaced by loose particles. To achieve a better insight into the wear of the formed agglomerates, it is recommended to model the particle build up as a single solid model, with the values such as density, poisson's ratio and the shear modulus values as well as the particle interaction parameters determined based on experiments. Even though the parameters for modelling bulk material flow with JKR model and the parameters required for modelling the particle bed as a single solid model could be determined from some samples by experiments, modelling the particles as a solid bed is nearly impossible at this moment and simulations with a huge number of particles with particles of size in the range 2-50 mm still remains a challenge.

Overall, it can be seen that the particle flow is ensured even if there is an agglomeration happening as much as the particle build up and for transfer of materials at a very high velocity application,chutes with rockbox concepts prove to be a best option. In Eurosilo application, where the impact pressure and the energy of the particle stream is very high, the material flow can be maintained if there is enough cross-sectional area at the point of lowest velocity of the bulk material and maintaining particle- particle contact to reduce wear. Considering the results of chapter 4 & 5, chute with modified wear plate and chute with multiple rockboxes prove to be the best choices for the Eurosilo application.

6. Conclusions and recommendations

The aim of this study was to improve the design of the wear plate/ chute in the Eurosilo. To achieve the same, the current situation has been modeled based on the available literature and considering Lunen powerplant design as reference.

The problem in the chutes was analysed and the prevailing literature related to the subject were reviewed. It is evident that curved chutes are not suitable and the rockbox option is the only approach to design a transfer chute for Eurosilo application. Even though there are no methodologies or analytical models to create a rockbox/stonebox chute, the basic design guidelines for chutes would give the necessary framework for new chute design.

Discrete Element modelling, as a result of the literature review, has been found to be a very imminent tool for simulation and evaluation of bulk solid systems. DEM has the capability to analyse complex situations such as wear and could enable the user to understand the state of the system even in transient condition. DEM has been utilized and recommended by various researchers as an effective tool to model bulk solid flow.

It has also been proved based on experiments that the rate of wear volume of the material is proportional to the energy dissipated at the contact surface. The evaluation of chute designs with respect to wear is carried out where the particles have the highest energy, expanded telescopic chute positions whereas for evaluation of chute with respect to flow is carried out when the particles have the lowest energy, retracted telescopic chute position.

To analyse the performance of chutes with respect to wear, the particle flow shall be governed only by the forces due to gravity and the interaction between the particle and material. Hence the material is assumed to be free-flowing and only Hertz-Mindlin with no-slip and Hertz-Mindlin with Archard Wear should be considered. The wear profile at the end of the simulation with current design was found to be similar to the wear profile in the real case scenario. The maximum wear depth has been identified as the key performance indicator for evaluating chute designs. Apart from that, parameters like total energy dissipated at the surface of the chute, the discharge velocity of the material from the chute are compared to have a better insight into the performance of the chute.

It is identified that for an improved chute design, the energy of the bulk material needs to be dissipated by material on material interaction and the improved chute needs to be designed to handle 360 deg transfer. Further the dimensional constraints on the design of the chute and the necessity to converge the discharge from the chute are found to be of prime importance for the design of new chutes. Three different chute designs – chute with modified wear plate, chute with central opening and chute with mini rockboxes were developed based on the basic chute design guideline and the limitations with respect to the Eurosilo application. On simulations, the chute with mini rock boxes and the chute with modified wear plate proved to be better designs when compared to the current design. With the chute with multiple rockboxes, the maximum wear depth is reduced by an extent of 68% at 180deg position and the lowest is at 16% for 90 deg position. In the chute with modified wear plate, the maximum extent of wear depth reduction is at 270 deg position at 87% while the lowest is at 16.8% at 90 deg position. At 90 deg position, the wear depth is high in all chute designs. It is found that the chute with modified wear plate(ribs) exhibits reduced wear because of the formation of material bed between ribs andbmaterial on material interaction, while in chute with multiple rockboxes, the material dissipates energy over a wider surface area rather than material on material interaction. Both these designs showed lower wear rate and significant reduction in maximum wear depth when compared to the current design and the chute with central opening.

The extreme flow conditions have been identified as when the bulk material has high moisture content and higher number of fines. The influence of these two factors on the cohesive strength of bulk solid could be modeled using Hertz-Mindlin with JKR model. The evaluation of the chutes with modified wear plate and multiple rockboxes was conducted for an extreme case of cohesive flow through the chutes with particle build as agglomeration. The model was calibrated by a qualitative method, based on the poured angle of repose tests. It was found that in both chute with modified wear plate and the chute with multiple rockboxes, the bulk material flow is ensured even when the agglomerated particles that were assumed to have formed, were not broken.

In Eurosilo application, the energy of the particles are varying over a very wide range of velocities between 15 m/s and 34 m/s. The chute needs to be designed such that the following parameters are satisfied. At any position and the orientation of the chute, the slope of the chute and the rockbox should be high enough(recommended above the angle of repose) so that the body forces are sufficient to enable the failure of the material, thereby ensuring the flow. To understand the performance of the chute against wear, proper calibration of the interaction between particle and material needs to be undertaken. The chute must be designed such that the energy is dissipated either by material- material interaction or energy dissipation over a wider area is facilitated. Due to the high energy of the particles at the end of the telescopic chute in extended position, the material flow is always possible. However in the retracted position, the energy of particles are not sufficient to cause the material flow. Hence to ensure flowability, the conditions of flow at the retracted position of the chute needs to be considered.

It is asserted that the results of the simulation incorporating such models are useful only when they are calibrated to replicate the real bulk solid to be handled. The wear constant considered gives a very high rate of wear as an output. To calculate the actual wear depth, it is recommended that the wear constant should be found out for this particular application by means of experiments to calibrate the model. However, based on the simulations conducted, both chute with modified wear plate and the chute with multiple rockboxes seem to be the best choice.

Recommendations for future work.

DEM proves to be a very efficient tool to simulate the bulk solid flow and evaluate the performance of the chutes for wear and flowability. However due to lack of literature, only qualitative analysis could be performed on flowability considering the time and scope of this project.

There are still a lot of challenges in modelling bulk solid flow which requires immense effort and technological advancement. However, based on the work done in this study, the following would be the recommendations for future work.

1. The actual wear depth in the chutes could be found by determining the wear constant of the interaction between coal and steel.
2. Given the current discrete element methods based on an elastic contact models, it is not possible to visualize the actual rate of wear and area of wear. The wear area as a result of the

simulation, may prove to be an effective tool for analysis but doesn't portray the actual deformation on the wall material in the direction normal to the surface.

3. A model could be developed to determine the lifetime of the chute against wear and also determine the thickness of the chute plate based on the EDEM simulations.
4. The effect of fines on the material build up could be further investigated.
5. Even though there are effective models to incorporate cohesion and adhesion in the bulk solid flow, there is a huge lack of research work, thereby understanding and determination, of cohesive energies influenced by liquid bridges, van der Waal's forces due to fines that prevails. More research work is needed in this field.
6. The effect of particle shape and cohesion together on the chute could be studied in general and could be applied for simulations at the retracted position for an effective chute design.

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List of Figures

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List of Symbols

Symbol	*Description*	*Unit*
v_i	Velocity of bulk stream corresponding to the drop height 'h' before impact on curved chute	m/s
v_{fo}	Output velocity of bulk material stream from feeder	m/s
v_∞	Terminal velocity of the bulk stream	m/s
v_o	Velocity after impact on chute plate	m/s
θ_1	Angle of impact of material on the chute	deg
e	Restitution factor	-
μ	Kinetic friction between material and chute	-
μ_e	Equivalent friction between material and chute	-
F_D	Drag force	N
F_N	Normal force component	N
K_v	Pressure ratio	-
H	Depth of flowing bulk material stream	m
B	Width of the curved chute	m
λ	Converging angle of the chute	deg
H_o	Initial stream thickness	m
B_o	Initial chute width	m
θ	Chute angle of curved chute, changes with position	deg
R	Radius of curvature of a curved chute	m
g	Acceleration due to gravity	m/s^2
$\emptyset_w$	Wall friction angle	deg
τ_w	Shear stress at the wall	Pa
σ_w	Normal stress at the wall	Pa
V	Volume of wear material removed	m^3
L	Sliding distance	m
W	Load on the surface	m
H_s	Hardness of the softer material of the contacting surfaces	-
K	Wear coefficient	-
$K_{1,} K_2, K_3$	Proportionality constants for adhesive, abrasive and corrosive wear respectively	-
W_c	Abrasive wear factor	N/ms
$\boldsymbol{N_{WR}}$	Non-dimensional wear number	-
Q_m	Mass flow rate	kg/s
K_c	V_s/V	-
V	Average stream velocity at section considered	m/s
V_s	Rubbing velocity for bulk solid on chute bottom surface	m/s
W_{csw}	Abrasive wear factor on chute side walls	-
F_n, F_t	Normal, tangential contact forces	N
F_n^d, F_t^d	Normal, tangential damping forces	N
δ_n, δ_t	Normal, tangential overlap	m
E_i, E_j, E^*	Young's modulus of particles i,j in contact and equivalent young's modulus of particles in contact, respectively	GPa
R_i, R_j, R^*	Radius of particles i,j in contact and equivalent radius of particles in	m

	contact, respectively	
m_i, m_j, m^*	mass of particles i,j in contact and equivalent mass of particles in contact, respectively	kg
v_i, v_j	Poisson ratio of particles i,j in contact	-
$\overline{v_n^{rel}}$, $\overline{v_t^{rel}}$	Normal, tangential components of relative velocity	m/s
β	Damping ratio	-
k_n, k_t	Normal stiffness	N/m
e	Coefficient of restitution	-
τ_i	Torque of object i	Nm
μ_s, μ_r	Coefficients of static and rolling friction	-
ω_i	Unit angular velocity of the object at contact point	rad/s
Q	Volume of material removed	m^3
d_t	Tangential distance moved	m
W_i	Wear constant	-
A	Area of the surface geometry	m^2
F_{coh}	Normal Cohesion force	N
k	Cohesion energy density	J/m^3
A_{coh}	Area of contact	m^2
F_{JKR}	Normal elastic force in JKR model	N
γ	Surface energy per unit area	J/m^2
a	Contact radius	m
δ_c	Maximum gap for which non-zero force exists in JKR model	m
a_c	Contact radius at δ_c	m
$F_{pulloff}$	Critical pull off force in JKR model	N
γ_s	Liquid surface tension	J/m^2

