

Redesign of a Tata Steel transfer chute with dust liberation problems

by

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Abstract

Dust liberation in transfer chutes has been a persistent problem in the bulk handling industry, with an increasing demand for solutions due to the tightening of environmental regulations. An investigation into the root causes of dust liberation and a chute redesign with improvements in dust liberation potential has been performed in this research. The biggest challenges of this redesign being that the case study chute is a multi-material, movable chute with differing flow rates and a redirection of material by 90°. The main, root causes of dust liberation have been found to be material impact, air entrainment and compact containment of the granular flow. Measurements at the current transfer chute have been performed to investigate and quantify the problems of the case study chute. Direct measurement of dust in and around transfer chute is often circumvented to measure related issues such as material degradation and air flow measurements, since this makes localizing dust liberation sources and quantification difficult. Therefore, stopped-belt sampling has been performed to find material degradation in a case study chute at Tata Steel, given that impacts cause degradation as well as dust liberation. No conclusive evidence was found due to a lack of samples. Iron ore pellets and sinter were dynamically calibrated using an inclined surface wear tester and simulations in EDEM software were performed for 800 t/h and 1600 t/h flow rates. Three problem areas were found where impacts and bulk density increases provided indications of potential dust liberation. A redesign proposal that uses a hood and spoon concept with movable hood, where the cut-off of the movable chute head needed to be heightened to fit a spoon that can improve flow conditions, was proposed. Improvements in the identified problem areas were found in simulations of the redesign.

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Nomenclature

List of abbreviations

AoR	Angle of repose
CFD	Computational Fluid Dynamics
CI	Confidence Interval
DEM	Discrete Element Modeling
KPI	Key Performance Indicator
MFR	Mass flow rate
PDR	Personal Data Ram
PIV	Particle Tracker Velocimetry
PSD	Particle size distribution

α	Angle of discharging belt conveyor
$\bar{x}$	Average of samples
δ_n	Overlap in m
$\dot{m}$	Material mass flow rate in t/h
$\dot{v}$	Acceleration in m/s^2
ϵ	Eccentricity in degrees
μ	The sample mean
μ_E	Actual friction coefficient between chute surface and bulk solid
Φ	Angle of repose
Ψ	Self-cleaning spoon angle, angle from belt up to spoon exit angle
ρ_b	Bulk density of the material in kg/m^3
σ_0	Adhesive stress in Pa
θ	Angle of discharge in degrees
θ_c	Angle of impact point of radius of curvature
A or A_{co}	Minimum chute area in m^2
A_p	Cross-sectional area of the incoming particle stream
C_R	Coefficient of restitution
C_{dc}	Belt design capacity in t/h
d_{50}	50% of cumulative particle mass in a PSD

d_t	Tangential distance moved in m
D_{avg}	Average material particle diameter in m
E^*	Equivalent Young's Modulus
F_n	Normal force in N
F_n^d	Damping force in N
g	gravitational constant 9.81 m/s ²
H	Material height on belt in m
h	Mean height of material in m
H/B	Height to width ratio of material cross-section
k	Conversion factor
m_s	Mass flow rate in kg/s
n	Number of samples
Q_m	Material throughput in kg/s
Q_{dis}	Displaced air in m ³ /s
Q_{ind}	Volume of induced air in m ³ /s
R	Radius in m
R^*	Equivalent radius in m
R_c	Radius of curvature in m
S	Material stream speed in m/s
S_n	Normal stiffness in N
$s_{between\ samples}$	Distance between two sample locations
$t_{startup}$	Start-up time
t_a	Student t-test value
U	Non-dimensional cross-sectional area factor
v_∞	Terminal velocity
V_a	Outgoing stream velocity after impact
v_b	Belt speed in m/s
v_i	Velocity corresponding to drop height 'h' at point of impact with chute
$\vec{v}_n^{rel}$	Normal component of the relative velocity in m/s
V_p	Incoming stream velocity before impact
v_{f0}	Vertical component of velocity of bulk solid discharging from feeder
$V_{p,xn}$	Normal component to incoming stream velocity before impact at impact plate
$V_{p,x}$	x-component of incoming stream velocity before impact
W	Dimensionless wear constant
x_c	x-position of radius of curvature circle
x_i	Sample output
y_c	y-position of radius of curvature circle

1

Introduction

This first chapter will introduce the goal of this research paper, as well as an elaboration on its context and scope.

1.1. Introduction transfer chute dust liberation

In the steelmaking process raw iron ore is smelted in blast furnaces to produce liquid pig iron, which is then cast into steel slabs. The raw iron ore is first processed to create iron ore pellets and sinter before being fed into the blast furnace together with cokes that are used as burning fuel. At steelmaking plants these raw and processed materials are transported across conveyor belts from the ships that import material to pelletization and sintering factories and finally the blast furnaces. At Tata steel in IJmuiden there is a vast and complex network of belt conveyors of over 44 km in length that provides this transportation. With general belt conveyor designs being restricted to a straight trajectory, lots of transfer points are needed. To guide material from one belt to another, metal constructions called transfer chutes are employed.

1.2. Problem definition

When material is dropped from a belt conveyor onto a surface below, the free fall in combination with the resulting impact forces and air displacements causes dust particles to shoot away from the bulk material. The resulting side effects of this dust liberation have made this a major issue in the design of transfer points from its inception [1]. A schematic picture of the dust liberation phenomenon at a transfer chute is shown in Figure 1.1.

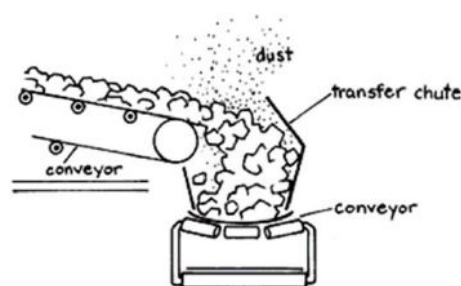


Figure 1.1: Dust liberation phenomenon at a transfer chute [2]

Dust liberation has many unwanted effects, from health concerns to equipment malfunctioning. A summary of the main negative side effects are listed below.

Environmental effects

Liberated dust originating from steelmaking plants pose a significant threat to the environment, being one of the biggest contributors to fine particles in the atmosphere. Despite significantly reducing fine particle matters ($PM_{2.5}$) from the environment since the early 90s (see Figure 1.2, left), ever stricter environmental reg-

ulations are forcing companies like Tata Steel to reduce their air pollution practices further. Environmental inspections by the government over the past seven years have fined Tata Steel for their problematic dust liberation at transfer points. Over 13 fines have been imposed for two transfer points, from belt A312 to A509 or A510, which mainly transports sinter, and from belt A330 to A652, which mainly transports iron ore pellets. A screenshot of a video made by an environmental inspector which illustrates the problem is shown on the right in Figure 1.2.

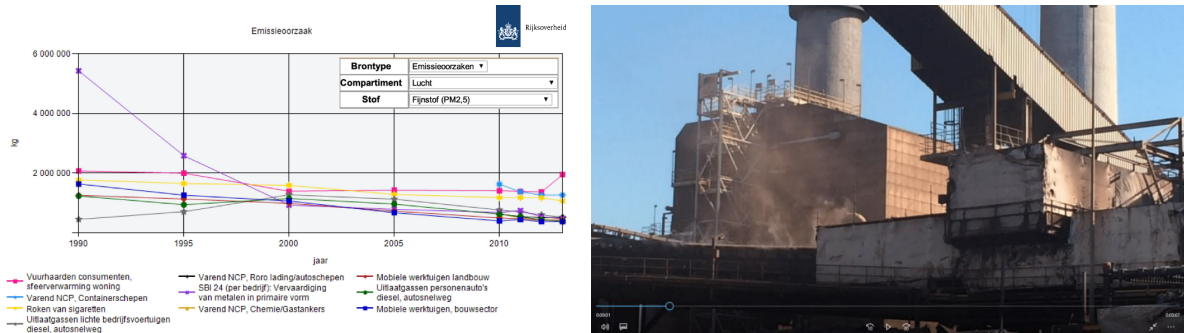


Figure 1.2: Environmental inspection video screenshot of dust liberation at Tata Steel transfer from belt A312 to the A509

Occupational hazards

Respirable dust, particles smaller than 10 microns in diameter, are not filtered out by the natural defenses of the human respiratory system and so penetrate deeply into the lungs [1]. Here they can get trapped and lead to serious health problems such as asthma, lung cancer, respiratory diseases, cardiovascular disease, premature delivery, birth defects, low birth weight, and premature death [3]. Besides the negative effects of dust inhalation, dust also settles on and around the premises. This causes a slippery and dirty work environment, which can be potentially dangerous and decreases worker morale. Dust emissions also increase the risk of a fire or explosions [4].

Production loss

Apart from environmental concerns and occupational hazards, fugitive dust can cause significant production loss with the amount of material that is spilled. Relatively small amounts of fugitive materials can accumulate to large quantities over time. A study by the Royal Institute of Technology in Sweden of fugitive materials in 40 bulk handling plants found that 0.2% of material was lost [1][5]. When taking into account not only the value of lost material, but also the cost of labor devoted to cleaning up fugitive material, the cost of parts and labor for additional maintenance arising from fugitive material and the cost of required medical checkups for personnel due to dusty environments, this value becomes even higher. An investigative report done on eight UK bulk material handling plants took these factors into account and arrived at an average loss of one percent per ton of throughput [1][4]. These factors combined makes it clear that dust control in transfer points is crucial for an efficient and environmentally friendly bulk handling process and a subject worthy of study.

1.3. Research objective and research questions

This research focuses on finding the causes for the dust formation in transfer chutes and proposing solutions to prevent or minimize this effect, taking into account the different materials that are being funneled through these chutes. The main research question that is answered through this research is

What are the causes and solution methods in minimizing dust creation and liberation at transfer chutes and how can these be applied in the redesign of a multi-material Tata Steel transfer chute with differing flow rates?

In order to answer this question, several smaller research questions are formulated that guide the investigation. These questions are

- *What is known in literature on the influencing factors on the creation and liberation of dust in transfer chutes and what are known transfer chute design considerations that provide solutions to these problems?*
- *What are suitable assessment methodologies for identifying transfer chute problems at Tata Steel that involve dust creation and liberation?*
- *What is the extend of material degradation at a Tata Steel transfer chute?*
- *How to calibrate bulk materials for dynamic simulations like transfer chutes?*
- *Where along the material stream in a transfer chute at Tata Steel is potential dust creation and liberation and what is the influence of different materials and mass flow rates in DEM software on this problem?*
- *What does a redesign for a Tata Steel transfer chute to minimize dust creation and liberation look like and what can be the quantifiable improvements to the original design?*

1.4. Report structure

This report consists of eight chapters, each answering one of the research questions listed above. This leads to the answer of the main research question, which will finally be answered in summary in Chapter 8 - Conclusions and recommendations. Chapter 2 will be a literature study on the known theory behind the design of chutes, the known causes of dust creation and liberation and the response of designers and the industry into the handling of these problems at transfer chutes. In the next chapter, Chapter 3, the literature on the methodologies for identifying and possibly quantifying dust liberation is gathered. Methodologies for transfer chute design that can aid in the minimization of dust liberation is also discussed. In this chapter, based on the literature found, methodology choices for the further investigation of transfer chute problems at Tata Steel are made. These choices involve the selection of a case study transfer chute at Tata Steel and experimental sampling of material at this chute to investigate material properties that are possibly affected by it. Also a choice is made for a numerical methodology to study the granular flow through the case study transfer chute and use this to later test redesign concepts. Chapter 4 will expand on the methodology of experimental sampling of material at a case study transfer chute at Tata Steel. The results and conclusions drawn from this methodology can also be found in this chapter. In Chapter 5, the calibration of a material model for two materials that are transported by the case study chute, sinter and iron ore pellets, for the usage in a simulation software to study the granular flow is performed. The focus of the calibration lies in the dynamic behavior of the material. With these material models, a simulation is setup to investigate the granular flow through the case study transfer chute in Chapter 6. The causes for dust liberation at this chute are identified based on the knowledge gained through literature from Chapter 2. The knowledge on transfer chute design from this chapter is used to calculate the characteristics of a redesign concept in Chapter 7. Two concepts are made, one where the current dimensional constraints of the case study transfer chute are used and one where a conceptual design of an ideal case is made for minimization of dust liberation. These concepts are simulated and the potential relative improvement in granular flow is studied. The final chapter, Chapter 8, will summarize the conclusions that are drawn from this research and provide recommendations for further research or implementation of a new design.

2

Literature study chute design and dust control

This chapter the literature that is available on transfer chute design is examined, focusing in particular on the minimization of dust liberation. The research question that will be answered in this chapter is

- ***What is known in literature on the influencing factors on the creation and liberation of dust in transfer chutes and what are known transfer chute design considerations that provide solutions to these problems?***

After a brief section on the definition and research scope of transfer chutes, the design objectives for transfer chutes design are listed and discussed in Section 2.2, along with some "rules of thumb" to meet these objectives. Section 2.3 will commence the investigation into dust liberation by expanding on the theory behind the dust liberation phenomenon. Section 2.4 will explain how this theory is used to try and minimize dust liberation at transfer chutes. Then in Section 2.5 chute configurations that deal with the design objectives in differing ways are laid out, discussing their advantages and disadvantages and areas of application. In Section 2.6 the more detailed, analytical models that govern chute design for a so called hood and spoon design (which is particularly useful for dust liberation minimization) are explained after which the research question for this chapter is answered in Section 2.7.

2.1. Transfer chute definition

According to *BS2890 - Specification for Throughed Belt Conveyors* by the British Standards Institution the definition for a transfer chute is "A straight, curved or spiral, open topped or enclosed, smooth through, by which materials are directed and lowered by gravity." [6][7]. This means that when bulk material that is being transferred from one bulk handling equipment to another, a transfer chute will help guide the direction of the material. A distinction can be made between feed chutes, which are build to accelerate materials, and transfer chutes, which are used in the transfer of bulk material from a belt, bin or hopper [7][8]. Belt to belt transfers are the most common, which usually involves a change in flow direction [9], as exemplified by the illustration in Figure 2.1. Belt to belt transfer chutes will be the main focus of this research.

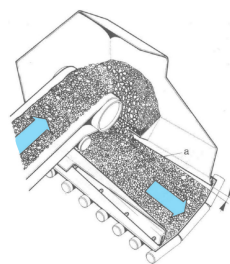


Figure 2.1: Illustration of a belt to belt transfer chute involving a 90° change in material flow direction [8]

2.2. Chute design objectives

Conventional transfer chute design is normally done by an experienced designer or bulk materials handling engineer using industry-accepted "rules of thumb" [1]. Many engineering firms establish their own design rules and with a large application variability, different industries have developed consistent approaches to chute design that solves issues particular to their applications. Still there exist general guidelines to properly designing conventional transfer chutes.

A conventional transfer chute generally can be separated into four basic parts, which are listed below [1] and depicted in Figure 2.2.

- **Head chute** The area surrounding the head pulley of the feeding conveyor
- **Drop chute** The area where the material is guided in its free fall
- **Loading chute** The area where the material is guided onto the receiving belt conveyor below
- **Settling zone** An extension area of the chutework to settle airborne dust, not technically part of the transfer chute

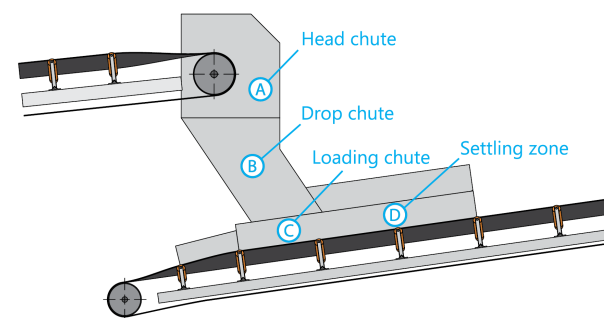


Figure 2.2: Schematic of conventional transfer chute consisting of four basic parts (edited from [1])

Each of these parts have to be designed to fit the design parameters given by the developer such as the geometric parameters of the belt conveyors or the flow capacity. Besides the adherence to these basic requirements, there are several main objectives in transfer chute design that need to be taken into account. These design objectives are [1][7][8]:

- **No blockage** of the material flow in the chute, while facilitating the required capacity
- **No spillage**, prevent the escape of fugitive materials
- **Minimize wear**, on all components (belt, chute, material) to provide the optimal value life cycle solution
- **Minimize degradation** of the transported material and the generation of dust
- **Return belt scrapings** to the main material flow
- **Minimize segregation** of the bulk material
- **Be service friendly** and protect personnel from injury
- **Proper loading of material onto receiving conveyor**, such that
 - the difference in velocity of the conveyor and the velocity component of the material in the direction of the conveyor is as close as possible (at least within 10%)
 - the velocity component of the material perpendicular to the receiving belt is as close to zero as possible
 - the flow is loaded in the center of the receiving belt to prevent the belt from misaligning and to avoid spillage

2.2.1. Blockage

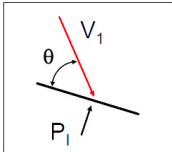
One of the biggest design aspects in the design of a transfer chute is the prevention of blockage. If material will not flow reliably through the chute, then meeting any or all other objectives is irrelevant. Bulk materials should maintain an even and consistent flow when travelling through the chute. Surge loadings can cause several problems such as belt tracking sliding off-center, over-stressing of conveyor system components (particularly the drive motor[10]) and of course chute blockage. The body of the chute should have an area that is at least 2.5 to 3 times the area of the material in order to prevent blockage from a chute that is too narrow [11]. The minimum area of the chute is given by the equation in Figure 2.3.

$$A = \frac{2.5 \cdot C_{dc}}{3600 \cdot S \cdot D}$$

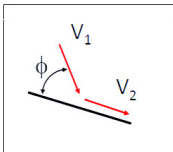
A = Minimum chute area [m²]
 S = Material stream speed [m/s]
 D = Bulk density of the material [t/m³]
 C_{dc} = Belt design capacity [t/h]

Figure 2.3: Equations for calculating the minimum area a chute should have to prevent blockage[11]

In order to prevent blockage close attention should be paid to the particle and bulk properties of the transported material and the nature and characteristics of the application [8]. The sliding surface inside the chute must be sufficiently smooth to allow the material to slide and to clean off the most frictional bulk solid that it handles. The steepness of the impact between the bulk material and the chute is also a factor. If the impact angle is not steep enough, sticky material will stay attached to the chute surface and cause plugging of the chute. The relationship between these variables is shown in Figure 2.4. When V_2 is significantly low to impede the flow of material, plugging will occur and when it is zero, the material will stick to the surface.