List of Abbreviations

DEM	Discrete Element Model
JKR	Johnson-Kendall-Roberts
MWP	Chute with modified wear plate
MRB	Chute with multiple rockboxes
CO	Chute with central opening

Appendix – Scientific Paper

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Development of an improved chute design for Eurosilo system using DEM

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ABSTRACT

The transfer chute design for Eurosilo system handling coal was found to fail due to wear. The current transfer chute was designed based on rockbox concept. There are no specific methodologies for design of chutes for a rock box concept involving a very high velocity transfer. New or improved designs were required to sustain in the industry. The designs were done based on the basic guidelines and application specific constraints and Discrete Element Method, which is becoming widely popular for modelling and simulating bulk solid flow is used to analyze the performance of the chute against wear. Three different improved designs were created and inbuilt models in EDEM were used to analyze for wear performance using Hertz-Mindlin with Archard wear model, while Hertz Mindlin with JKR is used for flow performance. Based on the results of the simulation, two chute designs proved to perform better against wear and worst flow conditions. DEM proved to be a very efficient tool in analyzing the chute design in a predictive way. However for better results on specific case scenarios, simulations with calibrated models based on experiments is highly recommended.

1. Introduction

Storage and handling of bulk materials in any logistic chain requires immense care and effort. Mammoth silos, by ESI Eurosilo BV, provides a complete solution for the storage of bulk solids in various industries in a very economical and environmental friendly manner and proves to be the best amongst the prevalent closed storage solutions. The application of Eurosilos varies over a variety of industries from potato starch, fertilizers till coal in power plants. With increasing need for the reduction of pollution due to coal fired power plants, coal handling and storage inside power plant has become prime importance for stake holders in recent times. The mammoth silo offers a completely controlled and enclosed environment for a bulk material storage.

In a Eurosilo system handling coal, the coal is fed into the silo by means of infeed conveyors on the top of the silo (the direction of coal flow is shown in figure 1 with red arrows). The conveyor at the top transfers the coal on to a transfer chute, down through a telescopic chute and is stacked by means of the screw augers. The screw auger along with its frame can be lifted or lowered by means of the winch system, also could be rotated by rotating the swiveling bridges.

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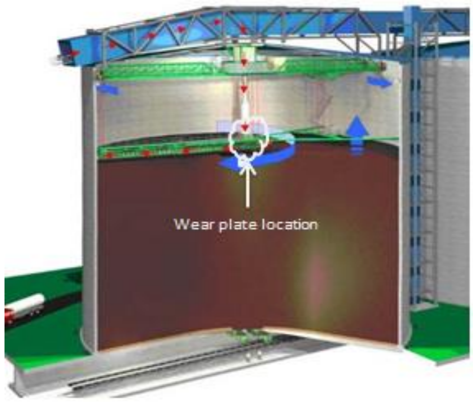


Figure 1 Eurosilo system

The transfer between the telescopic chute and the screw conveyor is achieved by means of a stone box chute with a wear plate, which changes the direction of the coal towards the screw auger. The location of the wear plate has been highlighted in figure 1. There were two cases wherein wear plate failed sooner with the formation of holes, one was the Helsinki power plant where the plate wore off in a very short period of time while in case of Lunen, the wear plate wore off almost at the end of 2 years of operation. The design for the Lunen powerplant has been considered for this study. The design of the wear plate and the wear plate after failure are shown in figures 2a & 2b Better design of this wearing plate would eradicate the downtimes due to replacement of the plate, increase the performance of the machinery inside the silo and gain good will of the customer.

a b

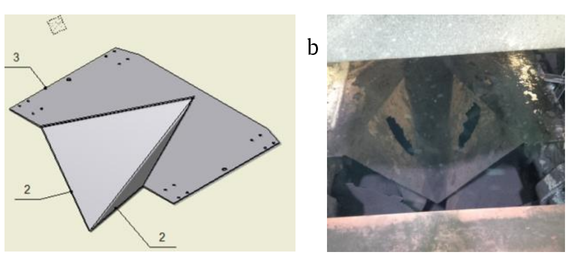


Figure 2 a.Wear plate design b. Failed wear plate

The challenge is to improve the design of the wearing plate/transfer chute to have a better operational period with no compromises on the flowability and the space available. In order to do that, the interaction between the material and the wearing plate has to be understood and analyzed. This is where simulation plays a pivotal role. Simulation enables to mimic the material properties and environment in which the interaction between the bulk material and the equipment takes place., enabling us to develop a better design, which would take a lot of time, effort and money otherwise.

Nomenclature

$\emptyset_w$	Wall friction angle	deg
τ_w	Shear stress at the wall	Pa
σ_w	Normal stress at the wall	Pa
V	Volume of wear material removed	m^3
L	Sliding distance	m
W	Load on the surface	m
H	Hardness of the softer material of the contacting surfaces	N
K	Wear coefficient	-
F_n	Normal contact force	N
F_n^d, F_t^d	Normal, tangential damping forces	N
δ_n, δ_t	Normal, tangential overlap	m
E^*	Equivalent young's modulus of particles in contact, respectively	GPa
R^*	Equivalent radius of particles in contact, respectively	m
Q	Volume of material removed	m^3
d_t	Tangential distance moved	m
W_i	Wear constant	-
A	Area of the surface geometry	m^2
F_{coh}	Normal Cohesion force	N
k	Cohesion energy density	J/m^3
A_{coh}	Area of contact	m^2
F_{JKR}	Normal elastic force in JKR model	N
γ	Surface energy per unit area	J/m^2
a	Contact radius	m
δ_c	Maximum gap for which non-zero force exists in JKR model	m
a_c	Contact radius at δ_c	m
$F_{pulloff}$	Critical pull off force in JKR model	N
γ_s	Liquid surface tension	J/m^2

1.1. Objective, Scope and limitations

The objective of this study is to improve the design of the wear plate/stone box chute that facilitates the transfer of coal from the telescopic chute to the screw auger. To achieve this, a virtual environment is developed to simulate the interaction between the coal particles and the wear plate. The base case is based on the wear plate designed for Lunen case. In the due course of achieving the above objective, the available literature for designing a new chute is studied, a few chute designs are developed and the performance of the chute designs against wear and flow are analyzed. following research question will be answered with the help of the simulation results.
The scope of this study is enormous. For the sake of clarity and focus on the objective, the scope and limitations of the listed below:

- The scope of the analysis is restricted to the transfer point between the telescopic chute and the screw auger.
- The material under consideration is coal.
- In virtue of the main focus of the study, particle breakage/degradation is not taken into consideration.
- The work will only cover the concepts of chute design, wear and extreme flow conditions in Eurosilo application.
- Specific analytical flow model for the improved chute designs have not been developed or reviewed.

- Experiments have not been conducted for determining the parameters used in the study. All the parameters have been chosen based on existing research papers or assumed, in case there is no research paper available.
- The air drag on the particles falling through the telescopic chute is neglected.

1.2. Significance of the study

The current transfer chute design in Eurosilo is a rockbox chute wherein the material forms a bed of particle with a slope and the material starts sliding beyond the slope. The rockbox chute is preferred when the material is very abrasive or for transfers with high rate of discharge when the chute material is expected to wear off quicker. The highest velocity for which any transfer chute has been designed is 15 m/s [1]. In the Eurosilo application the velocity of the materials varies between 15 m/s to 34 m/s at the retracted and expanded position respectively. It is found that there hasn't been any study conducted for design and analysis of chute design such a high velocity transfer in the bulk material handling field.

2. Literature review

2.1. Wear

In general, wear is defined as the removal of material from a solid surface as a result of mechanical action [2]. As per DIN 20320, this progressive loss of substance could be caused by any mechanical action on a solid surface such as contact and relative motion with a solid, liquid or gaseous counter-body. When two surfaces come together, they come into contact at the tips of their asperities and there is a very small area of contact subjected to a load, normal or shear[3]. When there is further motion amongst one of the surfaces, the total area of the singular contact varies and the surfaces fail at the vicinity of contact due to various phenomena. The wear theories explaining such phenomena are described below.

a. Adhesive wear

   Adhesive wear occurs as a result of momentary adherence of two sliding surfaces and when shear occurs, it takes place at some point other than the original interface [2]. The particle that adheres to the other surface comes loose at a later stage, thereby showcasing wear. Adhesive wear is considered to be the most occurring wear, which is always present.

b. Abrasive wear

   Abrasive wear occurs when a hard rough surface slides across a softer surface. ASTM International (formerly American Society for Testing and Materials) defines it as the loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface.

c. Corrosive wear

   When a material surface wears off due to corrosion, it is classified as corrosive wear. In this process, corrosion of a surface occurs, sliding happens and removes the corrosive product to expose new surface to undergo corrosion and so on. The wear rate increases based on the increase in the chemical reactivity in the environment and the wear surfaces and the temperature.

d. Fatigue wear

   Fatigue wear occurs in continuous process which includes contact in the form of pitting and rolling. This type of wear is so severe and plays a major role in the failure of the contacting surfaces. The number of stress cycles to cause failure of a surface decrease with the increase stress. The depth of material removed corresponds to the position of the maximum shear stress.

Archard derived that the total wear rate in the form of a generalized equation applicable for all able wear mechanisms and is given by

$$\frac{V}{L} = K.\frac{W}{H} \tag{1}$$

where K is the wear coefficient between the sliding surfaces.

From a thermodynamic point of view, the motion between the two bodies due to which friction might occur is either a sliding or a non-sliding contact. The resultant wear due to the sliding and non-sliding contact is mainly due to the frictional energy dissipated, which is mainly proportional to the applied load and the velocity in case of non-sliding contact and the applied load and sliding distance in case of a sliding contact. The material characteristics, relative velocity, size and shape of the materials also influence the distribution and the dissipation of energy leading to wear. The works of Mindlin and Deresiewicz [4] provided a major advancement in the study of energy dissipation under non-sliding contact. Many researches were done to experimentally confirm Mindlin and Deresiewicz's theory of surface damage due to energy dissipation. It was concluded that the wear volume varied linearly with the energy dissipation during a non-sliding contact(Fig. 3a).

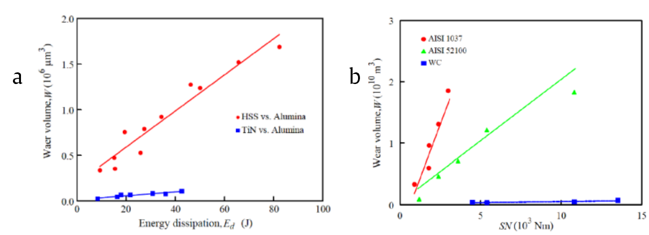


Figure 3 Wear volume as a function of a) cumulative dissipated energy b) work done by sliding force

For sliding contact, a similar energetic approach to wear established the correlation between energy dissipated by friction force and the wear volume. The experimental resultsas shown in fig 3b [5] , which were based on the extension of Archard's wear theory, stated the rate of change of wear is linearly related to the dissipated energy and the slope of the line in the graph between wear volume and the dissipated energy gives the estimation of the wear coefficient.

2.2. Chute design

Conventional chute designs are mainly performed with the considerations of accelerated flow assuming that the material is always in contact with the chute bottom and side walls [6].

Continnuum approach has been used to model the flow of bulk particles within the coal and bulk solid motions are described by a lumped parameter model [7]. For any chute design for transfer of bulk materials under gravity, the basic design principles to be considered are as follows [6].

- Prevent plugging at impact points.
- Ensure that the bulk material accelerates or decelerates sufficiently to match the receiving equipment's speed.
- Control stream of particles.
- Minimizing abrasive wear on the chute surface.
- Control generation of dust

Apart from the above guidelines, there are some restrictions specific to the Eurosilo application. The following points need to be considered for the design of chute specific to the Eurosilo application.

i. Energy dissipated and chute angle:

It can be seen from the literature reviewed that the wear on the chute surface is proportional to the energy dissipated. Hence wear on the wall surface would be higher if the energy is dissipated on the wall. Hence it is preferred to have a material on material contact and dead zone is preferred for the first impact of the material.

In practice, curved chutes are designed to be self-cleaning, hence there would be more material-wall interaction, which would mean higher wear on the wall surface. It has also been proven from experiments that the wear is higher at impact angles of 10-30 deg [8]. Hence curved chutes are not preferred. For an improved chute design, it has to be made sure that the angle of the chute is just enough to ensure the flow of the bulk solid in case of both material on material and material on chute contact regions.

ii. Space available

The restriction on the height and width of the chute available should be taken into consideration when making a new design for this application. The below pictures give the current dimensional space available in the transfer point between the telescopic chute and the screw auger in the end of the auger frame.

a b

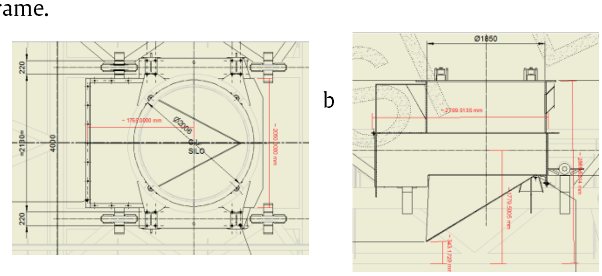


Figure 4 Space constraints a) Top view b) side view

The height and the breadth available are approximately 2540 mm each while the width available is around 2000 mm. There is no provision to extend the chute in the upper half or in the lower half. The total height of the chute cannot be more than 2540 mm because the telescopic chute connected to the chute is optimized for the height of the silo and any change in the height of the chute would result in lesser capacity inside the silo.

iii. Centralized material flow to create a material dead zone between the screw augers

The material flow needs to be controlled and directed to flow towards the zone between the screw augers. The reason is that the screw augers acting over a free surface needs a dead zone of material (indicated by shaded lines in figure below) between them to propel the material (indicated in large dots) for stacking.

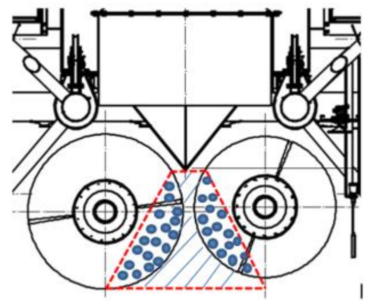


Figure 5 Material dead zone between screw augers

For a rockbox chute design, currently there aren't any literature available. However a few design principles discussed by the experts in bulk handling industry in an online forum are given below [9].

- The bulk material product size, shape, moisture properties, drop height, details of the stream pressure and the buildup of the product affect the design of rockboxes.
- The slope of the surface created is equal to the angle of repose at lower pressures. However the formed surface undergoes constant impact and shear at higher pressures. New surfaces are expected to constantly build up at lower pressures.
- The surface of the slope is not always planar and is expected to form a multiple curved concave surface depending on the product lumps and the cohesiveness of the fines.
- Away from the impact zone, the rock box can be expected to accumulate fines. The velocity of the particles perpendicular to the face of the wall is lost on impact.
- The space needed to create a static bed to deal with the expansion and the change in the direction of the flow stream is of primary importance when compared to the inclination of the geometrical surface.

The above points along with the basic design guidelines for a chute provides good framework for the rockbox chute design.

2.3. Flowability of bulk solid

A bulk solid is said to be "flowing" when it deforms plastically due to the loads acting on it. A bulk solid flows easily, when it does not consolidate much and flows out of a silo, hopper or a chute due to the force of gravity alone and no flow promoting devices are required. A bulk solid is considered to be "poorly flowing" if it experiences flow obstructions or consolidate during storage or transport. [3]

Typically for a transfer chute between two conveyors, where the bulk material flows by gravity and is constantly in contact with the chute, the wall friction angle is the predominant factor to be measured. The wall friction angle depends on the properties of both bulk solids and the wall material along with some external factors. The parameters that influence the wall friction angles are stated below [4].

1. Bulk Solid Parameters
    - Particle size and size distribution
    - Particle shape
    - Particle hardness
    - Moisture content
    - Particle density
    - Bulk density
    - Surface chemistry characteristics
    - Temperature
2. Wall Surface Characteristics
    - Roughness and roughness spectrum
    - Hardness
    - Chemical composition
    - Temperature
3. Loading and Environmental Factors
    - Normal pressure
    - Relative rubbing or sliding velocity
    - Temperature and humidity or moisture conditions
    - Wall vibrations

For measuring the wall friction between bulk material and the wall material in applications where materials undergo higher compressive stresses such as silos, bins, hoppers, Jenike's shear tester was originally used. The same has been modified as an inverted shear tester to measure the shear stress under lower compressive stress, enabling the design of chutes [5]. Using this shear tester, the shear force under which the material fails at varying normal force is determined and the wall yield locus, shear stress versus normal stress is plotted.

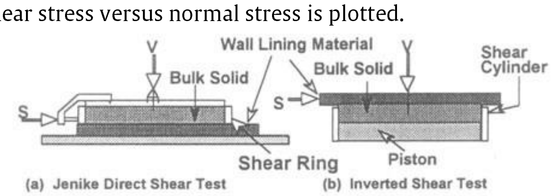


Figure 6 Shear testers

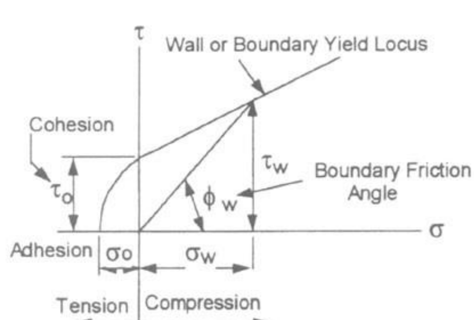


Figure 7 Wall yield locus and boundary characteristics [11]

Figure 7 illustrates a typical wall yield locus for cohesive material. The wall friction angle $\varnothing_w$ is given by:

$$\varnothing_w = \frac{\tau_w}{\sigma_w} \tag{2}$$

The disadvantage of the direct shear tester is the inability to determine the wall or boundary yield locus in the low pressure and tensile stress zones. This difficulty was overcome in the inverted shear tester, Fig. 6(b) and the cohesion and adhesion values could be determined by extrapolating the yield locus as shown in figure 7 [11] [7].

From experiments, it is observed that the wall friction angle decreases with increasing pressure on the bulk solid material as shown in the figure 8. However, wall friction angle is usually less compared to the angle of internal friction, which forms an upper bound limit. At lower pressure, the bulk solid tends to fail more by internal shear, rather than by boundary shear [11] [7]. The moisture content and the amount of fines also influence the values of wall friction angle and the angle of internal friction of the bulk solid. Both can cause building up of coal material on the wall surface and could lead to plugging of chutes. Hence chutes need to be designed considering the maximum moisture content and the percentage of fines in the coal into account.

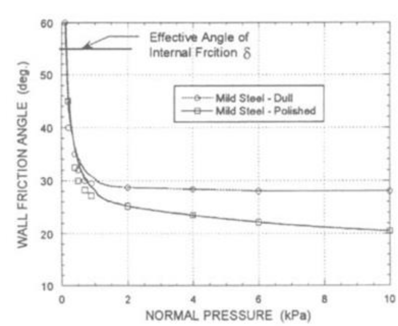


Figure 8 Wall friction angle vs Normal Pressure [11]

In general the bulk material fails when the body forces in the bulk mass are able to overcome the forces that resist the flow. The resisting forces are usually due to shear (in case of free flowing materials) and a combination of shear and adhesive, cohesive forces (inherently coherent materials, materials with high moisture content and fine powders) as shown in the figure 9. In a dynamic system such as bulk transfer, the body forces are normally influenced by the bulk density and the velocity of discharge of the bulk material.