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


γ = Bulk density
 V_1 = Impact velocity
 θ = Impact angle
 P_1 = Impact pressure
 g = Acceleration (gravity)

$$\frac{V_2}{V_1} = \cos \theta - \sin \theta \tan \phi'$$


V_2 = Velocity along chute after impact
 V_1 = Impact velocity
 θ = Impact angle
 ϕ' = Wall friction angle

Figure 2.4: Equations for calculating Impact pressure and particle velocity along chute after impact[11]

2.2.2. Spillage

Similarly to preventing blockage, spillage is countered by focusing on a reliable and consistent flow through the chute. The objective of avoiding spillage is linked to many of the other before-mentioned design objectives. If the chute blocks, or a hole is created in the chute material due to wear, material will spill. Some of these problems are depicted together in Figure 2.5. Many of the causes of spillage are related to the proper loading of the receiving belt. Off-center loading, which is placing the cargo predominantly on one side of the belt (as can be seen in Figure 2.5), is a problem at many transfer points that contributes to generation of fugitive materials [1]. This problem is most prevalent in transfer chutes with a change in flow direction. The displacement of the material causes belt tracking problems where the belt can suffer edge wear damage and may result in material spilling over the belt edge, both shown in Figure 2.5. Since training idlers are limited in their ability to counter the effects of off-center loading, it is imperative to design the chute to properly align the material onto the receiving conveyor belt. Besides loading the material in the center of the receiving belt, it is also desirable to keep the velocity component of the material perpendicular to the belt as close to zero as possible.

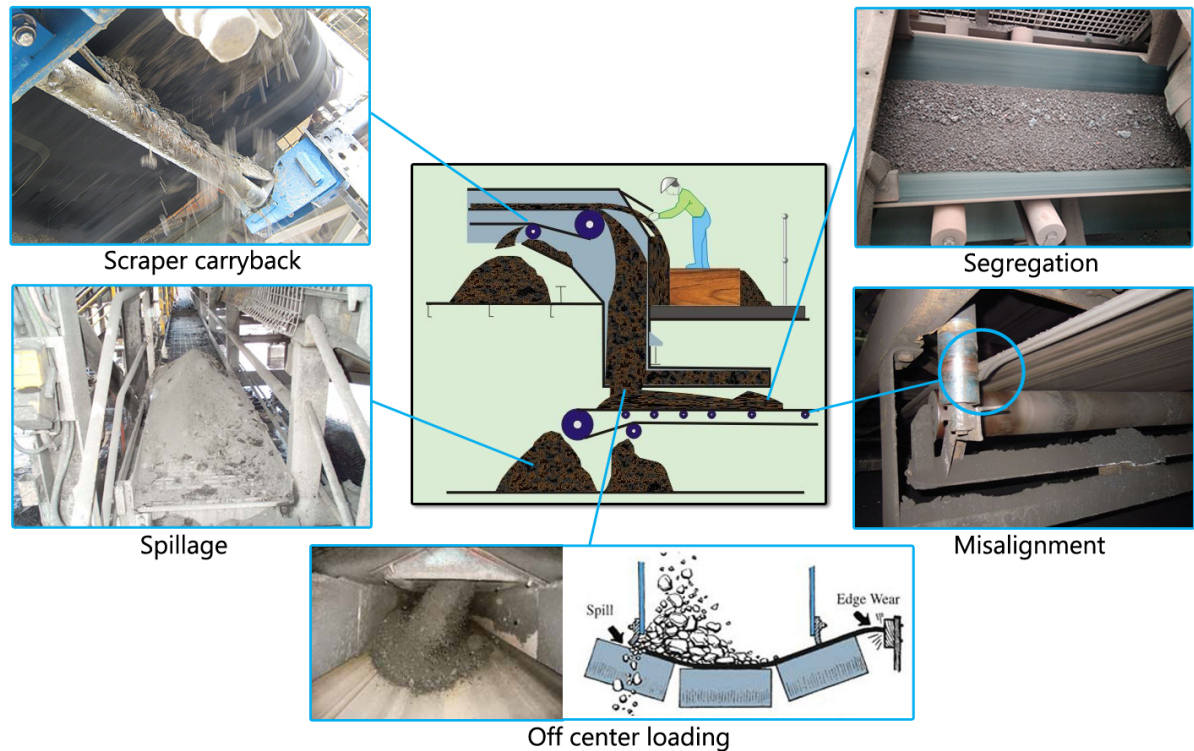


Figure 2.5: Overview of common problem when chute design objectives are not met (edited from [10][11])

2.2.3. Wear

The abrasive nature of particulate bulk solids such as iron ore, large scale handling commonly causes high wear on chute surfaces [12][13]. Wear causes volume loss on the surfaces that are in abrasive or high impact contact with bulk solids and consequently accelerate damage to these areas. Wear introduces lots of economic costs such as maintenance related costs (replacement parts, productivity loss due to downtime, maintenance personnel), spillage or development and procurement of abrasive resistant materials. Wear can be divided in abrasive wear and impact wear. Abrasive wear is caused by relatively sliding and rolling of particles against equipment surfaces, whereas impact wear is interpreted as a process of material removal from equipment surfaces by succeeding particle impacts [12]. Impact wear in transfer chutes may occur at points of entry or at points of sudden changes in direction. For ductile materials the greatest wear occurs when impingement angles are low, which is around 15° to 30° . For hard, brittle materials like iron ore the greatest impact damage occurs at steep impingement angles of the order of 90° [13]. To combat excessive wear, wear-resistant materials can be applied to wearing surfaces. A more significant contribution to wear reduction is made by controlling the flow of material with the optimization of chute profiles. This is done based on analytical predictions of material trajectories and chute surface wear rates. The theory behind this optimization is elaborated on in Section 2.5.2. Even the introduction of bionic designs on chute surfaces are being investigated and show promising results [12]. While wear on chute surfaces are most significant, wear on receiving conveyor belts can also be problematic. In order to minimize impact wear on conveyor belts, loading material directly onto belts from a certain height is avoided. Abrasive wear on belts is countered by attempting to match the material stream velocity and direction to that of the belt at the loading point. The calculations that accompany this theory is presented in Section 2.5.2.

2.2.4. Material degradation and dust generation

The impact force (see Figure 2.4) that is exerted when the material comes into contact with the chute not only affects the chute itself, but also the transported material. This can lead to the degradation of the material, which will generate dust particles in the stream that can get released as fugitive dust, among other problems such as inefficient further use of the material. There are different types of material degradation that can occur. The types of breakage that exist in the handling of bulk materials is illustrated and explained in Figure 2.6. A detailed analysis of the causes of material degradation and the resulting dust generation is performed in Section 2.3.

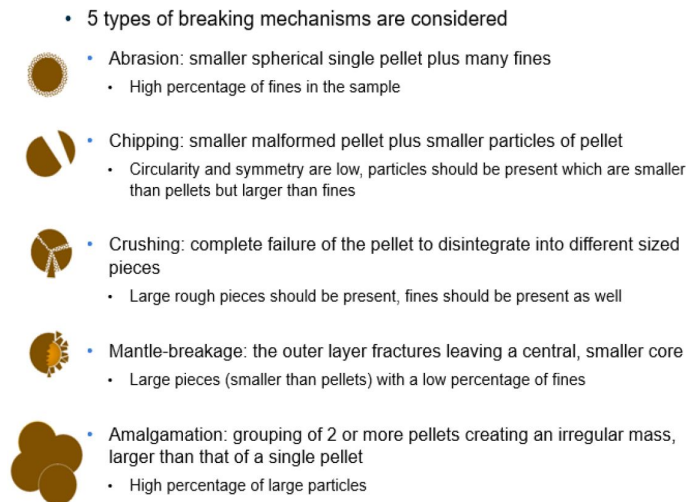


Figure 2.6: Breaking mechanisms in bulk material [14]

2.2.5. Belt scrapings

When conveying sticky bulk material, adhesion to the belt can occur when it is being dropped from the belt at the head pulley. At this discharge pulley belt cleaners are installed to remove residual material that has adhered to the belt beyond the discharge point. The material that gets scraped off these cleaners, called carryback, has a risk of build-up and eventual spillage if it is not returned to the main material flow properly, as depicted in Figure 2.5. The chute is usually extended underneath to catch this carryback. To ensure this already highly adhesive carryback returns to the main flow, the angle the chute makes to the ground has to be very steep. This angle, called the valley angle, has to be at least 70° [10]. In many cases additional remedies are required such as over-sizing the chute, low-friction chute liners and auxiliary devices like vibrating dribble chutes, air cannons and scavenger conveyors.

2.2.6. Serviceability

As noted before the enclosure of the chute is vital in minimizing spillage and dust liberation, as depicted in Figure 2.5. It is also imperative that the transfer chute is easily accessible for personnel to accommodate efficient maintenance. Inspection doors should be placed away from material trajectories to prevent spillage. With chute wear damage happening in predictable areas, the chute needs to be designed to easily access these areas and make them easily replaceable. Many suppliers provide service-friendly arrangements of their components to have these features cancelled out by the design of the structure or by the placement of utility piping and conduits or other components [1].

2.3. Dust liberation theory

2.3.1. Dust definition

To understand dust liberation theory, first a definition of dust needs to be determined. Definitions of dust and the size range of dust can vary depending on the field of study. According to the International Standardization Organization (ISO 4225 - ISO, 1994) dust is defined as "*Small, solid particles, conventionally taken as those particles below 75 μm in diameter, which settle out under their own weight but which may remain suspended for some time*"[3]. A definition of dust by the 'Glossary of Atmospheric Chemistry Terms' is given as "*small, dry, solid particles in the size range from about 1 to 100 μm in diameter, projected into the air by natural forces and by mechanical or man-made processes*"[3][15]. The 'Handbook of Chemistry and Physics' distinguishes three categories of dust, shown in Figure 2.7 [2][15].

Particle Size (μm)	0.01	0.1	1	10	100	1000
Types of Dust	Suspended Atmospheric Dust		Settling Atmospheric Dust		Heavy Industrial Dust	
Particulate Contaminants	Soot		Tobacco Smoke	Smoke	Cement Dust Fly Ash	
Visibility	Electron Microscope		Microscope		Naked Eye	

Figure 2.7: Table of dust categorizations and characteristics

Most handbooks dealing with ventilation and dust control for human health studies focus on particles ranging from 0.1 to 100 μm [3][16], while research papers that analyze dust tend to model dust particles that are 0.1 mm in diameter [2][17][18]. This is mainly since the smaller the diameter, the deeper particles can penetrate into the lungs and cause health problems, while in performing dust simulations, a minuscule particle diameter is difficult to work with.

2.3.2. Dust liberation principles

Dust control = air control

Dust liberation is when dust gets separated from the bulk material stream and released or expelled into the air. Since dust particles are light enough to travel through the air, there is great benefit in understanding the air flows in and around transfer chutes. According to [1], there exists a generalized, intuitive relationship for dust liberation, namely

$$\text{Dust liberation} \propto \frac{\text{Air velocity}}{\text{Particle Size} \times \text{Cohesiveness}} \quad (2.1)$$

If air velocity is increased, but particle size and cohesiveness remain constant, then airborne dust will increase. If velocity remains constant, but particle size or cohesiveness is decreased, then the amount of airborne dust will increase. It is therefore important to not only control the air, but also prevent material degradation (which decreases particle size), in order to minimize dust liberation.

Dust liberation regions

According to [19], three regions in a transfer chute can be indentified as sensitive for dust liberation, as illustrated in Figure 2.8 [4].

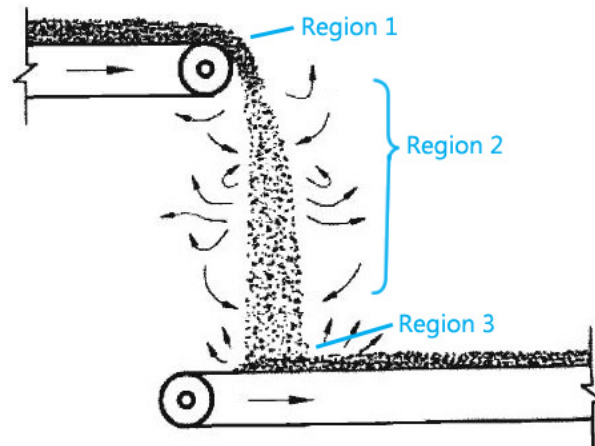


Figure 2.8: Graphical representation of dust liberation regions with belt to belt material transfer (edited from [4])

- *Region 1 – Material discharge*
The point of material discharge from the belt head pulley, emissions are driven by turbulence and delayed detachment of particles from the belt
- *Region 2 – Free fall*
Region where the material is in free fall, which is when dust particles get separated through a phenomenon called air entrainment [4][20]
- *Region 3 – Impact*
The point where the material suffers an impact after being in free fall, which is noted to be the biggest contributor to dust formation and emission [19]. The point and angle of impact and the number of impacts that the material endures in a transfer point are dependent on the chute design configurations.

Air displacement

When material is transported it pushes the air that is in its path. Bulk material entering a transfer chute will displace the air that is inside and this air will be pushed out. The displaced air can be roughly calculated using the following equation

$$Q_{dis} = \frac{k \times \dot{m}}{\rho_b} \quad (2.2)$$

where Q_{dis} is the displaced air in m^3/s , k is a conversion factor of 0.277, $\dot{m}$ is the material mass flow rate in t/h and ρ_b is the bulk density in kg/m^3 .

The movement of air inside and out of the transfer is related to the volumetric size of the transfer chute enclosure and the openings in the enclosure. A slightly negative pressure is desirable inside the chute, so that air is 'sucked' into the enclosure and keeps fines and airborne particles from liberation. Unfortunately when material enters the enclosure it pushes into the air already inside and brings in extra air through its movement, which inevitably creates an unwanted positive air pressure inside the enclosure. If this positive pressure is not addressed, dust liberation will occur. The positive pressure can be altered with proper control of material flow, adequate pressure relief or dust collection systems.

Air entrainment

Bulk materials that are on the move have a certain amount of entrapped air and carry a small amount of air with them as they travel on the conveyor belt. When the material gets dropped from the discharging conveyor pulley, the material stream expands. This creates new and expanding voids in between the particles that gets 'induced' inside the stream. This induced air can be roughly calculated by

$$Q_{ind} = k \times A_{co} \times \sqrt[3]{\frac{\dot{m}h^2}{D_{avg}}} \quad (2.3)$$

where Q_{ind} is the volume of induced air in m^3/s , k is a conversion factor of 0.078, A_{co} is the area of head chute opening in m^2 , $\dot{m}$ is the material mass flow rate in t/h , h is the height of material free fall and D_{avg} is the average material particle diameter in m .

A boundary layer of dust forms around this core stream with expanding radius as the drop height increases [4]. Smaller particles have a lower fall speed than larger particles, which means they have a higher chance of floating off to the sides of the core stream of material [16]. The study of air entrainment is very complex, since it involves the analysis of the aerodynamic properties of particles, which are extremely variable. The irregular size of particles and the presence of surrounding particles gives each particle a different air flow pattern and drag force, not to mention particle collisions in free fall. Air entrainment by free falling bulk materials can be influenced by material properties, such as particle size distribution and particle density. It can also be affected by process parameters, such as drop height and bulk material mass flow rates [4].

Impact

As explained in the previous paragraph, air gets entrained inside the particle stream when it is in free fall. When the material lands and compresses back into a pile, the entrained air is released in every direction, as illustrated with arrows at the bottom belt in Figure 2.8. This released air at material point of impact causes a pressure buildup [10][16].

Another phenomenon that occurs surrounding impact is material degradation. When particles are in free fall the gravitational force causes them to gain kinetic energy. This energy is dissipated when the material impacts the bottom belt or the chute wall. The energy dissipation happens through particle degradation (see also Section 2.2.4). Since the impact of material on a chute surface or belt both creates dust as well as liberates it, material impact should be avoided as much as possible in transfer chutes to minimize dust liberation [4][16][21][22].