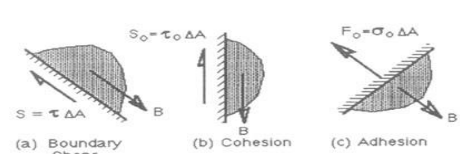


Figure 9 Bulk material failure conditions [11]

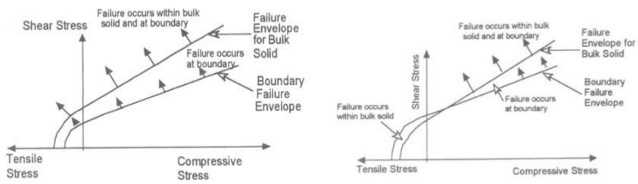


Figure 10 Failure conditions a) general case b) special case [11]

Roberts, Ooms & Wiche [11]also described the different conditions due to which a cohesive bulk solid may fail. In general case as shown in figure 10a, the failure envelope of a cohesive bulk solid is always greater than the failure envelope at the boundary(wall). Hence the bulk solid fails at the wall surface rather than internally. In a special case (figure 10b), where the cohesive bulk solid develops lower strength at lower consolidation pressure when compared to the corresponding strength at the boundary, the bulk solid shears internally leaving a layer of build solid adhering to the chute surface.

Hence for the failure to occur, the shear stress versus normal stress state within the bulk solid should always be higher than the failure envelope of the boundary (wall).

2.4. Discrete Element Method

Design of transfer chutes using lumped parameter model, as developed by Roberts [12] [13] [14] [8] has been widely followed all over the world in different case scenarios. Modelling the particle stream using a continuum approach is more on a macroscopic scale in steady state, which makes it difficult for the engineers to conceptualize or visualize complex situations. The properties of bulk solids tend to vary throughout the process which makes it difficult to analyze the design for situations such as cohesion, wear, handling multiple commodities etc. Hence defining very general continuum models applicable for many situations is tedious [15].

In recent times, Discrete Element Method (DEM) has gained popularity and has become a widely accepted technique for addressing engineering problems related to the flow of bulk solid materials. The limitation of continuum methods to account for local variation in particle concentration and localized flow behaviour can potentially be modeled using DEM [16]. There are a vast number of researchers who have recommended and used DEM for optimizing and improving design of bulk material handling equipments [16]. The software that has been chosen to simulate the particle flow based on DEM is EDEM from DEM Solutions Ltd., UK. The particles or equipments can be modeled by importing CAD geometry. Database for modelling materials are also readily available in software like EDEM. The concept of discrete element modelling has been discussed and reviewed in many research papers. Hence it has not been discussed. Only the choice of contact model for modelling the bulk solid flow in the required scenarios is discussed.

2.4.1. Modeling wear

The standard Hertz-Mindlin in-built model in EDEM based on the works of Hertzian contact theory, Mindlin-Deresiewicz [17] [4]and Tsuji, Tanaka, & Ishida [18]has been extended to incorporate the general equation of wear developed by John F Archard [19]. The model is based on the idea that the amount of material removed from the surface will be proportional to the frictional work done by the particles moving over the surface. The equation for the model is given by:

$$Q = W_i F_n d_t \tag{3}$$

Where Q is the volume of material removed, d_t is the tangential distance moved and W is the wear constant originally given by,

$$W_i = \frac{K}{H} \tag{4}$$

Where K is the dimensionless constant and H is the hardness measure of the softest surface. The eqn (3) is rearranged to give the depth of material removed per element from the calculated volume of material removed.

$$\text{Wear depth} = Q/A \tag{5}$$

EDEM involves both the concepts of Mindlin and Deresjewicz and J.F.Archard and records the energy dissipation at the surface and the wear depth. Hence the built-in DEM models would prove to be satisfying in assessing the performance of the wear in chutes.

2.4.2. Modelling cohesive bulk solid flow

The cohesive and adhesive properties of bulk materials could be due to a variety of mechanisms such as solid bridges, liquid bridges, chemical bonding, Van der Waals forces and electrostatic forces. The extreme condition in any bulk material handling equipment for transfer is when the bulk solid has a high moisture content and higher proportion of fines [16]. During the flow of bulk solid with mixed particle sizes, the larger particles move bodily while the material shears across the fines and the yield strength of the bulk solids is dependent on the fines [20]. Hence, the flowability of bulk solids is typically governed by powders and fine materials [10].

The significant mechanisms that govern the cohesive and adhesive properties due to the presence of moisture content and fines are liquid bridges and Van der Waal's forces. Both forces are proportional to particle size [10]. Wet bulk solids exhibit greater cohesive strength and the forces which oppose the flow can exceed the forces promoting the flow [16].

The following are the contact models available [19]:

- Linear Cohesion Model
- Hertz-Mindlin Model with JKR

Linear Cohesion model modifies the basic Hertz-Mindlin contact model by adding a normal Cohesion force, given by

$$F_{coh} = kA_{coh} \tag{6}$$

where $\mathbf{A_{coh}}$ is the contact area and k is a cohesion energy density in J/m3.This force added to the traditional Hertz-Mindlin normal force. No tangential force is added in this model however the magnitude of the non-cohesive normal force is increased beyond Hertz-Mindlin model. Therefore a stronger frictional force can be withstood before slippage.

Hertz-Mindlin with JKR model accounts for the influence of Van der Waals forces within the contact zone and allows the user to model strongly adhesive systems such as dry powders or wet materials and is based on the works of Johnson, Kendall, & Roberts [21]. The contact model calculates all the forces except the normal elastic force as per the Hertz-Mindlin(no-slip) contact model. The JKR normal elastic force is calculated based on the overlap and the surface energy as follows,

$$\mathbf{F_{JKR}} = -4\sqrt{\boldsymbol{\pi\gamma}\mathbf{E}^*}\,\mathbf{a}^{\frac{3}{2}} + \frac{4\mathbf{E}^*}{3\mathbf{R}^*}\mathbf{a}^3 \tag{7}$$

and

$$\delta = \frac{a^2}{R^*} - \sqrt{\frac{4\pi\gamma a}{E^*}} \tag{8}$$

where γ is the surface energy per unit area of contact in J/m2 and a is the contact radius.

For γ=0, the JKR normal force turns into Hertz-Mindlin normal force. This model provides attractive cohesive forces even if the particles are not in physical contact. The figure below shows normal force as a function of normal overlap for different contact models in EDEM.

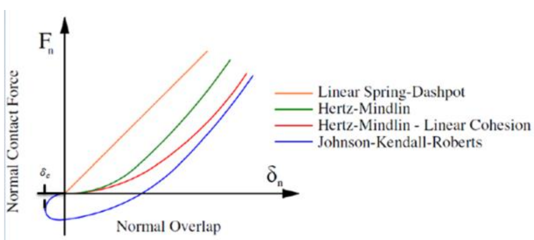


Figure 11 Normal force as a function of normal overlap

In the curve representing JKR model, negative overlap denotes the gap between two separated particles and there exists negative normal force or adhesion force for values of negative overlap till some value of positive normal overlap. Thus there are attractive forces even if the particles are not in physical contact. The maximum gap between particles with non-zero force is given by,

$$\delta_c = \sqrt{\frac{4\pi\gamma a_c}{E^*}} + \frac{a_c^2}{R^*} \tag{9}$$

For $\boldsymbol{\delta} < \boldsymbol{\delta_c}$, the model returns zero force. The maximum value of the cohesion force occurs when the particles are not in physical contact. For small normal overlaps, the total force is still negative (adhesive) and becomes positive for larger normal overlaps or contact area radii as shown in the figure above. The critical pull off force or the maximum value of cohesion force is given by,

$$F_{pulloff} = -\frac{3}{2}\pi\gamma R^* \tag{10}$$

This model could also be used to model wet particles by virtue of the force required to separate two particles under liquid surface tension $\boldsymbol{\gamma_s}$ and wetting angle θ.

$$F_{pulloff} = 2\pi\gamma_s \cos\theta\sqrt{R_i R_j} \tag{11}$$

Equating the above eqns 9,10 allows JKR surface energy parameter estimation if the EDEM particle is not scaled. It is evident from the above that the Hertz-Mindlin with JKR model helps to simulate cohesive material flow better than the linear cohesion model where there is no cohesive force at lower values of normal overlap and zero overlap.

3. Simulation and analysis for wear in current design

In DEM, to model a process, the following needs to be done: the modeling of the particle, the modeling of the geometry involved and the modeling of the particle-particle interaction and particle geometry interaction. Here the particle considered is coal. When the coal is stored, it is recommended that the particles have a maximum size of (-) 50 mm. Hence the particles are characterized based on equivalent sphere with 50 mm diameter. The properties of coal have been given in EDEM as shown in table 1 [22]. In order to replicate the particle flow on the top of the chute box and wear plate, the entire assembly from the conveyor discharge till the wear plate has been modeled. For geometry, the material of construction used in Lunen is AISI 304/SS 304. The properties given in EDEM are mentioned in the table 1 [23].

Table 1 DEM properties - Coal & steel

Particle properties in DEM		*Coal*	*Steel*
Poisson's ratio	:	0.23	0.29
Shear Modulus (GPa)	:	2	86
Density (kg/m3)	:	1357	8000

The following are the boundary conditions considered for the discharge of the belt conveyor.

Table 2 Coal discharge specifications

Coal discharge specifications		
Discharge capacity	:	1600 TPH 444.44 kg/s
Speed of discharge	:	2.6 m/s
Bulk Density	:	800 kg/m3

The interaction properties to be defined are the coefficients of restitution, static friction and rolling friction during coal-coal and coal-steel interaction. The properties considered are given below [24].