2.4. Dust liberation minimization

Based on the knowledge gathered from the physical theories underlying dust liberation, basic design principles can be distilled to control dust. All the measures that are taken in this area revolve around:

- Minimize dust creation at transfer
- Minimize spreading of dust at transfer

The first of which means to prevent material degradation, while the second revolves around the control of air flow in and around the transfer chute.

The design objectives that align with these ideas are summarized below.

Minimize drop height and impact force

In order to minimize both the creation and liberation of dust, minimizing the drop height and impact force is vital. The first remedy that could come to mind is to place the discharging and receiving conveyors as close together as possible. Once a conveyor is installed this is an incredibly complicated process to implement, but in the early design stages this can be relatively easy [1]. Risk of blockage, spillage and difficulties with air control using a smaller enclosure should be taken into account. Also the incorporation of a hood and spoon design can become impossible if the height difference between conveyors is too low. The added benefit of a hood and spoon chute is far greater than a reduction in drop height without proper flow control, so in this case it is not recommended.

Drop height reduction means limit the free fall of the particle stream. Therefore a hood and spoon chute design can be a solid solution since this will keep the material in contact with the chute walls. When designed properly, it can also keep the material flow speed more constant which will further improve the limiting of impact forces.

When a hood and spoon design is not in place, impact forces can be reduced by lowering the belt speeds. When material is being launched at an impact plate and suffers an impact force, this force can be lowered by reducing the speed of the particle stream.

Minimize material stream spreading As explained earlier air displacement inside transfer chute is when material acts on the air it is traveling through, carrying some of the air along with it. The larger the material stream, the more air gets swooped along and cause dust liberation problems. It is therefore recommended to keep the materials in a consolidated stream as they leave the head pulley and move through the chute. Deflectors can be used to do this, but they can cause flow problems and increase the number of impact

forces. Hood and spoon designs can be a more likely solution to this problem. They can also be shaped to converge the flow as the velocity increases in order to keep the flow compact, as shown in Figure 2.9

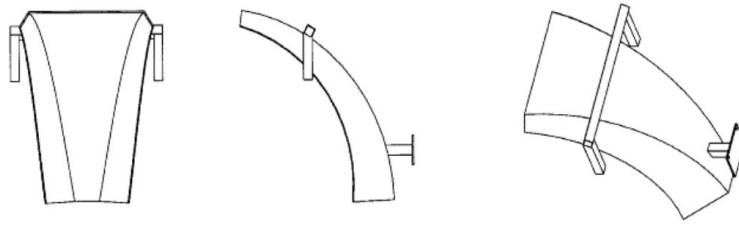


Figure 2.9: Illustration of a converging hood design [8]

Another method of keeping the material stream compact is increasing the cohesion of the material. This can be done by installing water hoses along the belts to spray the material on the material. This can however provide problems in the eventual use of the material or difficult to implement if the material is heated in some cases and the water quickly vaporizes. The added cost of the water spray installation and water usage make this solution not favourable.

Minimize air entering enclosure

One of the most inexpensive solutions to dust liberation that do not require sophisticated models and computations is to minimize the inlet of air into the chute enclosure. This will reduce the amount of induced air inside the chute, as can be derived from A_{co} in equation 2.3. Conventional rubber curtains can be installed at the entrance and exit of the chute enclosure (Figure 2.10, left), skirtboards can be installed along the receiving conveyor (Figure 2.10, right) and inspection doors should remain closed during normal operations.



Figure 2.10: Rubber chute entrance curtains (left) and skirtboards (right) [1]

Minimize air speed inside chute

When the air speed inside the enclosure is kept low, the likelihood of dust particles getting picked up and carried outside the chute is lowered. The easiest method to achieve a lower air speed inside the chute is lowering the belt speed. When this is not an option, the enclosure can be extended along the receiving conveyor to permit a significant reduction in the speed of air currents and, therefore, allow airborne particles to settle back into the load before the conveyor leaves the enclosure. An extension of the enclosure along the receiving belt can be made called the settling zone or 'calming tunnel' [23] for this purpose (see Figure 2.2). A larger enclosure also means the relative volume of air displacement caused by the incoming material is lowered, which reduces the positive pressure that can carry airborne particles out of the enclosure.

Water curtains and air filtration systems Other methods that have been applied in the industry are the implementation of a 'water curtain' inside the chute. This is a spray of water along the material stream that catches dust particles inside the water stream in order to minimize dust liberation. The water is then either returned onto the material stream or channeled to a filtration system.

Chutes can also be fitted with a complete air filtration system that controls the air flow inside the chute enclosure by extracting air from the chute and filtering it. Considering the air flow moves in the same direc-

tion as the material stream, the most efficient location for the air extraction is at the end of the enclosure, see Figure 2.11. After the dust is filtered from the device it is taken away from the material stream or is re-entered.

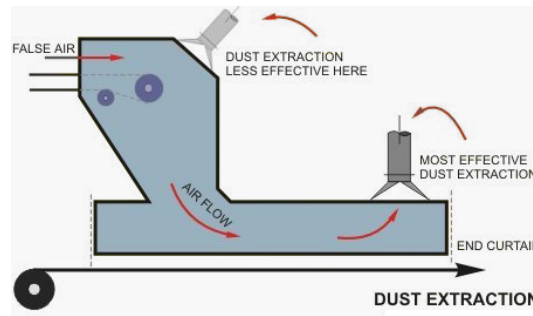


Figure 2.11: Air filtration system to extract dust particles [10]

2.5. Chute configurations

As stated before, a wide variety of material properties, system layouts and other specific requirements results in many different transfer chute designs. However, since the design objectives that have been laid out are always the same, some general design configurations for transfer chutes can be distinguished [7]. The most common chute designs are dead box chutes and hood and spoon chutes or approximations of these designs. A variation on the hood and spoon concept taken into account different materials is also examined.

2.5.1. Dead box chutes

A dead box chute has a slanted surface inside the drop chute where a pile of the transferred material accumulates, as illustrated in Figure 2.12. A small bar called a wear bar is placed on the ledge of this surface to encourage the accumulation of material, indicated in yellow in Figure 2.12. Subsequent material moving through the chute flows over the material bed that is formed on the slanted surface. By shifting the abrasive forces caused by the transferred material away from the chute material and onto the accumulated bed of material, wear on chute materials is significantly reduced [1].

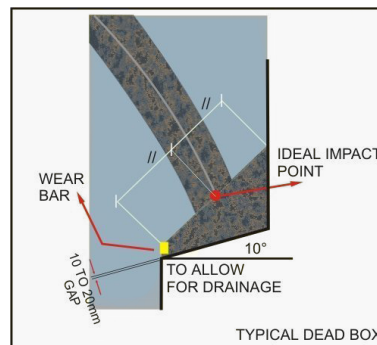


Figure 2.12: Cross section illustration of a typical dead box chute design [10]

The dead box configuration is applied in handling relatively dry bulk material, since sticky material could provide blockage problems [7][10]. Similarly, care must be taken to accurately judge more cohesive characteristics of the material, for example under wet conditions. Fragile bulk materials are not suitable to be guided through dead box chutes, since they might suffer material degradation. Dead boxes are also avoided when the conveyors carry more than one material, or when the bulk material may contain large enough lumps to potentially block the material flow. Dead boxes may be designed for belts of relatively high speed (belt speeds in excess of about 2.0 m/s) that carry washed and sized material of lump size greater than 30 mm [11]. The design should be self-draining, meaning that the slanted surface should be inclined at a minimum angle (10° , as depicted in Figure 2.12). A small gap is left between the wear bar and the dead box surface that allows the passage of water underneath when cleaned. In situations where a high drop of material is needed, configurations with several dead boxes stacked on each other can be implemented. This can be used to reduce impact and control material velocity over drops of greater distance. This configuration is called a cascading chute.

2.5.2. Hood and spoon chutes

A hood and spoon chute is a design configuration where a curved hood catches the material as it comes off the top belt conveyor and guides the material path downwards in a more controlled manner than free fall (see Figure 2.13). The spoon is a similarly curved surface that catches the material that slides down off the hood and guides the material onto the bottom belt.

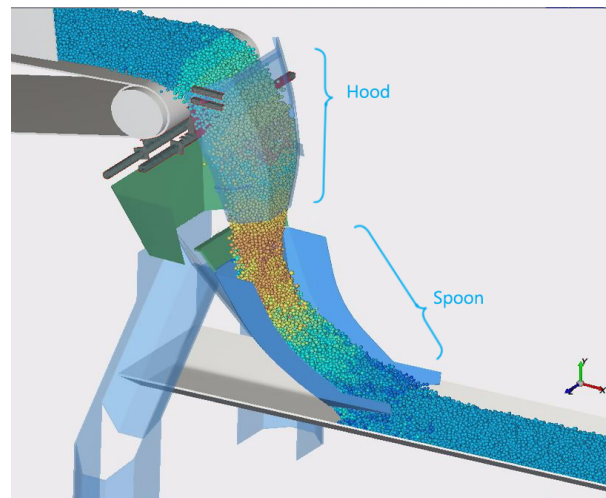


Figure 2.13: Software simulation screenshot of a hood and spoon design, edited from [24]

The goal of this design is to keep the material stream as close as possible to continuous flow, which has many advantages like reductions in belt wear, material degradation, spillage and dust liberation [1]. The curvature in the hood and spoon minimizes the material impact and reduces variations in the velocity of the material. The hood also has a converging shape, which minimizes the expansion of the material body. As the material falls, the gradual increase in velocity due to gravity allows for the narrowing of the material flow without plugging of the chute (see the equation in Figure 2.3, where an increase in S causes a decrease in A). The spoon reduces the velocity and force of material impact in the loading of the bottom belt conveyor [25].

The hood and spoon system depends upon gravity and friction to maintain the speed of the material flow through the chute. In order to properly design this system, a lot of material characteristics and continuum mechanics knowledge and computation is required. This can make the design of hood and spoon chutes relatively strenuous, complex and expensive [1]. Variations in flow rates of the belt conveyors or different materials flowing through the system add to this complexity and call for significant compromises in the chute design [23]. The configuration also requires a sufficient drop height to implement this design. In some cases only a spoon is used to change the direction of the stream. Spoons can also be prone to backing up or flushing if the characteristics of the bulk materials are variable [1]. This also requires compensation to be designed into the spoon to account for this variability. In some cases where available space or budget is limited, an impact plate is used instead of a hood [1]. An impact plate is a flat or lightly curved plate surface placed inside the chute to absorb the force of the moving material stream coming from the top belt and to divert it towards the bottom belt. Some impact plates have a mechanism that allows for a change in angle the plate can make in order to suit different materials and material flow rates.

2.5.3. Multi-material chutes

As stated before, when a transfer chute transports multiple materials, the hood and spoon design has a higher risk of encountering flow problems. Different products will have wide variations in every attribute, like particle size, moisture content and abrasion, giving the products significant flow property variations [23]. As an example, a product range from fine material to lumpy ore is considered and the chute angles to prevent build up of the fine material is significantly steeper (70°) than lumpy ore (50°). When the highest angle of 70° is chosen to eliminate fine material blockage, this same chute angle used with lumpy ore will produce high chute exit velocities, and could lead to spillage and high belt wear [23]. Rather than fighting symptoms with skirtboards or increasing maintenance, designers try to convince the end users to opt for a more expensive but potentially far more effective solution. A redesign concept of a multi-material transfer chute is presented by [23] at Beltcon 14 for instance, displayed in Figure 2.14. It contains an adjustable spoon that can change

the material flow angles to account for different material flow properties. It could potentially react automatically to potential build up of material or chute flow anomalies by performing pressure measurements on the hydraulic cylinder at the top of the spoon, as seen in the figure, or by positioning load cells under the chute respectively. When a conveyor is used to feed either of two discharge points, a so-called flopper gate can be opted for (see Figure 2.14, right). Care must be taken to adhere to general chute design guidelines to be self-cleaning, while the gate should be placed at the apex of the double chute to avoid jamming of the gate with rocks getting stuck.



Figure 2.14: Chute redesign with adjustable spoon using hydraulic cylinder [23]. Maximum flow (left) and minimum flow position (middle). Flopper gate concept [10] (right)

2.6. Chute design theory

When creating a hood and spoon chute, several models are made to predict the flow of material through the chute. With the increase in computational power, these analytical models can see a significant accuracy increase through the use of numerical models. The different models that are used for chute design are listed below [8]:

- **Trajectory model** Material flow from discharge of the top belt until chute hood impact
- **Impact model** Material impacting the chute hood
- **Hood chute flow model** Material traveling along the hood surface
- **Free-fall/Trajectory model** Material in free fall from hood to spoon
- **Impact model** Material impacting the chute spoon
- **Chute flow model** Material traveling along the spoon onto the receiving belt

2.6.1. Material trajectory

The path the bulk material takes as it is discharged from the delivery conveyor is called the trajectory [1]. The trajectory model consists of:

- Discharge load profile
- Angle of discharge
- Discharge trajectory

Discharge load profile

The load profile is the cross-sectional area of the material on the discharging belt. When the belt reaches the drive pulley it is flat, while along the rest of belt length it is supported by idler sets at a certain throughing angle. Equations along with descriptive drawings to find the loading profile dimensions at the drive drum is shown in Figure 2.15. The cross-sectional area of the material on the belt, A is found with a well known equation:

$$A = \frac{Q_m}{\rho v_b} \quad (2.4)$$

where Q_m is the material throughput in kg/s, ρ is the bulk density of the material in kg/m³ and v_b is the belt speed in m/s.

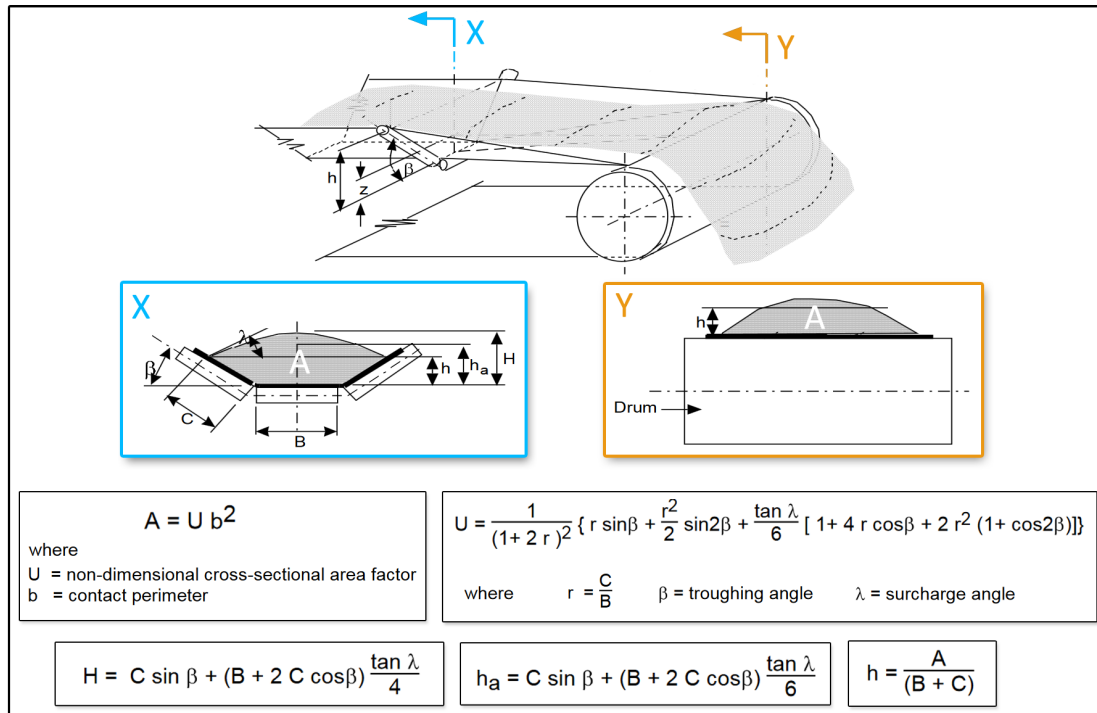


Figure 2.15: Discharge load profile equations (edited from [8][11])

The assumptions that are made for these calculations are[8]:

- Material lifts off at the tangent to the drive pulley
- No belt sag in the transition
- No cohesion
- Neglecting acceleration due to transition

Angle of discharge

The free body diagram and accompanying equations that govern the point where the material leaves the belt is presented in Figure 2.16. Slip can occur before lift-off takes place, hence the inclusion of the acceleration $\dot{v}$ and inertia force $\Delta m \dot{v}$, with v being the relative velocity [26]. In many cases this is insignificant and therefore neglected.