Table 3 Interaction properties - Coal, steel

Interaction properties		*Coal-coal*	*Coal-steel*
Coefficient of restitution	:	0.55	0.22
Coefficient of static friction	:	0.77	0.34
Coefficient of rolling friction	:	0.23	0.23

For interaction between coal on coal, the primary contact model of Hertz-Mindlin (with no slip) is used. For interaction between coal and the geometry, Hertz Mindlin with Archard wear is used. The wear constant for the Archard wear model has been specified only for the wear plate geometry. Wear constant is a characteristic property of the material by virtue of hardness and the application. Since this is a qualitative and comparative analysis, the wear constant specified wouldn't affect the results of this study, it is assumed to be 1.5 x 10-7. This value has been assumed taking into account the number of simulations planned and the time available. For actual case scenarios, the value of K could be determined experimentally. The simulation was performed with spherical particles of maximum particle size, 50 mm and assumed particle size distribution. The simulation results are shown below. In reality the chute box and the wear plate rotates about its axis to spread the coal inside the silo while the particle stream remains the same with respect to the axis. Hence the simulation is done for 4 positions (0, 90, 180 and 270 deg from initial position assumed) to understand the wear pattern in the chutes at different positions.

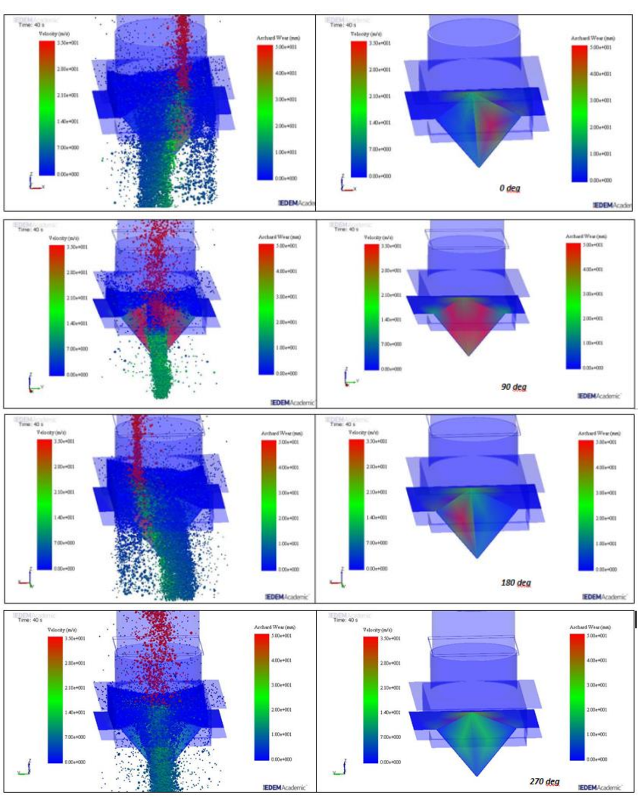


Figure 12 Simulation results with wear profiles - currentchute design

For the current design, the value of angle of slope of the plates is 53.83 deg with horizontal. The valley angle of the plates is 32 deg to the horizontal. It can be noticed that the wear pattern varies with every position of the wear plate. However, on overlap of the pictures of wear pattern in all positions, we get the following image (Fig 13) which shows the concentration of wear.

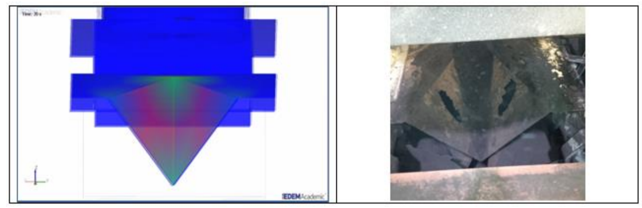


Figure 13 Wear profile from simulation & real

The parameters/ attributes that are chosen to analyze the performance of the chute design are listed below [25].

- Archard Wear (Maximum) – Key performance indicators(KPI) - This attribute provides the depth of the element removed from the surface of the geometry due to sliding/ abrasive wear and is dependent on the wear constant set for the geometry. This maximum wear depth would give an insight on how much the surface has worn off and has been chosen to be the keypoint indicator for the failure of the surface.

Apart from the above key performance indicator, the following parameters are also looked into to gain more insights.

- Velocity – the average discharge velocity would be of interest to understand the impact on the receiving equipment – screw auger.
- Normal and tangential cumulative contact energy (total): The relative wear model based on Mindlin and Deresjewicz works by the way of identifying regions of high impact (normal) and abrasive (tangential) wear on the equipment within a simulation. It is calculated based on the relative velocity and associated forces between the bulk material and the equipment. The total value of each attribute gives the amount of energy lost thereby causing impact and abrasive wear on the wear plate. From the magnitude of these values, the phenomenon which plays a dominant role in causing the wear on the surface could be identified. The total energy dissipated at the surface of the wear plate can be calculated from these values. The relation between wear volume Q and total energy dissipated is

$$Q \propto E_d \qquad (12)$$

From eqn 5,12 it can be seen that wear depth d is directly proportional to the wear volume Q.

This implies that the average wear depth should also have a linear relation with the total energy dissipated at the surface of the chute. The results of the simulation are enclosed in the Appendix 1.

4. Improved chute designs

Three different chute designs have been made as per the classic design guidelines, design considerations for the stone box chute in general and the considerations with respect to the Eurosilo application.

4.1. Chute with a central opening (CO)

In the current design the material falls partially on the flat plate and on the sliding section on the wear plate. The velocity of the particles are very high when it impacts on the plates and there is a huge wear when the chute's orientation is such that the material falls directly on the sloped plates(Figure … – 90 deg),unless it is protected by a material bed. In this design, it was decided to create material bed for impact in all positions of the chute.

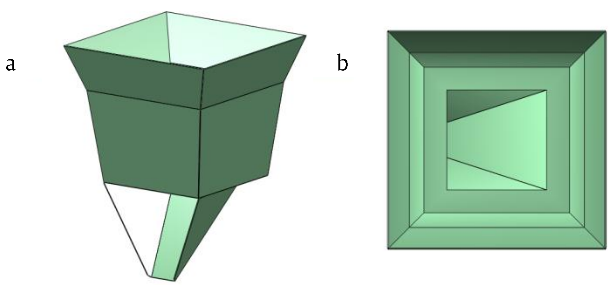


Figure 14 Chute with central opening

The majority of the particles fall between the distances of 400mm to 900 mm from the axis. Moreover the chute needs to rotate and material on material impact needs to be ensured to have low wear. After the material gets slowed down because of the rockbox, the material needs to be guided such that it flows in between the screw auger. Hence a spout like arrangement could be considered inevitable. In this form of the chute, a flat plate is provided to form a rockbox like arrangement on impact and a central opening in the form of a square to enable the flow of material down the spout like arrangement. The bottom plate of the spout is at an angle of 50 deg with the horizontal and the central opening is a square of side 820 mm.

4.2. Modified wear plate with ribs(MWP)

The design incorporates a well-known concept in the industry to reduce material on chute wall impact, ribs. The ribs on the chute surface should be placed in the direction of particle impact, so that when the material hits the chute, particles are captured in between the ribs and creates a bed of particles within a very short time. In the current design the particles form a bed on the flat region of the plates and the wear is very high due to sliding action on the plates. Hence the ribs are placed on the spout like plates. The design of the improved chute with ribs is shown in figures below.

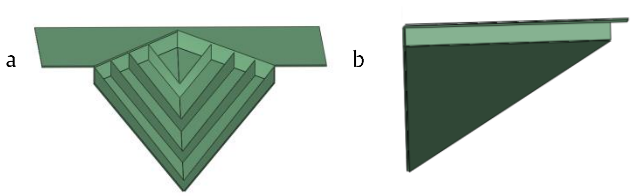


Figure 15 Modified wear plate

In the current design the angle of the plates is about 53.83 deg to the horizontal and the valley angle is about 32 deg to the horizontal. In the improved design with ribs, the angle made by the edge of the ribs would be the influencing factor since the material bed would be formed in between the ribs. The angle of edge of the ribs are 52 deg to the horizontal and the valley angle is about 32 deg with the horizontal. To obtain this angle with the horizontal, the sliding plate structure is given a depth of about 150 mm at the joint as shown in the figure below.

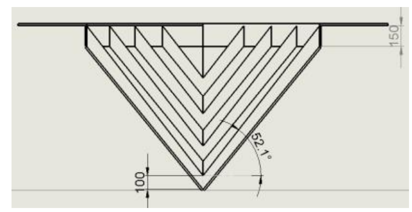


Figure 16 Modified wear plate - dimensions

4.3. Chute with multiple rock boxes(MRB)

In the current design and the improved designs stated above, the rock box concept is utilized just once to make sure that there is material on material contact. Due to the spout like arrangement to concentrate the material flow to the region between the screw augers, wear is always higher. The discharge velocity is also considerably high when compared to the speed at which the screw augers operate. Hence a concept in which there are multiple rock boxes to minimize wear due to abrasion is considered. In this type of chute, the entire slope is made up of small rock boxes. So the material slides from one rock box to another, fills up the rock boxes and reduces the chute area exposed for material impact. The height and breadth of the chute spans 2540 mm symmetrically and the width is about 2000 mm. Since the slope is 52 degrees, which is high enough to ensure flow on particle-particle contact, flowability is achievable for the conditions considered. The design of the chute with multiple rock boxes is shown in the figure below.