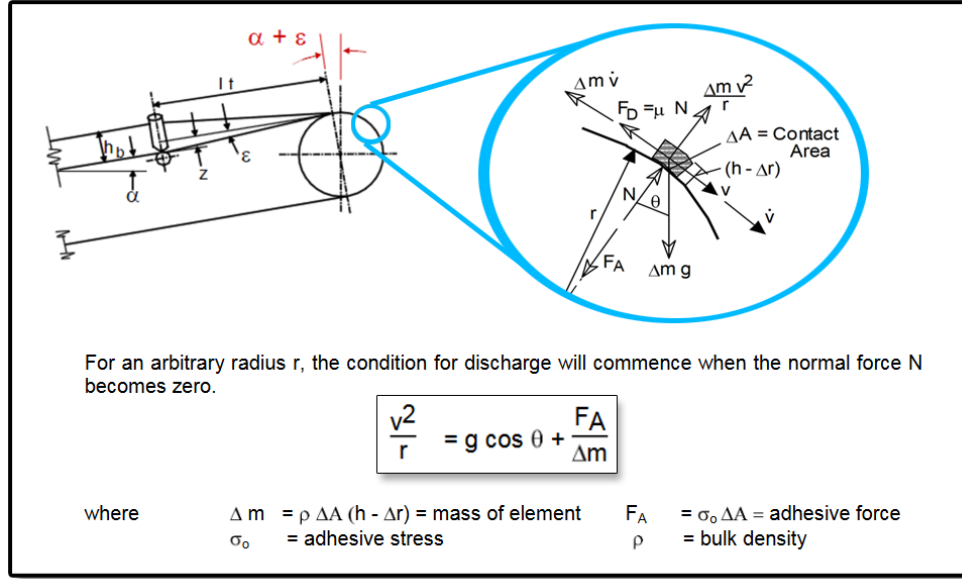


Figure 2.16: Angle of discharge free body diagram with accompanying equation (edited from [8][11][26])

In most cases the speed of the top conveyor is fast enough to discharge the material as soon as the belt makes contact with the drive pulley. In this case $\theta = -(\alpha + \epsilon)$ (shown in red in Figure 2.16), where $(\alpha + \epsilon)$ is the slope of the belt at contact point with the drum [8]. The critical case will be for the belt surface, that is, when $\Delta r = 0$. The minimum belt speed for discharge at the first point of drum contact is

$$v_b = \sqrt{Rg \left(\cos \theta + \frac{\sigma_o}{\rho g h} \right)} \quad (2.5)$$

Discharge trajectory

The trajectory the material makes after it leaves the discharging belt is governed by common equations of motion. When air drag is assumed to be negligible, which holds true in most cases [26], the equation of the path is defined by the x and y coordinates according to

$$y = x \tan \theta + \frac{1}{2} g \frac{x^2}{v^2 \cos^2 \theta} \quad (2.6)$$

The upper and lower bounds for the trajectories may be determined for the two radii $(R + h)$ and R for which the angle θ is obtained from Equation 2.5.

2.6.2. Hood design

After the material trajectory from the discharging conveyor is found, the hood is the next phase of the particle flow through the chute. The radius of curvature of the discharge trajectory is given by

$$R_c = \frac{\left[1 + \left(\frac{gx}{v_b^2 \cos^2 \theta} \right)^2 \right]^{1.5}}{\frac{g}{v_b^2 \cos^2 \theta}} \quad (2.7)$$

When the chute hood is designed with a constant radius, R , the radius of curvature of the trajectory at the point of contact has to be such that

$$R \geq R_c \quad (2.8)$$

Ideally the chute hood 'catches' the material at a tangent, so where the chute radius matches the radius of curvature of the material at the point of contact. This is visible in the left illustration in Figure 2.17.

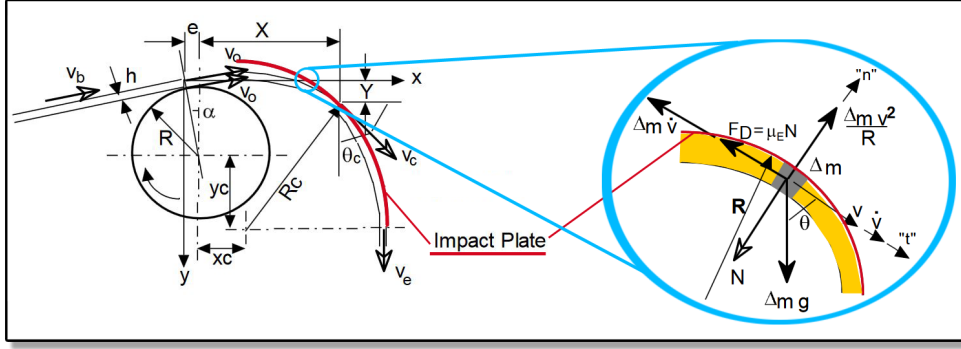


Figure 2.17: Matching radius of curvature of material and chute hood[26]

When an x-value for the hood location is picked, the position of the hood circle can be found by finding the values from Figure 2.17

$$\theta_c = \cot^{-1}(y') \quad (2.9)$$

$$x_c = X - R_c \cos \theta_c \quad (2.10)$$

$$y_c = Y + R_c \sin \theta_c - (R + h) \cos(\alpha + \epsilon) \quad (2.11)$$

On the right illustration in Figure 2.17, the free body diagram of forces that are present in this phase are depicted. The differential equation that follows from these forces is

$$-\frac{dv}{d\theta} + \mu_E v = \frac{gR}{v} (\cos \theta + \mu_E \sin \theta) \quad (2.12)$$

The solution to this equation is Equation 2.13, when a constant radius is assumed, as well as an average, constant value for μ_E for the stream, which holds when a thin cross-sectional stream is assumed ($H/B \ll 1$).

$$v = \sqrt{\frac{2gR}{4\mu_E^2 + 1} [\sin \theta (2\mu_E^2 - 1) + 3\mu_E \cos \theta] + K e^{2\mu_E \theta}} \quad (2.13)$$

For $v = v_0$ at $\theta = \theta_0$, then

$$K = \left\{ v_0^2 - \frac{2gR}{1 + 4\mu_E^2} [3\mu_E \cos \theta_0 + (2\mu_E^2 - 1) \sin \theta_0] \right\} e^{-2\mu_E \theta_0} \quad (2.14)$$

Of course the velocity of the material needs to be high enough as to not lose contact with the chute. Therefore, for the condition of positive contact to be true, equation 2.13 is only applicable when

$$\frac{v^2}{Rg} \geq \sin \theta \quad (2.15)$$

2.6.3. Spoon design

After the material leaves the hood, it undergoes a brief moment in free fall. In this period of free fall the velocity v_i can be estimated when neglecting air resistance to be

$$v_i = \sqrt{v_{fo}^2 + 2gh} \quad (2.16)$$

When air resistance is taken into account, the relationship between height of drop and velocity v_i is

$$h = \frac{v_\infty^2}{g} \log_e \left[\frac{1 - \frac{v_{fo}}{v_\infty}}{1 - \frac{v_i}{v_\infty}} \right] - \left(\frac{v_i - v_0}{g} \right) v_\infty \quad (2.17)$$

where v_∞ is the terminal velocity, v_{fo} is the vertical component of velocity of bulk solid discharging from feeder and v_i is the velocity corresponding to drop height, h , at the point of chute impact.

The theory of spoon design is almost identical to the hood design theory, apart from the direction of the gravity force. Where the hood design had a minimum speed for maintaining contact between hood and material, the spoon chute deals with an acceleration of the material followed by a retardation. To ensure the material slides off the spoon, a self-cleaning check needs to be performed. This determines the minimum angle the spoon exit makes to the receiving belt, defined by

$$\Psi > \tan^{-1} \mu_E + 5^\circ \quad (2.18)$$

The material stream suffers energy loss along the spoon trajectory due to sliding along the chute bottom. Energy loss due to sliding against side walls and inter-particle sliding is also present, but not as significant.

So far only constant radius hood and spoon designs have been discussed. Gains can be made using non-constant radius chutes, however the optimization is difficult. Construction of non-constant radius plate material can also prove challenging.

2.7. Conclusions

The research question that was answered in this chapter was

- *What is known in literature on the influencing factors on the creation and liberation of dust in transfer chutes and what are known transfer chute design considerations that provide solutions to these problems?*

In transfer chute design the objectives are to avoid unwanted effects that occur in bulk material transfer such as dust liberation, blockage, spillage, excessive wear or material degradation. Many of these effects can aggravate each other when they occur and it can therefore be extremely beneficial to prevent or minimize them. This can be accomplished with a proper guidance of the granular flow through the chute (no big velocity fluctuations, compact streams, center belt loading, etc.).

Dust liberation specifically is a result of air displacement of the material stream. In order to minimize dust liberation, the main considerations to be implemented in the design are

- minimize material impact
- minimize free fall of material
- compact containment of flow stream

These design considerations are not merely minimizing dust liberation, but also the creation of dust through material degradation. Methods of dust liberation minimization such as chute curtains, skirtboards, water curtains and air filtration systems can also be employed to fight dust liberation. These methods tend to be deployed when an existing chute has dust liberation problems. The focus lies more on the containment of dust as opposed to the prevention of dust creation, which is ultimately a better solution due to addressing the root cause instead of fighting symptoms.

A proven chute design configuration that addresses all these design considerations is the hood and spoon configuration. Here curved chute surfaces guide the material in a controlled manner, where material free fall and impacts are minimized, and the flow can be contained using a converging design. This method does provide greater challenges for engineers, since an accurate prediction of the material flow behavior is needed. Multiple materials transported through the same chute complicates the design even further and forces the engineer into compromises in its design.

3

Methodology selection for problem assessment at Tata Steel

When an existing transfer chute is suffering from problems such as excessive spillage or dust liberation, several methodologies are usually combined to solve these problems. Measuring methodologies are used to identify and quantify the problem, which can be used to compare with an improved design later. Modeling techniques where the granular flow or the air streams around it are modeled can also be used to specify the source and severity of the problem, as well as aid in finding improved designs that solve these issues. To redesign transfer chutes at Tata Steel, a selection of assessment methodologies is made. The research question that this chapter answers is therefore:

- ***What are suitable assessment methodologies for identifying transfer chute problems at Tata Steel that involve dust liberation?***

In order to find the answer to this question, criteria that will define what 'suitable' means in the context of this research have to be determined. These criteria are made explicit in Section 3.1. Measurement techniques that can be used when dust liberation problems occur at a transfer chute are discussed in Section 3.2. Then numerical modeling as an investigative tool for granular flow problems in transfer chutes are expanded on in Section 3.3. In Section 3.4 the situation at Tata Steel is laid out in order to look at the possibilities in investigating the causes of their dust liberation problem to eventually find feasible solutions. This chapter is concluded in Section 3.6 with the conclusions drawn and a summarized answer to the chapters' research question.

3.1. Selection criteria

Multiple measuring and modeling techniques are discussed in this chapter and choices for the most suitable methods for this research are made. Separate criteria for measurement and modeling techniques are formulated, since the measurement methodologies are used to solely assess the transfer chute problem of dust liberation and its causes, whereas the modeling techniques are also used to perform an eventual redesign. The criteria that are set to choose a suitable measurement methodology are

- **Equipment** - (Measuring) equipment has to be available or possibly constructed
- **Time** - Methodologies have to be implemented within time frame of research
- **Manpower** - Amount of manpower required should be limited
- **Identification** - Methodology should identify chute problem(s)
- **Quantification** - Methodology should have some form of quantification of the problem

The criteria for choosing a suitable modeling methodology are

- **Material modeling** - Methodology for modeling of material and interaction between particles

- **Equipment-material interaction** - Modeling of material and equipment interaction
- **Time** - Modeling and computational time required should be within time frame of research
- **Identification** - Methodology should be capable of aiding identification of chute problem(s)
- **Quantification** - Methodology should have some form of quantification of the problem
- **Redesign suitability** - Methodology should be applicable in testing redesign chutes for comparison of performance

3.2. Measurement methodologies

Since the quantification of dust liberation is very challenging, most quantitative dust measurements for transfer chutes are performed in controlled test setups for research purposes. Dust towers for example are test setups used to test the effectiveness of dust suppressants or different pelletization methods on fine generation. Material in a closed off tower is dropped through cascading zig-zagging trajectory where it suffers many impacts, while a vacuum system pulls air up through the tower and trapping dust particles in filters [27][28]. Another example is a scale model of a spoon chute made by Wheeler et al. [29] in an enclosure where in several sections of plastic plates on the bottom the settled dust was extracted and weighed. Also Particle Image Velocimetry (PIV) was used to measure the air velocity profile across the chute outlet to analyze the flow pattern.

Accurate dust measurements on actual, operational transfer chutes can be difficult, time consuming and prone to contamination. Therefore, when actual transfer chutes in operation suffer from dust liberation, not only dust measurements, but also air flow and material degradation measurements can be employed to assess the problems. An overview of these existing methodologies that can be used in assessment of dust creation and liberation is found in Table 3.1.

Measurement methodology	Description	Measures
Visual inspection	Visually identify dust liberation quantity and source	Airborne dust and settled dust
Area sweep	Periodic cleaning and weighing dust	Settled dust
Dust monitors	Dust measurement equipment placed in/around chute	Airborne dust
Air velocity measurements	Air velocity measuring device placed at chute entry and exit point	Air velocity and direction
Material sampling	Taking samples and checking amount of dust before and after chute	Material degradation
Camera's inside chute	Record video of granular flow inside chute to identify problem areas	Granular flow visualization

Table 3.1: Overview of measurement methodologies related to dust liberation problems

Visual inspection

The accurate measurement of the amount of fugitive materials at transfer points can be difficult to quantify. Dust liberation can usually be spotted with a visual inspection, but providing any quantitative results can be difficult. Within the enclosure of a transfer chute the dust that gets liberated can be visible, but locating the origin of the dust liberation along the material stream within the chute is much more challenging. Visual inspection is however a quick, easy and cheap way to determine a transfer chute dust liberation problem.

Area sweep

A very basic technique besides a simple visual inspection for dust liberation sources is to clean a defined area around a transfer chute and weigh the amount of material collected. This 'area sweep' is then conducted after regular intervals in time. Whether this interval should be weekly, daily, or hourly will depend on the plant conditions [1]. A big downside to this methodology is the added difficulty of the environmental conditions

that affect measurements. Wind can carry dust from other liberation sources into the measurement area and rain and humidity variation can cause measurement inaccuracies in the amount of airborne dust that is measured. In order to provide a useful study based on the interval data has to take into account the many variables that may influence these results. Common operating conditions should be recorded alongside the fugitive material measurements that include environmental conditions, operating schedules, material moisture content, among other factors that potentially contaminate the results. Therefore a study like described only seems reasonable when meticulous records over an extended period of time are collected.

Dust monitors

Many bulk handling plants have installed towers with dust measuring equipment to monitor the amount of dust in the surrounding air, since dust liberation has negative consequences on the environment and their employees. The measurement equipment used for dust measurements in the air are called PDRs (Personal Data Rams), see Figure 3.1 (left). Through emission of pulsed, near-infrared lighting, PDRs are able to perform opacity measurements to find the amount of dust in the air in mg/m^3 [30]. The origin of the dust for these tower measurements is unknown and can be from stockpiles to handling equipment. Companies that specialize in transfer chute design use these PDRs to quantify a dust problem near a transfer chute and compare the results before and after a design change is made. For instance, in 2014, WEBA used this technique when replacing older coal chutes at Laramie River Station in Wyoming, USA [21]. They placed five PDRs at different areas around a chute, including by the inlets and outlets, and measure the dust levels for eight hours under normal operations. Then averages were used to compare the dust levels before and after chute upgrades.



Figure 3.1: Personal Data Ram, PDR, measures dust in air (left) [30], Anemometer, measures air velocity (middle) [1], camera footage inside chute (right) [7]

Air velocity measurements

As explained in Section 2.3.2, in order to control the amount of dust that is liberated, the air streams around the material stream are an important influencing factor. The pickup velocity of dust particles is generally around 1 to 1.25 m/s [1], but still vary widely depending on many factors, such as particle size, material cohesiveness, and moisture content. Listed among liberation minimization methods for transfer chutes in Section 2.4 is the minimization of air flow entering and leaving the chute enclosure, as well as keeping the air velocity inside the enclosure at a minimum. A method to check this air flow on operational transfer chutes is to monitor the air flow at the entrance and exit of the chute with an anemometer, depicted in Figure 3.1 (middle).

Material sampling

As explained in Section 2.3.2, material degradation and dust liberation go hand in hand. When dust gets formed through impact, this is also where dust has the potential to be liberated. That is why in some cases instead of looking at dust in and around the transfer chute, material samples can be taken before and after transfer chutes to quantify material degradation and provide a relative measure for dust liberation at a transfer chute. A transfer chute upgrade performed by WEBA [22] at the Isdemir Steel Plant in Turkey used exactly this method to find material degradation after complaints on excessive dust levels, material degradation and noise levels. The methodology for sampling material is standardized and is outlined in Chapter 4.

Camera's inside chute

Finding out what happens with the material stream inside a problematic transfer chute is necessary to provide a solution that properly addresses the problem. This could potentially be accomplished by placing camera's inside the working chute and examine the footage (see Figure 3.1 (right)), which could also be compared to calculated analytical or numerical models of the flow. The darkness and dust levels inside the chute can

cause difficulties in obtaining clear footage, and any form of quantification of dust liberation is not possible using this method.

3.3. Numerical modeling methodologies

With the increase in demand for better performing chutes in regards to performance criteria such as minimum chute and belt wear or minimum dust generation and liberation, simple rules-of-thumb design methodologies that permits flow without blockage are insufficiently detailed. This, along with the rise in computational power, gives rise to numerical modeling methodologies that can incorporate a large number of flow properties into simulations. Two main approaches exist for building models of granular flow, the Lagrangian and the Eulerian approach (see Figure 3.2).