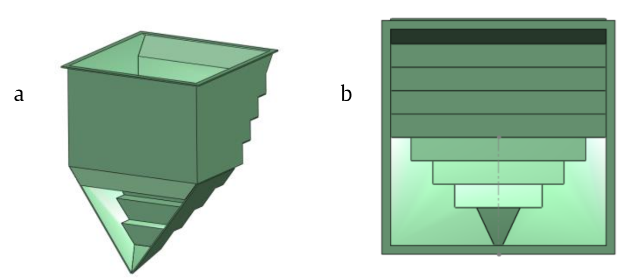


Figure 17 Chute with multiple rockboxes

The spout like structure is still incorporated to concentrate the material flow but the difference is that there is a rockbox like structure even in such a zone when the material is concentrated towards the region between the screw augers. The wall opposite to the rock boxes is provided so that the material doesnot fly out immediately after impact. These kinds of chutes are widely used in high velocity transfers and transfer points for abrasive materials. However for highly wet, cohesive materials, use of this design is criticized.

4.4. Improved chutes - Dimensional aspects

In the current design, the arrangement of the chute box and wear plate above the screw augers is shown in fig 18. The clearance prevailing in the current chute design is about 419 mm. The clearance for the proposed chute designs are also given in the figures below.

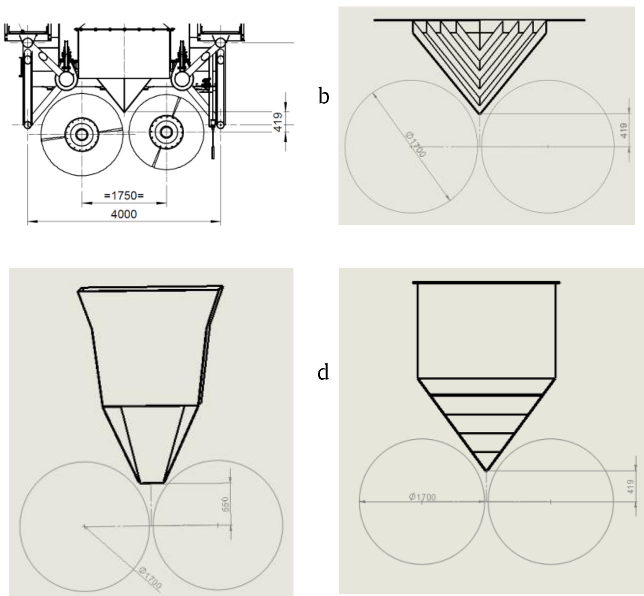


Figure 18 Clearance with screw auger a) current chute b) modified wear plate c) chute with central opening d) chute with multiple rockboxes

The clearance possible for the chute with modified wear plate, chute with central opening and the chute with multiple rockboxes are 419, 550 and 419 mm respectively. The modified wear plate is a bit deeper by 100 mm in construction when compared to the original design. This should be taken into account during the design of the chute box for the modified wear plate.

5. Simulation and analysis for wear in improved designs

The simulations are carried out in 4 different orientations of the improved chutes as done for the current design. As expected there has been considerable reduction in wear on the plates in all the chute designs since the material on material contact has been increased. The values of maximum wear depth which is considered as the key point indicator has been extracted for all chute designs at the end of all simulations. The total energy dissipated and the output velocity of the particles have also been extracted and compared with the trends from the current design.

A summary of the key point indicators are mentioned in the following sections and the comparison of trends of wear depth, total energy dissipated and the discharge velocity are provided in the Appendix 1.

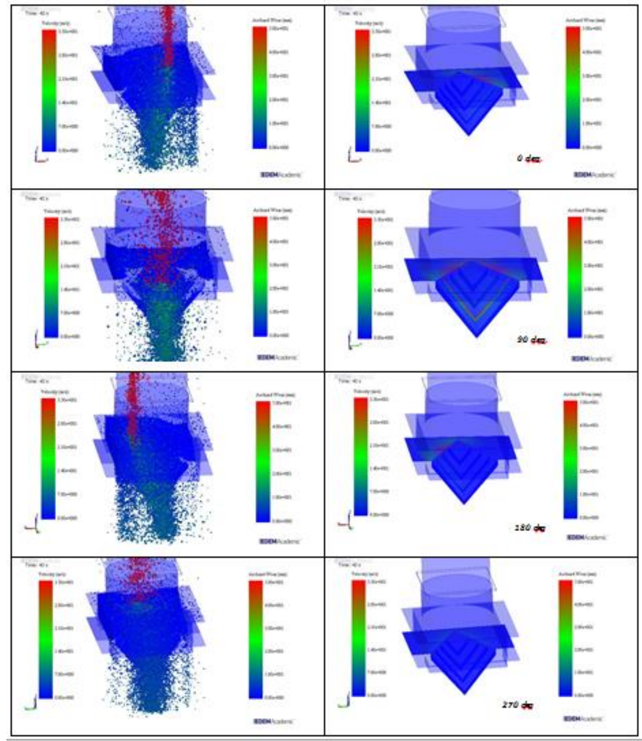


Figure 19 Wear pattern at end of each position - modified wear plate

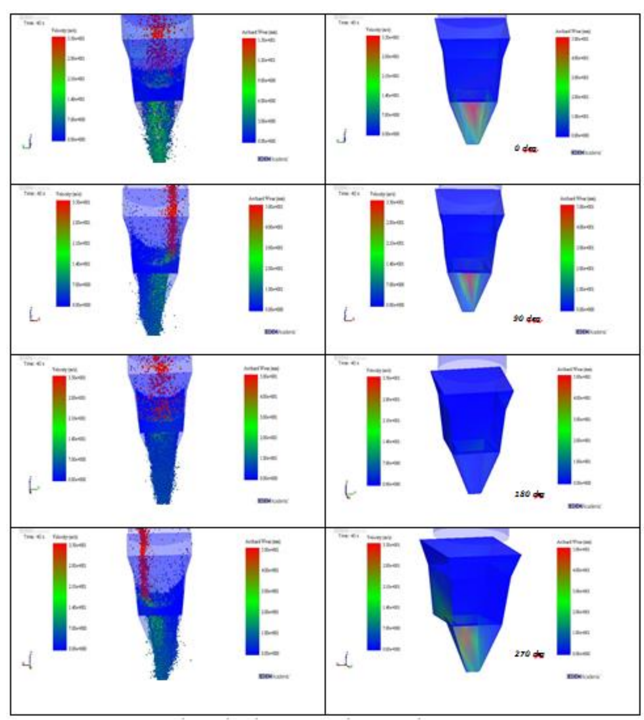


Figure 20 Wear pattern at end of each position - chute with central opening

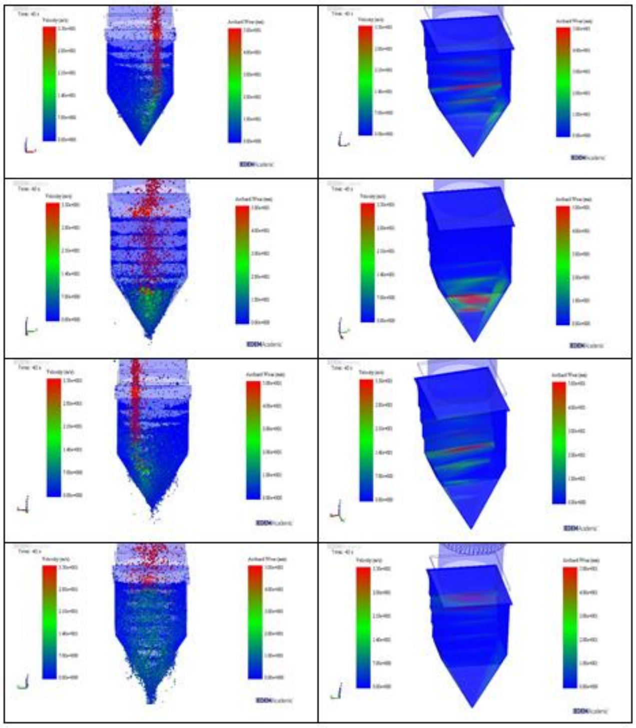


Figure 21 Wear pattern at end of each position - chute with multiple rockboxes

From the tables 4-6, it can be identified that all three chute designs provide lesser wear when compared to the current design. The modified wear plate and the chute with multiple rockboxes are better in terms of max wear depth amongst the three improved chute designs. With the chute with multiple rockboxes, the maximum wear depth is reduced by an extent of 68% at 180deg position and the lowest is at 16% for 90 deg position. In the chute with modified wear plate, the maximum extent of wear depth reduction is at 270 deg position at 87% while the lowest is at 16.8% at 90 deg position. At 90 deg position, the wear depth and the rate of change of wear is high in all chute designs.

Table 4 Comparison of max wear depth of all designs

KPI	Maximum Wear depth (mm)						
Position	Current design	Modified wear plate	% inc/ % dec	Chute with central opening	% inc/ % dec	Chute with multiple rockbox	% inc/ % dec
0 deg	193.3	94.9	50.90	131.3	32.04	90.8	53.03
90 deg	148.4	123.3	16.88	130.7	11.90	124.4	16.11
180 deg	197.3	96.6	51.01	117.4	40.47	63.1	68.03
270 deg	142.8	17.8	87.47	130.5	8.62	82.3	42.39

The total energy dissipated at the surface is considerably reduced at the modified wear plate design in all positions of discharge. This is mainly due to the formation of the particle bed between the ribs. In case of chute with central opening the total energy dissipated at the surface is not as good when compared to the results of the modified wear plate. Whereas with the chute with multiple rockboxes, the total energy dissipated is much higher than other designs. It is even higher when compared to the current design in all positions except one. However, the wear depth and the rate of change of average wear rate is lower because the energy is dissipated over a larger surface area when compared to the other positions. The amount of particle on particle impact is lesser when compared to all the designs and the energy is dissipated at the surface.

Table 5 Comparison of total energy dissipated at the surface of all designs

	Total energy dissipated at the surface (x100000 J)						
Position	Current design	Modified wear plate	% inc/ % dec	Chute with central opening	% inc/ % dec	Chute with multiple rockbox	% inc/ % dec
0 deg	6.21	2.41	61.24	6.35	-2.28	9.87	-59.00
90 deg	19.25	5.97	68.99	6.37	66.89	8.04	58.25
180 deg	6.23	2.41	61.26	4.69	24.78	9.76	-56.57
270 deg	6.67	2.13	68.08	6.38	4.33	8.18	-22.56

From table 6, it can be seen that the discharge velocities of modified wear plate and the chute with multiple rockboxes are also considerably lower when compared to the current design and the chute with central opening. The low velocities of the particles in the chute with mini rockboxes can be attributed to the total energy dissipated in the chute by the particles sliding horizontally after the first impact and dissipating low energies multiple times as they slide down the rockboxes for positions 0 and 180 deg while the velocities are considerably higher at 90deg and 270 deg positions because at 90 deg, the particles fall closer to the outlet of the chute while at 270 deg position there is more particle on particle interaction and the material rolls down easily owing to the lower rolling friction coefficient. In case of the modified wear plate, the velocities are normalized to a range of 3.5 m/s for 0, 180 and 270 deg positions due to the material on material impact while at 90 deg the velocity is a bit higher at 4.93 m/s owing to the proximity towards the outlet.

Table 6 Comparison of discharge velocity of all designs

	Discharge velocity (m/s)						
Position	Current design	Modified wear plate	% inc/ % dec	Chute with central opening	% inc/ % dec	Chute with multiple rockbox	% inc/ % dec
0 deg	4.57	3.57	21.87	5.84	-27.87	2.61	42.80
90 deg	8.40	4.93	41.24	4.37	47.91	4.33	48.49
180 deg	3.39	3.77	-11.33	3.99	-17.75	2.84	16.21
270 deg	6.63	3.53	46.73	4.24	36.00	4.19	36.88

The wear constant considered gives a very high rate of wear as an output. To calculate the actual wear depth, it is recommended that the wear constant should be found out for this particular application by means of experiments to calibrate the model. This would also help in choosing the material of the chute and optimization of the plate thickness required for the chute to perform for a desired life time. Given the current discrete element models based on elastic contact theories, it is not possible to visualize the actual rate of wear and area of wear using EDEM. The wear area as a result of the simulation, may prove to be an effective tool for analysis but doesn't portray the actual deformation on the wall material in a direction normal to the surface.

Based on the chosen KPI, the maximum wear depth, the chute with modified wear plate and the chute with multiple rockboxes are the best choices. Even though both designs provide a better solution against wear for the application under study, the performance of the chutes with respect to flowability in other scenarios inside the Eurosilo system needs to be investigated.

6. Simulation and analysis for flow

The simulations for analyzing the chute design with respect to wear were performed with the telescopic chute at an extended position since the energy of the particles would be the highest in that scenario, thereby becoming the worst case of wear. The particles were considered to be free flowing since that would be the best conditions to analyze the performance of the chute with respect to wear. However, one of the key aspects of chute design, to have a smooth material flow without blockage, should never be overlooked regardless of the nature of flow of bulk materials. In industry, these concepts ring an alarming bell to customers, since the materials that are handled with rockboxes tend to agglomerate over time and might cause flow problems. There are not many researches that could be found related to the simulation of flow of cohesive bulk solid in chutes. However an attempt is made here to evaluate the performance of the chute qualitatively based on some assumptions.

6.1. Qualitative calibration

For JKR model, the cohesive energy as denoted by the surface energy per unit area of contact is the main input. The value of cohesive energy is in J/m2 and shall be modeled to replicate the effect of Van der Waals forces and liquid bridges. The cohesive strength of a bulk solid mixture is dependent on a lot of factors like particle size distribution, moisture content, material properties and the wall material properties. Since there are no determined methods to calibrate the cohesive energy that could incorporate all these factors and could be translated to the flowability of bulk solids, a qualitative calibration method is followed. Depending on the poured angle of repose, a basic guide to determine the flowability of the material was developed by Hill [26]as given in the table below.

Table 7 Flowability based on Angle of Repose

Angle of Repose (deg)	Flowability
25-30	Very free flowing
30-38	Free flowing
38-45	Fair flowing
45-55	Cohesive
>55	Very Cohesive

Since the particle size hasn't been scaled, the above method could prove to provide a satisfactory calibration method for the particle size distribution as mentioned earlier. The cohesive energy values were input on trial and error basis until the material slope was high enough indicating that the material is cohesive. The material properties and the particle size distribution remain the same as per the simulation for evaluation for wear. The angle of repose for 25 J/m2 and 35 J/m2 was found to be greater than 60 deg which means the material is very cohesive.

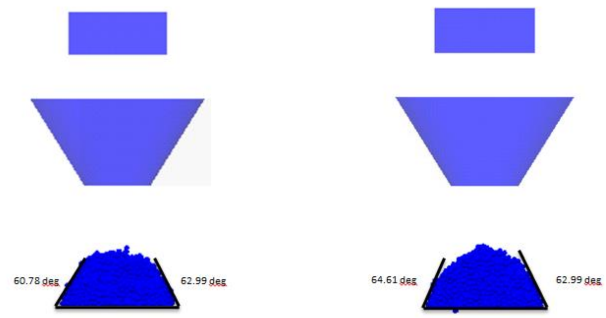


Figure 22 Poured Angle of Repose – Qualitative calibration

6.2. Simulation setup

When the particle hits the chute plate, it loses energy, thereby velocity and moves by itself or is pushed by the following particle in some random direction. If the direction in which it moves is toward a open space, where it doesn't lose much energy, the particle moves. Otherwise when the particle hits an enclosed space or loses its energy and velocity becomes zero, the material becomes stagnant. The particle bed could be formed inside an empty chute at both retracted and expanded positions. The spatial orientation of the particle stream hitting the chute is shown below in figure 23. The inner circle represents the tube diameter at retracted position and the outer circle represents the telescopic tube diameter at expanded position.

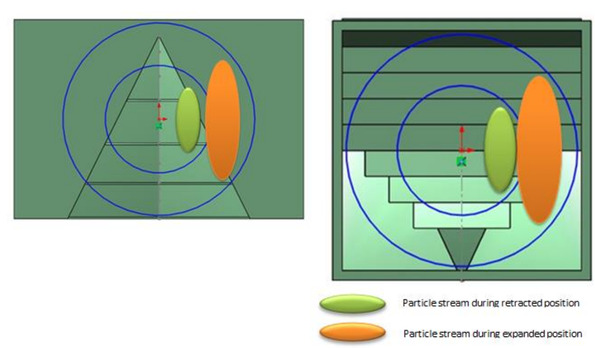


Figure 23 Particle stream concentration

The particle stream at the expanded position has higher probability to form a stable particle bed than at retracted position. Since the pressure of the particle stream is the lowest at the retracted position at 0.18 MPa and increases till the expanded position upto 0.96 MPa and the particle stream impact area at the expanded position of telescopic chute is on a wider space, it is assumed that the particle bed/ material accumulation formed at the expanded position disturbs the particle bed formed at previous positions and is stable compared to every other position. The particle bed formation has been achieved by simulating particle flow and stopping the particle flow for the at 0,90,180,270 deg at the expanded position in both chutes with modified wear plate and the chute with multiple rockboxes. The particle properties are the same as mentioned in the section 3 except that the contact model chosen is JKR with a surface energy of 25 J/m^2 between the particles and the surface energy of 10 J/m^2 between the particle and the wall of the chute. The results are shown in the figure 24

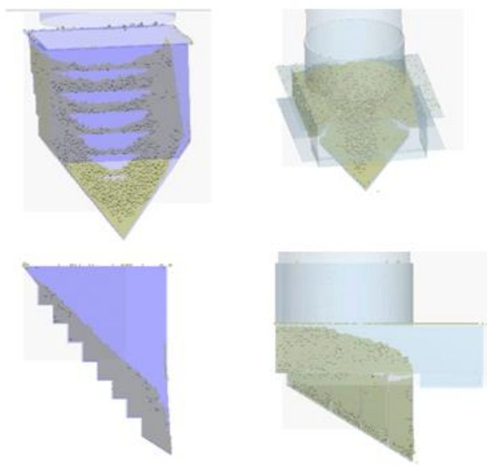


Figure 24 Particle bed formation

To simplify and prove that the material flow is ensured in both cases, i.e after formation of the particle bed (loose particles) as well as the formation of agglomerates(hard solid), the particle bed obtained as a result of simulation above is assumed to be the agglomeration formed by the fine particles over time. There are two ways possible to model the above particle bed as a solid agglomerate.

1. The particle positions could be exported along with the diameter of the particles and modeled as a single solid structure and imported to EDEM.
2. A very high value of cohesive energy density could be specified to exist amongst the particles and between the particle and the wall using JKR contact model in EDEM.

The first option requires a lot of work and the current solid modelling softwares could not model 30,000+ particles in a single file to be exported into an IGS file for using it in EDEM. Hence the second option was chosen. This would also mean that when the incoming particle stream exerts a higher force good enough to break the bond between the coal particles, the agglomerate deforms, which is desired.

The model is set up for retracted position. The length of the telescopic chute is reduced to about 10 m with a diameter of 1000 mm in the EDEM model. A new particle is defined for generation from particle factory with the same properties of coal, called Coal 1. The interaction properties of Coal 1-Coal 1 and Coal1-Coal are the same as that of the interaction properties of Coal-coal defined previously in Chapter 3. The interaction properties of Coal1-steel are the same as that of the properties of Coal-steel. The JKR bond properties specified are as below.

Table 8 JKR Bond parameter values

Bond	JKR cohesive energy value(J/m^2)
Particle-particle	
Coal- Coal	500
Coal1-Coal1	35
Coal1-Coal	25
Particle-Chute	
Coal-Chute	400
Coal1-Chute	10

The chute is also given a rotation of 2 deg/s about the central axis to understand the behaviour of particles. On simulation with the chute with multiple rockboxes, there was particle buildup and plugging due to the fact that the cross sectional area wasn't sufficient for the material to flow out due to the wall in front of the chute as shown in the figure 25a.