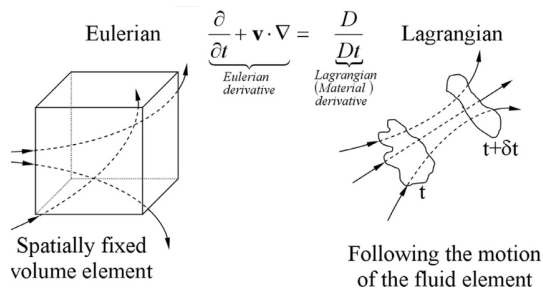


Figure 3.2: Mathematical difference between the Eulerian and the Lagrangian approach [31]

The Lagrangian approach models the material stream as discrete particles and calculates their motion and collisions, whereas the Eulerian approach models the material stream as a artificial, continuous gas-solid flow stream [2][32]. One widely used modeling methodology for transfer chute design is Discrete Element Method, which uses the Lagrangian approach, but Computational Fluid Dynamics typically uses a multi-phase simulation where the granular flow can also be modeled using an Eulerian approach. An overview of the modeling methodologies used in transfer chute design are listed below in Table 3.2, which are expanded on in the next section.

Modeling methodology	Description	Model type
Discrete Element Method	Timestep based particle and geometry modeling and calculating interaction forces	Granular flow by modeling motion and collisions of discrete particles
CFD Eulerian-Eulerian	Predicting fluid flow behavior using Navier-Stokes equations	Granular flow as continuous mass
Coupled DEM-CFD	Coupling of numerical methods to predict granular flow and air flows	Granular flow as particles or fluid and air flow as fluid flow

Table 3.2: Overview of modeling methodologies related to dust liberation problems

Discrete Element Method

As explained above, the basic principle of DEM is to model each individual particle as a separate entity that undergo a range of forces as in reality. These forces typically include gravity, inter particle contact forces, particle to wall contact forces and cohesive and adhesive forces in particles if applicable. After every time step in a simulation these forces and their resultant displacements are calculated, making DEM simulations very computationally intensive. Different contact models are used to define the interaction between particles and environment, which is visualized in Figure 3.3.



Figure 3.3: Visualization of contact between particles in DEM, including springs, dashpots, friction slider and cohesion bond[31]

When evaluating dust emission in transfer chutes, it is often sufficient to analyze the material flow in the system using DEM [18]. From Section 2.3.2 it was found that abrupt changes in flow speed, impacts, as well as periods of free fall that dilate or disperses the material stream are a clear indicator of potential dust liberation. Applying this knowledge from dust liberation theory, dust liberation causes and redesign proposals can be made in DEM simulation software. An example of an updated chute design that compacts the material stream and provide smooth redirection of material flow using a hood and spoon design is shown in Figure 3.4.

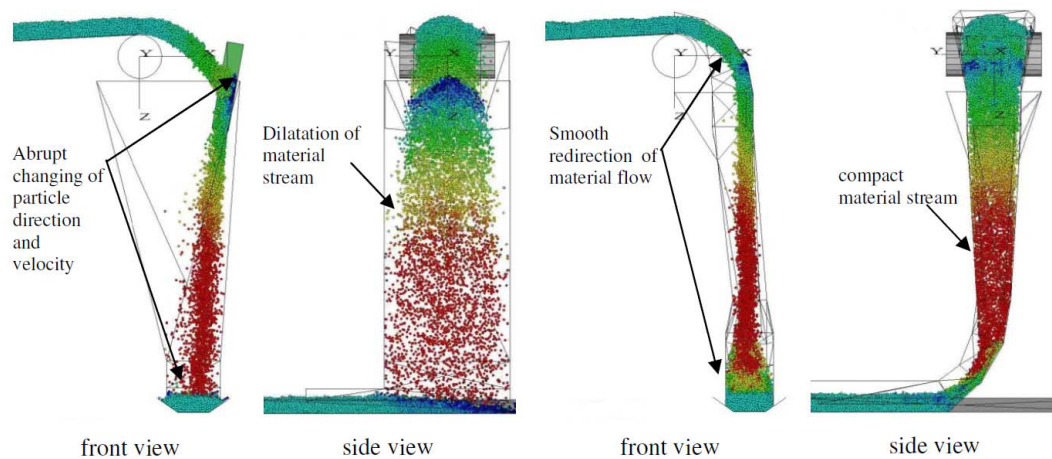


Figure 3.4: Example of a redesign of a transfer chute using DEM software [18]

CFD Eulerian-Eulerian approach

When CFD is used in modeling transfer chutes with material streams including dust or air flows, a multiphase simulation is required [18]. When the material stream is modeled as a continuous mass, as well as the surrounding air, this is called the Eulerian-Eulerian approach. Typically three phases are modeled, a continuous phase representing air and two solid dispersed phases of different sizes representing the granular particles and the dust particles [17][32]. This method can be used to solve flow fields for densely packed solids, however a major drawback of this method is that no friction can be accounted for between the dispersed solid phases (granular particles and dust) and the chute wall, since these flows are modeled as fluids[17][18]. The only options for the wall boundary condition are no slip and free slip, where typically no slip is selected for the continuous phase, the air flow, while free slip is selected for the solid dispersed phases. Additionally, only mono-sized particles are involved in these models, while typically material streams contain a large particle size distribution [33]. An example result of a CFD model of a transfer chute flow is shown in Figure 3.5. There are several research papers that have used the Eulerian-Eulerian approach [17][18][29][32][33], but this method is not widely used in transfer chute design.

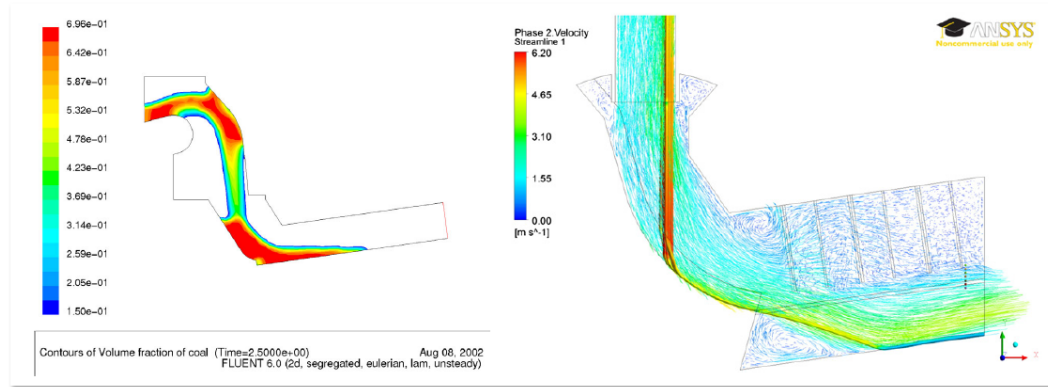


Figure 3.5: Examples of research results using the Eulerian-Eulerian approach in CFD modeling (left[32], right[29])

Coupled CFD-DEM

Another methodology for modeling transfer chutes that can include dust particles and air flows is the Eulerian-Lagrangian approach. Here the material stream is modeled with Lagrangian-based software such as DEM to model discrete particles and interparticle and wall interactions, whereas the air and dust flows are modeled as a fluid using the Eulerian approach. This involves coupling DEM software with CFD software. The information exchange between Newton's laws of motion in DEM and the local averaged Navier-Stokes equations that are solved in CFD is illustrated in Figure 3.6.

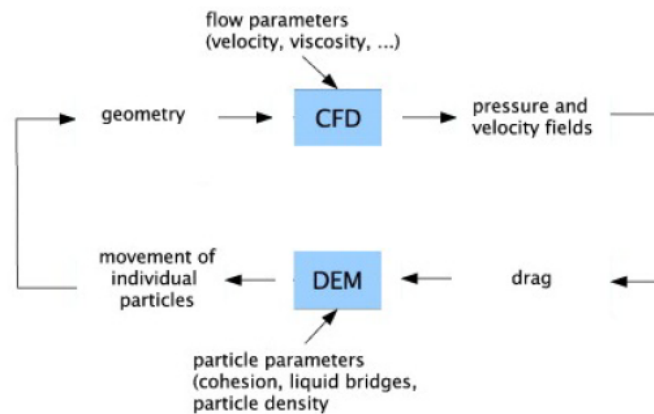


Figure 3.6: Information exchange between CFD and DEM [34])

This method is potentially more accurate than the previously mentioned methodologies, since both individual granular particles are modeled, as well as the interacting air and dust flows around the material stream. However, in the current research literature there is a lack of validation and verification presented [35]. Additionally, long computation times can be a significant problem in its application of large numbers of particles or long duration of simulations [2]. Simulation times greatly depend on the CFD mesh size of the calculation volume domain, as well as the choice of either 2D or 3D meshes, which in turn affect the accuracy of the simulation [34]. Some academic research that uses both DEM and CFD will opt for first simulating granular flows in DEM to find its properties (such as porosity[17]), which are then converted for use in Eulerian-Eulerian multiphase CFD models. Companies have started to implement CFD into DEM simulations as well, where ANSYS Fluent has been used in combination with RockyDEM for instance by the company Rocky [36]. Dust flows in and around transfer chutes have been investigated with the use of the Rocky software package.

CFD-DEM coupling definitely shows promise in analyzing airflows at transfer chutes in great detail. The implementation in the industry will surely grow in the future if accurate models will be able to be produced.

3.4. Analysis Tata Steel chutes

With the knowledge of dust liberation investigation methods, the next step is to analyze the situation at Tata Steel and see which methodology can be applied. An investigation into all the transfer chutes at the section 'Grondstoffenlogistiek' (GSL), or raw material logistics at Tata Steel has been performed, in order to get an overview of the types and size ranges of its transfer chutes. The results of this analysis have been summarized in Table 3.3.

Transfer chutes	
Number of transfer chutes	137
Number of belt to belt chutes	121
Chute types	Impact plate, dead box, straight onto belt loading
Drop height range	0.8 m - 6.2 m
Average drop height	2.5 m
Material direction changes	unknown
Conveyor belts	
Belt speed range	1.05 m/s - 4.05 m/s
Average belt speed	2.18 m/s
Mass flow rate range	90 t/h - 23197 t/h
Most used mass flow rate	1600 t/h
Belt width range	650 mm - 1800 mm
Most used belt width	1200 mm
Throughing angles used	30° and 40°
Material transported	Iron ore pellets, sinter, cokes and iron ore mixture
Support under receiving belt	Guirlandes, impact idler sets regular idler sets and impact bars

Table 3.3: Data on GSL Tata Steel transfer chutes

3.5. Case study at Tata Steel and methodology choices

3.5.1. Case study

Since it is not practical to analyze over a hundred chutes, a case study will be chosen that is the most common design of transfer chute at GSL Tata Steel. A set of transfer chutes which have noticeable dust liberation (see Figure 1.2) and received fines for environmental contamination as mentioned in Section 1.2 is investigated.

The chute system that is chosen for the case study is a movable chute that can load material from a top belt, called A317, onto three belts below, named A508, A509 and A510. The belts and chute in question are very close to the most common characteristics investigated, shown in Table 3.3. The relevant data of this case study chute is listed in Table 3.4.

Transfer chutes	
Chute type	Impact plate
Bottom of chute	Deflector plates
Drop height	3.04 m
Material direction change	90°
Conveyor belts	
Discharging belt name	A317
Receiving belts names	A508, A509, A510
Belt speed	2.19 m/s
Mass flow rate	800 or 1600 t/h
Belt width	1200 mm
Throughing angle	30°
Material transported	Iron ore pellets, sinter, cokes and iron ore mixture
Support under receiving belts	Guirlandes

Table 3.4: Case study chute system data

The material that flows over the chutes usually comes from an outside storage area called EO1, 'Ertsopslag 1'. Many different materials are being transported over this section. A series of eight bunkers with a capacity of 1600 tonnes are located with their exits on the top belt, A317. When material gets loaded onto the belt, one or two bunkers can be unloaded onto the belt simultaneously. This results in a mass flow rate that is usually either around 800 t/h or 1600 t/h, as can be seen in Figure 3.7.

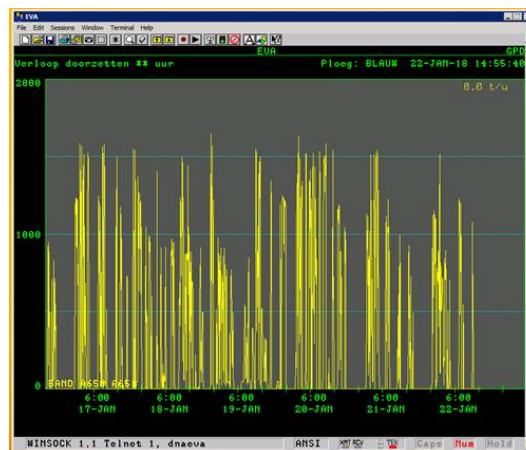


Figure 3.7: Mass flow rates over case study chute (source: Tata Steel control panel)

3.5.2. Methodology choices

From Section 3.2 and Section 3.3, the known measurement and modeling methodologies for this research have been discussed. After checking the availability of these methodologies, as well as the advantages and disadvantages of each methodology, grading tables are created, shown in Table 3.5 and Table 3.6.

Measurement methodology	Equipment	Manpower	Time	Identification	Quantification
Visual inspection	++	++	++	—	—
Area sweep	+	+	--	--	+
PDR measurements	—	+	+	+	++
Air velocity measurements	—	++	+	--	+
Material sampling	+	++	+	+	+
Camera's inside chute	—	+	+	+	—

Table 3.5: Grading of measurement methodologies according to criteria

Modeling methodology	Material	Equipment	Time	Identification	Quantification	Redesign
DEM	++	++	+	+	+	++
CFD	+	--	++	+	+	—
Coupled DEM-CFD	++	++	—	++	++	+

Table 3.6: Grading of modeling methodologies according to criteria

Material sampling proves, although not a direct measurement of dust liberation such as PDR measurements, to be the most suitable method in combination with DEM simulations to identify the source of the dust liberation in Tata Steel's A317 transfer chute. For measurements in and around the chute, resources for an area sweep and material sampling are available. However, time constraints eliminate the possibility of the former. Like many chute redesigns that suffer from flow problems such as blockage, dust liberation or spillage for example, the investigation of the problems and eventual redesign is performed using granular flow simulations with DEM software [7][17][23]. CFD can model the material as a continuum, but this lacks the crucial material-equipment interaction calculations to accurately model the material flowing through the chute in enough detail. Coupled DEM-CFD is not chosen due to the complexity of the simulation setups, where the analysis and redesign of the entire transfer chute is deemed too large for DEM-CFD models to simulate within a reasonable, computational time frame.

3.6. Conclusions

This chapter has answered the following research question

- ***What are suitable assessment methodologies for identifying transfer chute problems at Tata Steel that involve dust liberation?***

Actual measurement of dust is challenging due to the difficulty of pinpointing the source of liberation. Therefore other measurement tools can also be used besides dust monitoring equipment such as area sweeps, air velocity measurements and material sampling to find dust creation and prove the source of dust liberation.

Numerical modeling techniques can be a very helpful tool in the assessment of dust liberation at transfer chutes. DEM, CFD and the coupling of the two methods are capable to varying degrees at modeling granular and/or dust and air flows inside transfer chutes.

For this particular research, the following conclusions regarding the suitability of these methodologies is summarized below.

- Dust measurement techniques such as dust monitors or periodic dust collection are not possible for this research due to a lack of resources
- Material degradation will be investigated through sampling to attempt to gain physical evidence and quantification of material flow problems leading to degradation and liberation of material
- Modeling chute material flow in DEM software is chosen as investigative method and for eventual chute redesign steps
- After investigating Tata Steel transfer chutes, a case study chute is chosen that represents the most common chute design at Tata Steel

4

Quantifying material degradation

The research question to be answered in this chapter is

- *What is the extent of material degradation at a Tata Steel transfer chute?*

Through the use of sampling according to standardized methods, this chapter will lay out the process of answering this research question. First the standardized sampling methodology will be explained in Section 4.1. In this section a methodology that fits within the possibilities for this research is chosen as well. Section 4.2 will show the results of the sampling performed, after which a discussion and conclusions on the findings is expanded on in Section 4.3 and Section 4.4 respectively.

4.1. Material degradation sampling methodology

The sampling of iron ores is standardized in many countries all over the world, where in Europe the standard *ISO3082-2009 Iron ores - Sampling and sample preparation procedures*[37] is used. This standard outlines many different sampling methods, some of which are depicted in Figure 4.1.

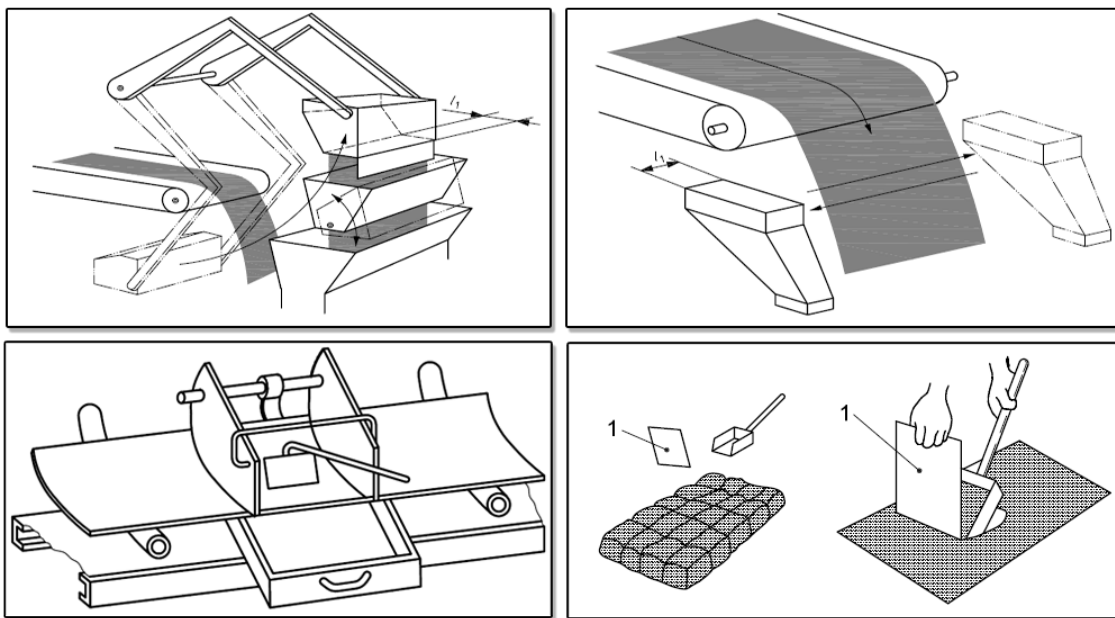


Figure 4.1: An excerpt of moving belt (top) and stopped-belt (bottom) sampling methods outlined in ISO3082 (edited from [37])

From this figure it can be seen that large equipment is needed to take samples of material from the belt and that a distinction is made between moving belt samples and stopped-belt samples. In order to find material degradation in samples, the particle size distribution of each sample needs to be determined. When

samples are taken right before and right after the material passes through the transfer chute, the indication that material degradation is present can be identified when the percentage of smaller sized particles is increased in the samples taken after the transfer chute.

For this particular investigation into material degradation a stopped-belt sample methodology is chosen over a moving belt sample. To avoid differences in the 'before' and 'after' sample due to other factors beside the transfer chute, it is important to take the samples as close together along the material stream. When moving belt samples are taken, this becomes increasingly difficult, due to sample locations being limited to transfer points. The 'after' sample would have to be taken at the discharge point of the bottom conveyor, which is over a 100 m.



Figure 4.2: The sampling tools on the top belt, A317 (left), the process of sampling (top right) and a finished sample(bottom right)

The sampling tools that were used in the stopped-belt sampling are a combination of the bottom two illustrations in Figure 4.1 and are shown in Figure 4.2. An iron tool is constructed similar to the bottom left illustration that can isolate a cross-sectional 'slice' of material to be sampled off the belt, and a small scoop is available to collect the sample. The smaller particles in the sample are collected with a vacuum cleaner with a clean vacuum bag, that is released into a bucket with the rest of the sample. The sampling tool sides are made to match the cross-sectional shape of the conveyor belt with a throughing angle of 30°. The width of the sampling tool, which equals the minimum length along the conveyor of ore to be removed, is dependent on the nominal top size of the ore according to the ISO standard. This minimum length is at least three times the nominal top size of the ore, subject to a minimum of 30 mm [37]. With neither pellets, sinter or cokes being above this size, 90 mm length is sufficient. For the sampling tool a length of 100 mm is chosen. The mass of each sample in kg is determined by [37] to be

$$m_i = \frac{q l_2}{3.6 v_b} \quad (4.1)$$

Where q is the flow rate in t/h, l_2 is the length in m of the complete cross-section of ore removed from the conveyor and v_b is the speed of the conveyor belt in m/s. With the samples being taken when one bunker is being emptied, the sample mass over which the PSD is determined becomes

$$m_i = \frac{800 \text{ t/h} \cdot 0.1 \text{ m}}{3.6 \cdot 2.19 \text{ m/s}} = 10.15 \text{ kg} \quad (4.2)$$

The suitable locations for sampling from the belt before and after the chute are found to be at 13 and 12 meters from the chute respectively. First a sample from the top belt is taken, after which the belt is turned on for a set time and the second sample at the bottom belt is taken. It is important that the second sample is:

- taken as close by the first sample as possible to minimize differences between accompanying samples
- the material that is sampled went through the chute at full speed
- taken after the first sample location has passed to eliminate contamination due to moved material during the first sample

Using video footage taken of the material flow inside the chute after sampling the top belt, the startup time for the belt is approximated at 6 seconds. In order to find the time when the location on the material stream where the first sample was taken passes the second sample location, $t_{\text{between samples}}$, the following equation is formulated

$$t_{\text{between samples}} = t_{\text{startup}} + \frac{s_{\text{between samples}} - \frac{1}{2} \cdot t_{\text{startup}} \cdot v_b}{v_b} \quad (4.3)$$

where t_{startup} is the startup time, $s_{\text{between samples}}$ is the distance between the two sample locations and v_b is the belt speed. This gives a time between sample locations when startup is included of

$$t_{\text{between samples}} = 6 \text{ s} + \frac{(13 \text{ m} + 12 \text{ m}) - \frac{1}{2} \cdot 6 \text{ s} \cdot 2.19 \text{ m/s}}{2.19 \text{ m/s}} = 14.42 \text{ s} \quad (4.4)$$

Therefore after every first sample the belt is turned off after 10s, in order for the belt to be stationary after 16s, taking into account a stopping time of 6s.

The case study transfer chute transports sinter, iron ore pellets, cokes and different mixtures. The methodology described is tested on iron ore pellets, sinter and cokes; different mixtures were unavailable at the time of research. The methodology proved unsuccessful for cokes only. The lump sizes of coke particles are too large for the sampling tool to penetrate the material cross-section. Despite a sampling plan where samples of iron ore pellets and sinter are taken until the samples show a certain measuring accuracy using student t-tests, the heavy usage of the conveyor belt line at Tata Steel for the continuation of production made it possible for only two samples of sinter from before and after the chute to be successfully extracted. The samples are compared and according to student t-tests with a confidence interval (CI) of 95% their accuracy is determined, as described in [38]. In the form of the student t-test used, the standard deviation, s , is unknown and estimated based on the sample information [38]. The equations governing this form of the student t-test are shown below.

$$\mu = \bar{x} \pm \frac{t_{\alpha/2, p}}{\sqrt{n}} s \quad (4.5)$$

$$\bar{x} = \sum_{i=1}^n \frac{x_i}{n} \quad (4.6)$$

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (4.7)$$

Where μ is the mean, $\bar{x}$ is the average of the samples, t_a is the student t-test value, n is the number of samples, s is the estimated standard deviation and x_i is a sample output.

4.2. Sampling results

Two samples of sinter from before and after the chute have been collected in the course of this research. Unfortunately no iron ore pellets have been sampled. The PSD of each sample is determined and the results of the comparison between them is shown in Table 4.1.

Particle diameter range [mm]	A317 'before chute' $m_{1,1}$	A510 'after chute' $m_{1,2}$	Sinter difference m_1	A317 'before chute' $m_{2,1}$	A510 'after chute' $m_{2,2}$	Sinter difference m_2	Total difference (with 95% CI)
>40	2.3%	0.0%	-2.3%	2.9%	0.0%	-2.9%	-2.6% $\pm$ 3.8
20-40	9.2%	13.9%	4.7%	9.8%	10.7%	0.9%	2.8% $\pm$ 24.1
10-20	44.7%	49.0%	4.3%	42.8%	43.4%	0.6%	2.4% $\pm$ 23.5
5-10	36.5%	32.4%	-4.1%	37.5%	39.0%	1.6%	-1.25% $\pm$ 36.2
3,15-5	5.4%	3.5%	-1.9%	5.0%	5.0%	0.0%	-0.95% $\pm$ 12.1
<3,15	1.9%	1.2%	-0.7%	2.0%	1.9%	-0.1%	-0.4% $\pm$ 3.8

Table 4.1: Difference in percentage between samples of different particle diameter ranges

From the total difference taken from the sinter samples m_1 and m_2 it can be seen that there is an increase in particles in the 10-40 mm range, while there is a decrease in particles of smaller diameter, as well as in particles over 40 mm. This is counter to the idea that particles are degraded through the chute, which would lead to an increase in smaller particles.

It can be seen from the confidence intervals in Table 4.1 that is found between the difference in the sinter samples m_1 and m_2 that the results are still very inaccurate. This is obvious with only two samples, but the accuracy can potentially increase with more sample results being incorporated. It appears from the CI results that they could be linked to the PSD values, but tracing the results back to the biggest anomaly in the data, it appears that this is due to the differing values of $m_{1,2}$ in the diameter range of 5-40.

4.3. Discussion

Due to the lack of samples taken the accuracy of the sample results is not sufficient to draw pertinent conclusions. The methodology applied will most likely require a significant amount of samples in order to be sufficiently accurate, since it is prone to measurement errors. In order to sample the exact slice of material caught in between the sampling tool, no dust particles should be left on both the belt or the vacuum cleaner bag. Placing the sampling tool onto the belt requires a significant amount of force, which could lead to potentially damaging the material and contaminating the results. It is also difficult to lower the tool right onto the belt without small particles rolling underneath the tool into the sample when material is scooped out between the tools plates, which can happen in various degrees per sample. With a larger sampling tool and many more samples taken the likelihood to get results within a reasonable range with CI of 95% is increased. These result data can be used to get a good indication of the overall particle size distribution of a material, which can be used in material simulation calibrations for instance. This is done in Section 5.2.

4.4. Conclusions

The research question to be answered in this chapter is

- ***What is the extent of material degradation at a Tata Steel transfer chute?***

Unfortunately this question is not answered to a satisfactory degree with the methodology used in this research. Conclusions that can be drawn from this chapter are

- Stopped-belt sampling according to *ISO3082-2009* is possible on iron ore pellets and sinter, but not with cokes. This is due to the large lump size of cokes, making the penetration of the material on the belt with the sampling tool not possible.
- Using a stopped-belt sampling tool of 100 mm width to determine PSD within a reasonable range with CI of 95% requires more than two samples. It is unclear how many samples are required.
- To minimize sample inaccuracies between samples before and after a chute the samples need to be taken as close together as possible, while still having the material travel through the chute at full speed and while the location on the material stream where the first sample was taken has passed the second location before the second sample is taken.

5

Calibration dynamic material model

In order to properly redesign a chute and find current chute flow problem causes, it is essential to get a material model that accurately represents the real life bulk material flow behavior. The research question to be answered in this chapter is

- *How to calibrate bulk materials for dynamic simulations like transfer chutes?*

In order to answer this research question, an appropriate experimental test setup needs to be found. The chosen setup and the following experimental plan for the calibration is found in Section 5.1. The calibration process and step wise calibration is described in detail in Section 5.2.

5.1. Experimental setup and working principles

5.1.1. Inclined surface wear test setup

In the process of calibration experimental setups are used to record material behavior, which can be matched in DEM simulation software to accurately model particle and bulk behavior. On iron ore many calibrations have been performed using a wide variety of experiments [12][31][39]. There are tests to study single particle properties such as pin-on-disk tribometer for the measurement of friction coefficients or drop tests to find restitution coefficients [39], but also many bulk material tests to find bulk material properties such as bulk density tests, angle of repose tests or penetration tests for examples [31]. Usually a combination of tests is used to find a suitably calibrated model. An important aspect of calibration is to use testing methods that will accurately portray material behavior after calibration in the aspects that the calibrated material model is eventually used for. For instance, when material is being tested when it is picked up by a grab, a penetration test for calibrating the interactions between the grab and the material is very suitable. Since the material in this research is being used in a dynamic setting where it is always moving and interacting with the belt and chute surfaces, a dynamic test setup should be selected that can model these interactions between belt, chute and material. For this purpose the inclined surface wear tester is chosen. The wear tester and its dimensions shown on the geometry that is made in DEM is depicted in Figure 5.1.

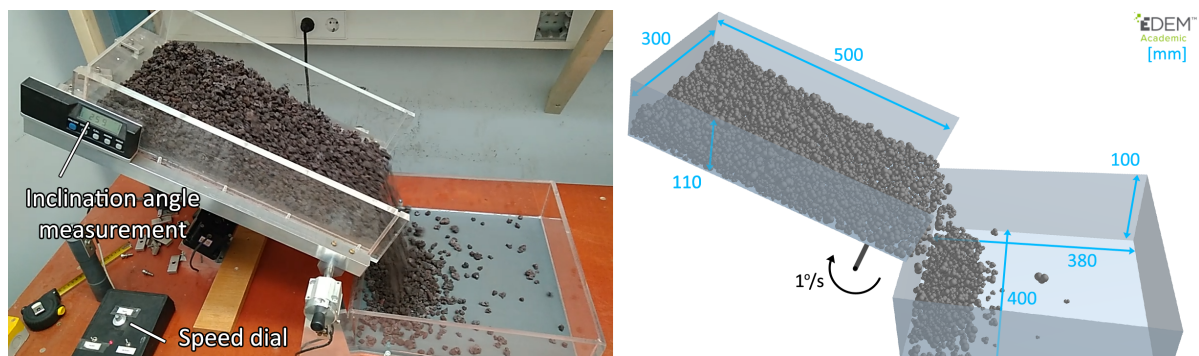


Figure 5.1: Picture of inclined surface wear tester during a test with sinter (left) and a simulation of the tester in DEM (right)

This tester rotates the top bin (see Figure 5.1) to pour the material into the bin below. This allows the material to be studied as it collapses, slides and/or rolls from one bin to the other. Even though the chute that is investigated transports iron ore pellets, sinter, cokes and different mixtures, for this research pellets and sinter are chosen. Cokes consists of lumps that are too large in relation to the test set-up and different mixtures are unavailable at the time of research. The material that is tested is taken from the top belt case study chute and weighs 8 kg. The top bin has an interchangeable bottom surface of steel and rubber. Steel is used to represent the chute material, while rubber is used as bottom of the top bin to represent the belt interaction.

5.1.2. Performance indicators and test procedure

Four combinations of tests are performed using sinter and pellets and using rubber and steel as bottom surface for the top bin. Every combination is tested seven times and the range of accuracy of the resulting performance indicators is determined with a confidence interval of 95%. Each test has eight performance indicators, which are depicted in Figure 5.2. Some picture are simulation screenshots, in order to explicitly show the movement that is recorded as dynamic performance indicator.

As can be seen in Figure 5.2, the material is loaded as a fixed sized box shape on the left side of the top bin. The bulk density check is the first performance indicator. The height of the box is measured and used to visually check the bulk density when compared to the simulations. In the simulations the bulk density is determined within this box of material and calibrated to bulk density values found in literature. Then the plastic plate in front is swiftly taken away for the material to collapse on one side. The resulting angle of repose that the material forms is the second performance indicator for the material calibration. The inclined surface tester is turned on and the top bin starts to rotate at a speed of $1^\circ/\text{s}$. The material is filmed during the rotation as the pile collapses and falls into the bottom bin. This is done to identify four dynamic performance indicators, shown and explained in Figure 5.1 with an accompanying DEM simulation screenshot for illustrative purposes. These indicators are timed using the inclination angle that the top bin has at the moment of occurrence. When finally the material is all poured in the bottom bin, two final performance indicators in the form of angles of repose can be determined. The most important experimental setup data is listed in Table 5.1. The results of the experiments along with their accuracy using a 95% CI are found alongside the simulation results in Section 5.3 and Section 5.4.