Hence the chute was modified without the wall and the particle build up simulations were performed once again. Again the simulations were re-run for the situation with particle agglomeration. The results of the simulation are shown in fig25b & 25c . From the simulations, it was seen that there were no broken bonds between Coal-Coal. However, there has been no chute blockage in both cases inspite of that.

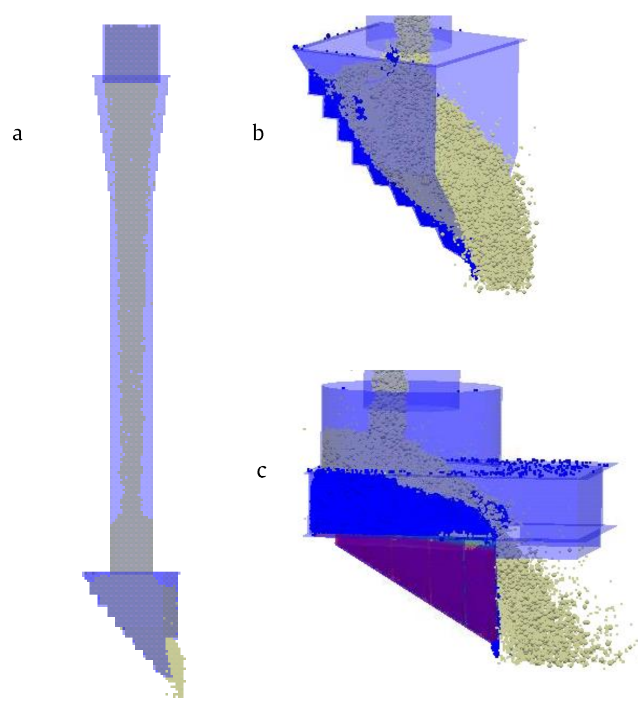


Figure 25 a) plugged chute - chute with multiple rockboxes b) flow with particle agglomeration - chute with mini rockboxes c) flow with particle agglomeration - chute with modified wear plate

It was preferred to model the particle build up as a single solid model so that the number of particles in the simulation will be lesser and Hertz Mindlin with Archard wear model could be used to find out the amount of particle would wear off the agglomeration, by providing the wear constant for coal on coal impact. However, in order to get a satisfactory result, the particle agglomeration needs to be studied and modeled with different parameters.

The simulations with JKR contact model requires a lot of simulation time owing to the number of forces to be calculated and the number of particles involved in the simulation domain. It does give an insight into the particle bed formation after material flow through each position, flow of cohesive material after particle build up. However, it is expected that due to high energy dissipated at the particle bed, the agglomeration would wear off and the worn surface would be replaced by loose particles. To achieve a better insight into the wear of the agglomerates formed, it is recommended to model the particle build up as a single solid model, with the values such as density, poisson's ratio and the shear modulus values as well as the particle interaction parameters determined based on experiments. Even though the parameters for modelling bulk material flow with JKR model and the parameters required for modelling the particle bed as a single solid model could be determined from some samples by experiments, modelling the particles as a solid bed is nearly impossible at this moment and simulations with a huge number of particles with particles of size in the range 2-50 mm still remains a challenge.

Overall, it can be seen that the particle flow is ensured even if there is an agglomeration happening as much as much as the particle build up and .for transfer of materials at a very high velocity application,chutes with rockbox concepts prove to be a best option. In Eurosilo application, where the impact pressure and the energy of the particle stream is very high, the material flow can be maintained if there is enough cross-sectional area at the point of lowest velocity of the bulk material and maintaining particle- particle contact to reduce wear. Considering the results of chapter 4 &5, chute with modified wear plate and chute with multiple rockboxes prove to be the best choices for the Eurosilo application.

7. Concluding remarks

The aim of this study was to improve the design of the wear plate/ chute in the Eurosilo. To achieve the same, the current situation has been modeled based on the available literature and considering Lunen powerplant design as reference.

Discrete Element modelling proves to be the best choice for simulation of modelling particle flow and the evaluation of the chute designs with respect to wear. To analyse the performance of chutes with respect to wear free flowing bulk solid is modeled and Hertz Mindlin with Archard wear proves to be an efficient tool. The extreme flow conditions have been identified as when the bulk material has high moisture content and higher number of fines. The influence of these two factors was modeled using Hertz-Mindlin with JKR model. It is asserted that the results of the simulation incorporating such models are useful only when they are calibrated to replicate the real bulk solid to be handled. The evaluation of chute designs with respect to wear is carried out where the particles have the highest energy, expanded telescopic chute positions whereas for evaluation of chute with respect to flow is carried out when the particles have the lowest energy, retracted telescopic chute position.

Three different chute designs – chute with modified wear plate, chute with central opening and chute with mini rockboxes were developed based on the basic chute design guideline and the limitations with respect to the Eurosilo application. Maximum wear depth is chosen as the Key point indicator for analysis of wear. On simulations, the chute with mini rock boxes and the chute with modified wear plate proved to be better designs when compared to the current design. It is found that the chute with modified wear plate(ribs) exhibits reduced wear because of the formation of material bed between ribs and material on material interaction, while in chute with multiple rockboxes, the material dissipates energy over a wider surface area rather than material on material interaction. Both these designs showed lower wear rate and significant reduction in maximum wear depth when compared to the current design and the chute with central opening.

The evaluation of the chutes with modified wear plate and multiple rockboxes was conducted for an extreme case of cohesive flow through the chutes assuming the particle build up as agglomeration. The model was calibrated by a qualitative method, based on the poured angle of repose tests. It was found that in both chute with modified wear plate and the chute with multiple rockboxes, the bulk material flow is ensured even when the agglomerated particles that were assumed to have formed, were not broken.

It is asserted that the results of the simulation incorporating such models are more accurate only when they are calibrated to replicate the real bulk solid to be handled. The wear constant considered gives a very high rate of wear as an output. To calculate the actual wear depth, it is recommended that the wear constant should be found out for this particular application by means of experiments to calibrate the model. However, based on the simulations conducted, both chute with modified wear plate and the chute with multiple rockboxes seem to be the best choice.

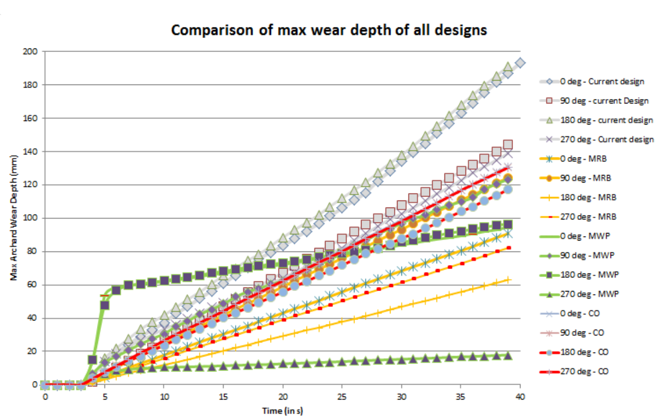
Recommendations for future work.

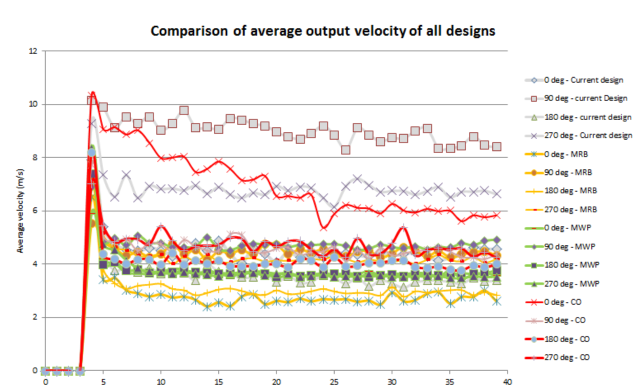
DEM proves to be a very efficient tool to simulate the bulk solid flow and evaluate the performance of the chutes for wear and flowability. However due to lack of literature, only qualitative analysis could be performed on flowability considering the time and scope of this project.

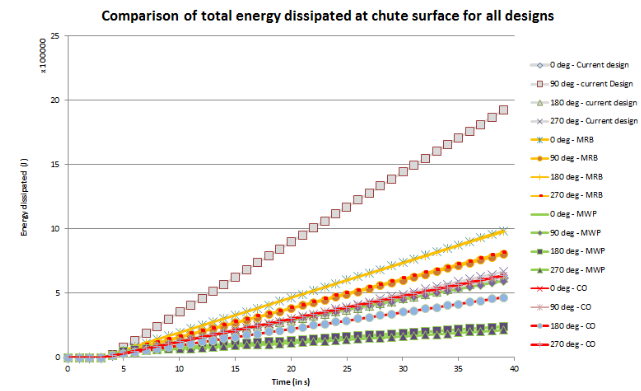
There are still a lot of challenges in modelling bulk solid flow which requires immense effort and technological advancement. However, based on the work done in this study, the following would be the recommendations for future work.

- The actual wear depth in the chutes could be found by determining the wear constant of the interaction between coal and steel.
- Given the current discrete element methods based on an elastic contact models, it is not possible to visualize the actual rate of wear and area of wear. The wear area as a result of the simulation, may prove to be an effective tool for analysis but doesn't portray the actual deformation on the wall material in the direction normal to the surface.
- A model could be developed to determine the lifetime of the chute against wear and also determine the thickness of the chute plate based on the EDEM simulations.
- The effect of fines on the material build up could be further investigated.
- Even though there are effective models to incorporate cohesion and adhesion in the bulk solid flow, there is a huge lack of research work, thereby understanding and determination, of cohesive energies influenced by liquid bridges, van der Waal's forces due to fines that prevails. More research work is needed in this field.
- The effect of particle shape and cohesion together on the chute could be studied in general and could be applied for simulations at the retracted position for an effective chute design.

Appendix A. Comparison graphs for max. wear depth, average output velocity and total energy dissipated at the chute surface







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