Experimental test setup data	
Bulk material used	• Sinter • Iron ore pellets
Bottom surface tester used	• Rubber • Steel
Material weight	8 kg
Rotational speed	$1^\circ/\text{s}$
Number of repetitions	7
Number of performance indicators	8
Confidence interval	95%

Table 5.1: Some basic data on the experimental setup

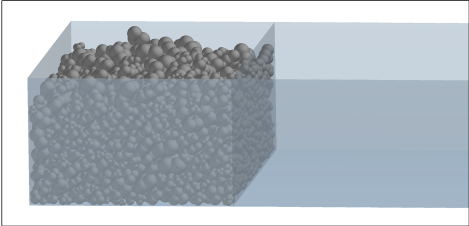
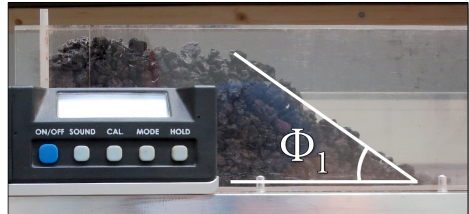
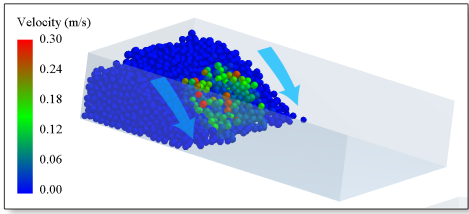
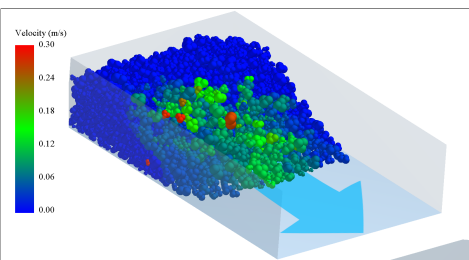
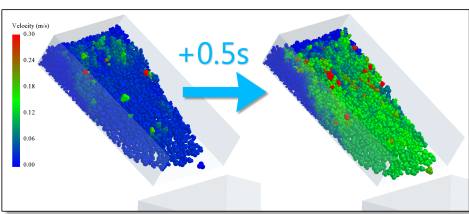
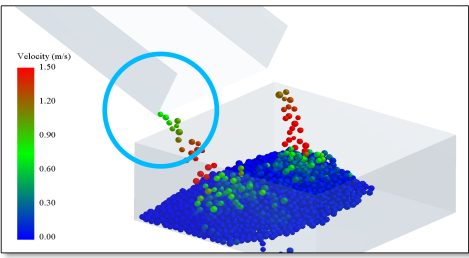
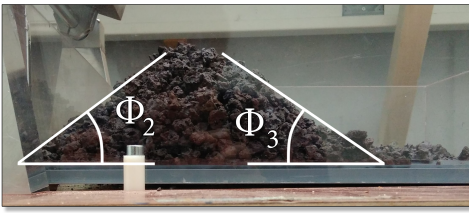
Picture of performance indicator	Performance indicator	Description
	Bulk density check	Boxed-in material to check bulk density in simulation and visually check volume size
	First angle of repose (Φ_1)	One side of box is taken away and results in an angle of repose
	First material-material shift	Inclination angle when material starts to slide/roll over each other, but not yet sliding or rolling over the top bin surface (notice the blue particles on the bottom)
	First material-plate shift	Inclination angle when material starts to slide/roll over the top bin surface for the first time
	Biggest material shift	Inclination angle of the top bin when the biggest shift in material happens, always a combination of sliding/rolling between particles and between particle and bottom surface
	Top bin empty	Inclination angle of the top bin at the moment when all the material has been poured into the bottom bin and the top bin is empty
	Second and third angle of repose (Φ_2 and Φ_3)	When all the material is poured into the bottom bin, the pile that remains forms two angle of repose

Table 5.2: Performance indicators inclined surface wear tester

5.2. Calibration setup

Armed with the experimental data, calibration of the bulk materials inside the DEM simulation environment can begin. Often in a material calibration, first the particle properties are tested with experiments and used as input for the simulation model, after which the bulk behavior is checked with reality and final adjustments are made. In this research the testing of particle properties is taken from extensive

First the simulation material parameters that will be adjusted for calibration are determined. Then using data gathered from literature and sampling, a reference case is made as a starting point in the calibration process. Finally the procedure and reasoning for the calibration methodology used is explained.

5.2.1. Calibration parameters

The material parameters that will be varied for the calibration of both iron ore pellets and sinter are listed in Table 5.3. These are considered to be the values that are of influence to the bulk behavior that is examined in the experiments and will be used for calibration.

Calibration parameters
• Particle density
• Static friction particle - particle
• Rolling friction particle - particle
• Static friction particle - steel
• Rolling friction particle - steel
• Static friction particle - rubber
• Rolling friction particle - rubber

Table 5.3: Calibration parameters

5.2.2. Reference case

The next step in the calibration process is to define a reference case. This is a working model of the bulk material, which can then be calibrated through trial and error. The reference case consists of particle and bulk material parameters for sinter and iron ore pellets and their interaction parameters with both rubber, steel and plastic. The plastic properties are needed for the walls of the surface tester.

Particle shape and size distribution

The particle size distribution that is used of the simulation material models for iron ore pellets is found in literature. An accurate representation of the PSD for pellets from Tata Steel was found in a PhD research by Stef Lommen [31] and is depicted in Figure 5.2 (left). The approximation is normal distribution with an average diameter of 11 mm and a normalized standard deviation of 0.1 and has an R^2 of 0.9997.

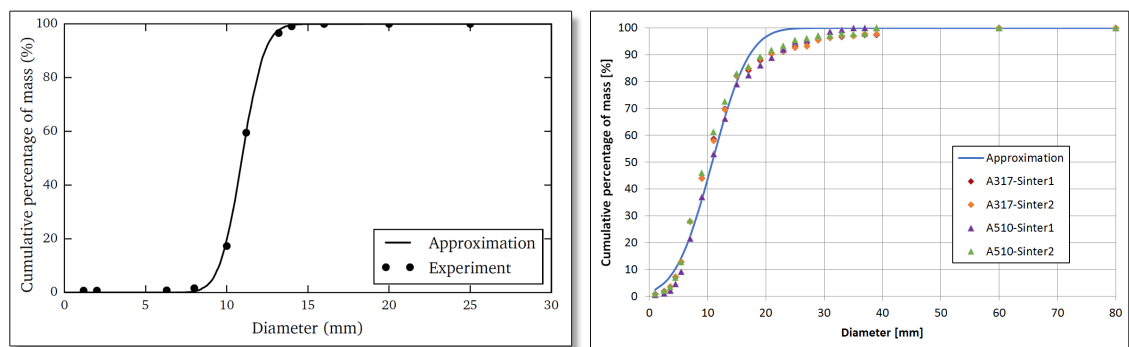


Figure 5.2: Particle size distribution of iron ore pellets [31] (left) and sinter (right)

For sinter, a similar approximation was made based on the sample results shown in Section 4.2 in Table 4.1. All the PSDs from the sample results are plotted and approximated with a normal distribution. The results are shown in Figure 5.2 (right). The normal distribution has an average particle diameter of 10.8 mm (the d_{50} result from sampling, which is 50% of cumulative particle mass in a PSD), with a normalized standard

deviation of 5, resulting in an R^2 of 0.9877. This method is preferred due to its significant simulation time savings when compared to an input of the PSD manually into DEM.

Particle shape

The d_{50} for sinter is taken from the average results of the sampling performed in this research, described in Chapter 4, which is 10.8mm. The d_{50} for iron ore pellets is taken from Lommen [31], which studied pellets originating from Tata Steel. With the shape of iron ore pellets being fairly round, the pellets are chosen to be simulated as spheres. This can prevent excessive simulation times when large bulk quantities of pellets are to be placed in transfer chute simulations. With sinter particles being very sharp and rough and having no round shape whatsoever, the model of a sphere is less accurate. In order to get more accurate bulk behavior, it is decided to model sinter particles as an irregular shape, despite the added simulation computation times. A three-spherical shape (see Figure 5.3) is chosen to have the minimum amount of shapes per particle, while eliminating the natural inclination for rolling that a single sphere has.

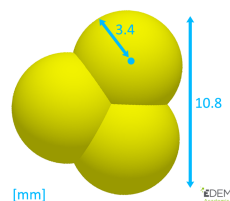


Figure 5.3: Three-spherical model for sinter particle

Reference case calibration parameters

The values that are picked for the reference case along with their source is listed in Table 5.4. The remainder of the simulation settings and material properties are listed in Appendix A. The friction coefficients for sinter in Table 5.4 are selected slightly lower than the literature [40][41], where spherical particles were calibrated as opposed to the irregular sinter particles in this research. No literature is found for the interaction coefficients between sinter and rubber and are therefore estimated.

Calibration parameters	Pellets value	Sinter value	Source pellets / sinter
• Static friction particle - particle [-]	0.45	0.3	[31], [42] / [40], [41]
• Rolling friction particle - particle [-]	0.15	0.2	[31], [42] / [40], [41]
• Static friction particle - steel [-]	0.5	0.5	[39], [42] / [40], [41]
• Rolling friction particle - steel [-]	0.25	0.2	[39], [42] / [40], [41]
• Static friction particle - rubber [-]	0.71	0.5	[39], [42] / *
• Rolling friction particle - rubber [-]	0.29	0.4	[39] / *
• Particle density [kg/m ³]	3700	2650	[31], [42] / [42]

Table 5.4: Reference case calibration parameters (*explained in text)

5.2.3. Calibration procedure

A calibration with multiple variables can be complex and call for a design of experiments methodology to find the factors of influence on the results. However, with the effects of the parameters used as variables being known, and due to constraints in time, a design of experiments is foregone and from a reference case a manual calibration process through trial and error is adopted.

The reference case is run through a simulation and the results are compared with the performance indicators determined in the experiments. Then the calibration parameters are adjusted according to the type and extend of the deviations found between experiment and simulation results. These parameters can be increased when a certain behavior in simulations is found, which is described in Table 5.5. Since some adjustments can be made in similar situations, one has to be chosen. One type of behavior that can lead to an increase in all variables, apart from particle density, is the biggest shift in material happening too late in the simulation. With this knowledge, combined with proper analysis of the simulations, a calibration using trial and error is performed.

Calibration parameters	Value increased in simulation when
• Static friction particle - particle	First mat-mat shift is too late and/or when AoRs are too low
• Rolling friction particle - particle	First mat-mat shift is too late and/or when AoRs are too low
• Static friction particle - steel	First mat-plate shift is too late and/or the top bin is empty too early
• Rolling friction particle - steel	First mat-plate shift is too late and/or the top bin is empty too early
• Static friction particle - rubber	First mat-plate shift is too late and/or the top bin is empty too early
• Rolling friction particle - rubber	First mat-plate shift is too late and/or the top bin is empty too early
• Particle density	Bulk density is too low

Table 5.5: Calibration parameters and their corresponding adjustment reasoning (mat = material, par = particle, AoR = angle of repose)

5.3. Calibration process

In Table 5.6 the trial and error calibration process steps for iron ore pellets with a steel inclined surface tester bottom is shown. Simulation 1 starts with the reference case data and the results are compared with the experimental results, with the aim of getting the simulation results within the range of the 95% CI experimental results. Almost all results are too high and therefore friction coefficients need to be lowered, where in this case the static inter-particle friction and the static ore-steel friction is chosen. Simulation 2 already shows results much closer to the experiments with regards to the ore-steel interaction. Still the AoRs and the first mat-mat shift is too high, so the static inter-particle friction is slightly lowered for the next simulation. Simulation 3 has most performance indicators within range, with only a notable discrepancy with the empty box inclination angle. This phenomenon is traced back to the last stage of the emptying of the box, where the particles are dispersed and only a single or double layer of particles is left. This most likely causes the particles to slide easier than in the experiments. With a focus on the bulk material dynamics, this is deemed less significant than the earlier phase of the test. Also the final AoRs vary from the experiments, which is most likely due to an imperfect model of the the plastic container bottom of the bottom bin. Therefore the first AoR in the simulations is taken to be more representative than the final two AoRs. The third simulation is repeated three times to verify the calibration simulation results. The 95% CI is calculated from this and is shown in Table 5.6 under Sim 3. The thought process for the remainder of the calibrations is similar, of which the resulting tables can be found in Appendix C.

Calibration parameters		Sim 1	Sim 2	Sim 3
• Static friction particle - particle [-]		0.45	0.35	0.3
• Rolling friction particle - particle [-]		0.15	0.15	0.15
• Static friction particle - steel [-]		0.5	0.3	0.3
• Rolling friction particle - steel [-]		0.25	0.25	0.25
Performance indicators	Experiments			
• First angle of repose, Φ_1	30.9 $\pm$ 0.2	34.4	33.2	30.7 $\pm$ 0.3
• Inclination angle at first mat-mat shift	8.4 $\pm$ 0.3	13.8	9.6	9.0 $\pm$ 0.7
• Inclination angle at first mat-plate shift	11.3 $\pm$ 1.9	18.7	10.1	9.2 $\pm$ 0.6
• Inclination angle at biggest mat shift	14.3 $\pm$ 1.2	19.6	15.4	14.7 $\pm$ 0.2
• inclination angle at empty top box	22.4 $\pm$ 0.2	24.5	19.7	<u>19.7 $\pm$ 0.1</u>
• Second angle of repose, Φ_2	22.8 $\pm$ 1.6	29.5	24.6	24.6 $\pm$ 1.0
• Third angle of repose, Φ_3	32.2 $\pm$ 0.7	41.5	36.9	<u>34.2 $\pm$ 0.3</u>

Table 5.6: Calibration process iron ore pellets - steel

5.4. Results

A comparison of the experimental and calibrated model results are shown in Table 5.7. In Figure 5.4 and visual comparison can be found between experiment and simulation of the first angle of repose.

Performance indicators	Iron ore pellets - Steel		Iron ore pellets - Rubber	
	Experiment	Simulation	Experiment	Simulation
• First angle of repose, Φ_1	30.9 $\pm$ 0.2	30.7 $\pm$ 0.3	32.9 $\pm$ 0.3	32.8
• Inclination angle at first mat-mat shift	8.4 $\pm$ 0.3	9.0 $\pm$ 0.7	9.0 $\pm$ 0.8	9.5
• Inclination angle at first mat-plate shift	11.3 $\pm$ 1.9	9.2 $\pm$ 0.6	13.5 $\pm$ 2.1	13.1
• Inclination angle at biggest mat shift	14.3 $\pm$ 1.2	14.7 $\pm$ 0.2	14.2 $\pm$ 1.0	15.3
• inclination angle at empty top box	22.4 $\pm$ 0.2	<u>19.7 $\pm$ 0.1</u>	23.9 $\pm$ 0.6	24.2
• Second angle of repose, Φ_2	22.8 $\pm$ 1.6	24.6 $\pm$ 1.0	19.7 $\pm$ 1.8	<u>24.1</u>
• Third angle of repose, Φ_3	32.2 $\pm$ 0.7	<u>34.2 $\pm$ 0.3</u>	29.6 $\pm$ 1.9	<u>34.6</u>

Performance indicators	Sinter - Steel		Sinter - Rubber	
	Experiment	Simulation	Experiment	Simulation
• First angle of repose, Φ_1	35.9 $\pm$ 0.4	35.4	35.2 $\pm$ 0.4	35.1
• Inclination angle at first mat-mat shift	13.8 $\pm$ 0.5	13.9	13.3 $\pm$ 1.5	13.1
• Inclination angle at first mat-plate shift	18.2 $\pm$ 0.7	<u>20.5</u>	22.2 $\pm$ 2.4	23.8
• Inclination angle at biggest mat shift	23.1 $\pm$ 0.7	23.0	28.3 $\pm$ 1.8	27.1
• inclination angle at empty top box	31.3 $\pm$ 0.2	<u>30.2</u>	35.1 $\pm$ 0.5	35
• Second angle of repose, Φ_2	32.1 $\pm$ 1.5	<u>38.0</u>	27.8 $\pm$ 0.9	<u>36.5</u>
• Third angle of repose, Φ_3	34.9 $\pm$ 1.3	34.2	33.6 $\pm$ 0.7	<u>41</u>

Table 5.7: Comparison of experimental and calibrated model results

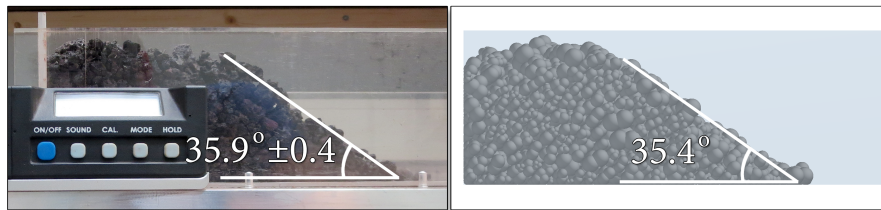


Figure 5.4: Comparison of first angle of repose, Φ_1 , in experiment and simulation

The performance indicator results that fall outside the experimental data range are indicated with a red underline in Table 5.7. The focus for the calibration was put on the first angle of repose and the four dynamic indicators, whereas the last angle of repose was secondary due to the inaccuracy of the bottom bin parameters. The final calibrated parameters are shown in Table 5.8.

Calibration parameters	Iron ore pellets	Sinter
• Static friction particle - particle [-]	0.3	0.25
• Rolling friction particle - particle [-]	0.15	0.15
• Static friction particle - steel [-]	0.3	0.5
• Rolling friction particle - steel [-]	0.25	0.3
• Static friction particle - rubber [-]	0.4	0.6
• Rolling friction particle - rubber [-]	0.29	0.5
• Particle density [kg/m ³]	3700	2850

Table 5.8: Results calibration parameters

5.5. Discussion

While good agreement with the experimental results is found in the simulations, a sensitivity analysis of the calibration parameters and their level of influence using a design of experiments can be very useful in a more accurate calibration. The bottom bin angle of repose is deemed not a good indicator. This is not only because in this research the plastic bin was not calibrated. It is found that the bottom surface of the receiving bin was very bouncy for the iron ore pellets and sinter used and caused the material to spread out very wide within the bin, as seen in Figure 5.5. The irregular shape of the iron ore and sinter in reality caused them to bounce in every direction, which was not possible to replicate in the simulations. Another factor making these angle of repose measurements difficult is the speed increase in the material throughout the dropping time into the bin, as depicted in Figure 5.6. Notice the increase in speed as well as the more forward trajectory of the particle stream.

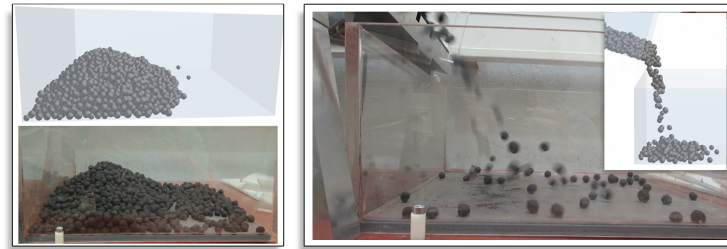


Figure 5.5: Difference in dispersion of iron ore pellets in bottom bin (left), Bounciness of plastic in bottom bin not present in simulation (right)

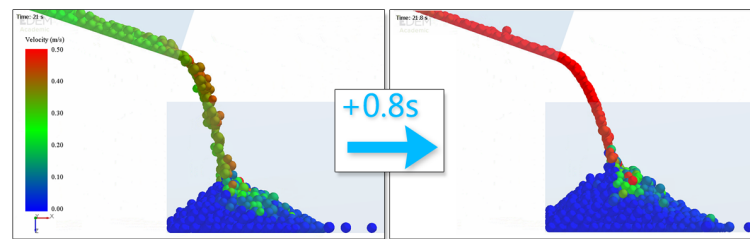


Figure 5.6: Material trajectory difference 0,8s apart

In reality this caused the material to spread out even more, making a less distinctive material cone. In the simulation a similar phenomenon occurred, but the cone stayed more compacted, most likely due to a higher friction of the bottom surface. This results in higher angle of repose recorded in the simulations compared to the experiments. Another caveat in the validity of the angle of repose measurements is the high ratio of the particle size to the height of the material piles which make it difficult to get an exact measurement. This effect is visible in Figure 5.4. Finally, the camera perspective distortions could have a minor impact on the experimental results.

5.6. Conclusions

In this chapter the following research question was posed:

- *How to calibrate bulk materials for dynamic simulations like transfer chutes?*

A dynamic calibration of iron ore pellets and sinter is performed on an inclined surface tester with steel and rubber surfaces. This test setup is suitable to get static indicators in the form of angles of repose, while simultaneously record dynamic flow behavior when time is a factor. Verification of the simulations was done by comparing results of three repeated simulations. The trial and error methodology used leaves sensitivity analyses and the level of influence each parameter has out of the calibration process, which is a strong recommendation for future research. Eight performance indicators are used in combination with six calibration parameters, and while good agreement was found between experimental and simulation results, not all parameters are calibrated within the experimental range of results. The bottom bin angle of repose are not prioritized due to several reasons, outlined in Section 5.5.

6

DEM analysis Tata Steel chute

In this chapter the aim is to answer the following research question:

- *Where along the material stream in a transfer chute at Tata Steel is potential dust creation and liberation and what is the influence of different materials and mass flow rates in DEM software on this problem?*

The key performance indicators, KPIs, used to investigate the DEM chute model are explained in Section 6.1. The geometry modeling and simulation setup for the DEM simulations of the Tata Steel case study chute is expanded on in Section 6.2. Results of the simulations performed, along with discussion and conclusions is shown in Section 6.3, 6.4 and 6.5 respectively.

6.1. Key performance indicators

With the dynamically calibrated material models for iron ore pellets and sinter from Chapter 5, the material flow through the case study transfer chute at Tata Steel is simulated using DEM software. The influencing factors in the creation and propagation of dust is found in Chapter 2 to be:

- Minimize material impact
- Minimize free fall of material
- Compact containment of flow stream

To find where these factors are present in the current chute design, key performance indicators, or KPIs for short, are defined for quantification of the dust liberation potential. These primary KPIs are listed below along with a short description:

- Velocity fluctuations in material flow
 - General overview of the 'smoothness' of the flow, big fluctuation spikes indicate impacts
- Impact velocity and reaction force
 - Calculates the impact normal reaction force for quantification
- Bulk density along material trajectory
 - Measures the compactness of the material along its trajectory, where bulk density drops indicate air entrainment potential

From Section 2.2 many other chute design objectives should be met for a properly functioning chute. Therefore the following, secondary KPIs are introduced for comparison with the redesign and for a better understanding of the quality of the simulation model.

- Belt center loading
- Segregation
- Chute wear

6.2. Simulation setup

Geometry

With the aid of design drawings from Tata Steel and the use of on site measurements, a close approximation of the case study transfer chute geometry is made. To convey the layout of the A317 movable transfer chute, Figure 6.1 depicts the Tata Steel design drawings of the chute, along with pictures of the current state. The design drawing is edited to represent the current situation, since many adjustments have been made on the design throughout its operation. The head chute (blue in Figure 6.1) has a v-shaped impact plate inside and moves with the drive pulley and the top belt, A317, over a rail (green in Figure 6.1) to locate itself above one of the bottom belts. Stationary deflector plates above each bottom belt help to guide the material onto these belts.

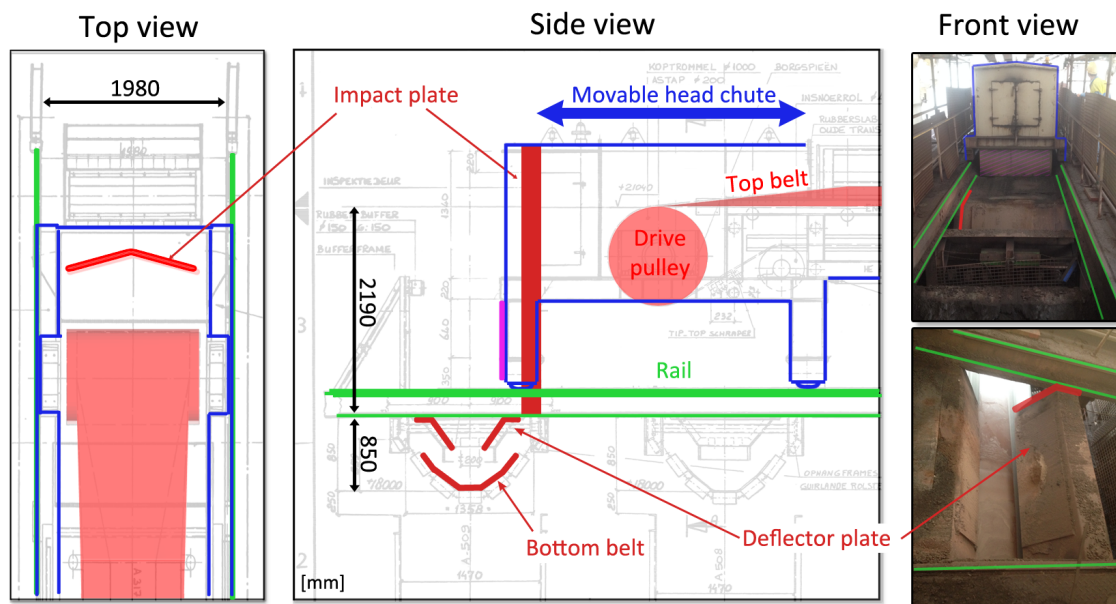


Figure 6.1: Schematic overview of the chute geometry configuration of the A317 case study chute with two of the three bottom belts. A509 and A508 depicted underneath

The geometry created in EDEM features only the parts of the geometry that are in contact with the material, which are all the parts indicated in red in Figure 6.1. The geometry as created in EDEM with a completed simulation of the material flow is shown in Figure 6.2.

Simulation

As shown in Figure 3.4, the case study chute transports material from one or two bunkers simultaneously, which translates to a mass flow rate of 800 t/h and 1600 t/h. Table 3.4 shows that the case study chute transports iron ore pellets, sinter, cokes and iron ore mixtures, of which iron ore pellets and sinter have been calibrated in Chapter 5. In order to assess the influence of different materials and different flow rates on the KPIs, there will be four simulations that will be run with the following combinations:

- Iron ore pellets with a 800 t/h mass flow rate
- Sinter with a 800 t/h mass flow rate
- Iron ore pellets with a 1600 t/h mass flow rate
- Sinter with a 1600 t/h mass flow rate

To achieve a continuous flow of bulk material from the top belt onto the bottom belt with the smallest amount of particles in the simulation to limit computation time, only a very short part of the belts is modeled. The placement of a particle factory at the top belt is at a distance from the pulley such that the material is settled on the belt before discharge. The high density of sinter required a larger shaped particle factory and a higher speed at creation for the flow rate of 1600 t/h to be achieved, as depicted in Figure 6.2. Mass flow rate sensors at the discharge and bottom belt are placed and when at both points the flow is constant at the desired flow rate, the simulation is stopped. In Figure 6.2 this is depicted in the graph which shows the 800 t/h simulations for iron ore and sinter.

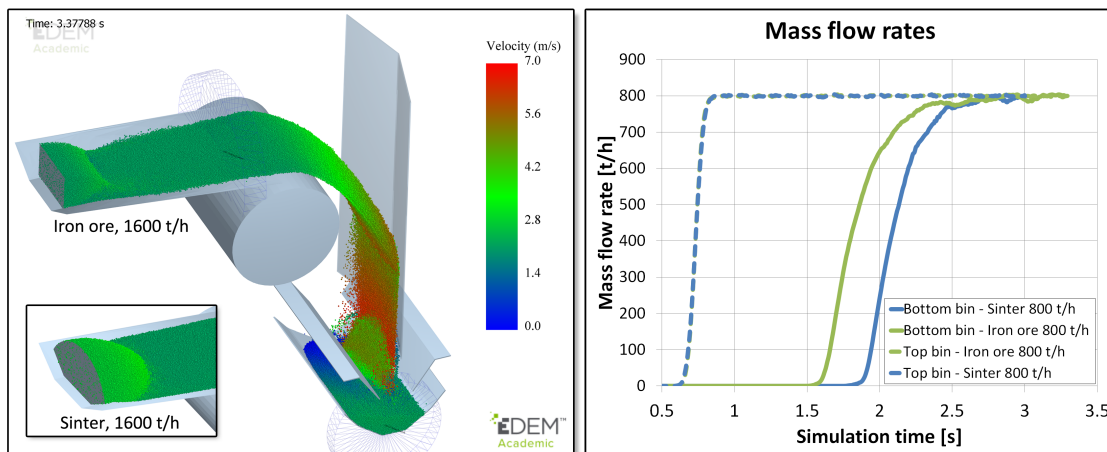


Figure 6.2: Case study chute simulation, particle factories (left), mass flow rate sensor data (right)

It can be seen from the mass flow data on the left in Figure 6.2 that both bottom bins reach the same flow rate of 800 t/h that is measured before discharge and therefore continuous flow is achieved without spillage, similar to what is observed at Tata Steel. The impact point on the impact plate is measured at 1.6 m downwards from the top of the discharge pulley, which is close to what is measured inside the chute at Tata Steel, although measuring this point in real life presented accuracy problems. The wear and material residue found on the deflector plate, as shown in Figure 6.1 on the bottom left image, is also found in the simulations, as shown in the results in the next section.

6.3. Methodology and results

This section presents the methodology and underlying theory for the chosen KPIs alongside the results from the simulations.

6.3.1. Velocity fluctuations

To graphically represent the bulk material speed as it navigates through the chute, the average velocity of a small selection of particles is tracked. The results are presented in Figure 6.3, along with a visual aid of the side view of iron ore pellets at 800 t/h.

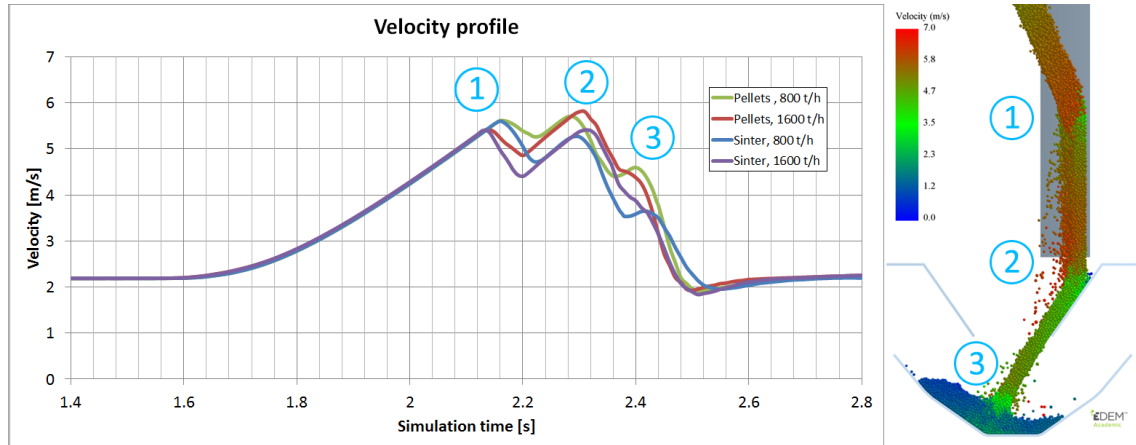


Figure 6.3: Graph of average velocity profile of a small material selection (left), side view of pellets, 800 t/h (right)

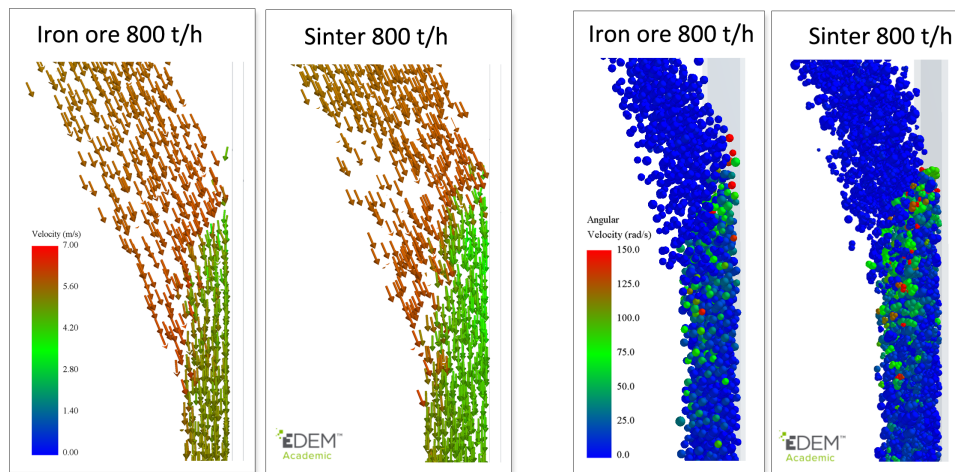


Figure 6.4: Vector plot comparison of cross-sectional slice of the material stream in contact with impact plate (left), angular particle velocity comparison (right) with rotation around the horizontal axis parallel to impact

As can be seen in Figure 6.3, the particles are part of a continuous flow as it starts and ends at the same speed of the top and bottom belt at 2.19 m/s. Indicated in the graph and in the side view image in Figure 6.3, it can clearly be seen that there are three impacts that the material stream encounters throughout the chute, onto the impact plate, the deflector plate and the bottom belt respectively. The higher flow rate simulations reach the impact plate slightly earlier, since they have a 'taller' material stream cross-section. Sinter particles decelerate faster upon impact compared to iron ore, indicated by the steeper declines in the velocity profile. The high flow rate simulations, especially for sinter, show a very mild bump and no acceleration in the velocity profile at the third impact. A better view of the velocity difference at impact is displayed in Figure 6.4, while the difference at the third impact is shown in Section 6.3.4, where results on belt loading aspects are presented. The vectorplots on the left in Figure 6.4 show a larger deceleration at impact, which is less prevalent in particles furthest from the impact plate. The stream thickness after impact is significantly

smaller for iron ore. Angular velocities (Figure 6.4, right) show little difference, besides a more defined line where particles rotate, 'splitting' the stream before and after impact sideways.

6.3.2. Impact velocity and force

To quantify the level of impact that occurs in the simulations, a method presented by Korzen [43] is used, also exemplified in an impact research performed by Wypych et al. [44]. It uses the impulse-momentum equation to calculate the magnitude and direction of reaction forces exerted by bulk material striking a flat surface. Figure 6.5 shows a schematic drawing of the forces present at impact.

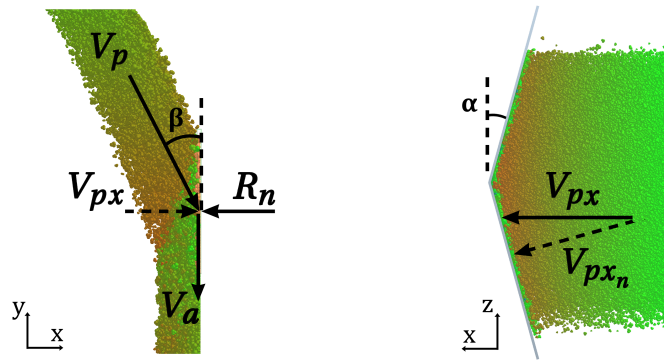


Figure 6.5: Schematic drawing of forces present at impact (left: side view, right: top view)

The impulse-momentum is given by

$$\sum F = (\vec{V}_p - \vec{V}_a) m_s \quad (6.1)$$

where V_p and V_a are the incoming and outgoing bulk velocities respectively and m_s the mass flow rate. The normal reaction force is determined from this theory to be [43][44]

$$R_{nx} = (\rho_b A_p V_p) V_{px} = m_s V_{px} \quad (6.2)$$

Where ρ_b is the bulk density and A_p the cross-sectional area of the incoming particle stream. This equation is adjusted for the angles α and β , shown in Figure 6.5, to yield the normal reaction force to the impact plate

$$R_n = m_s V_{px} \sin \beta = m_s (V_{px_n} \cos \alpha) \sin \beta \quad (6.3)$$

The x-component of the stream velocity, V_{px} is extracted from the simulation using bins placed right above the impact location. The impact angle β was found to be 28° and the angle α from Figure 6.5 is 15.3° . The reaction forces are calculated using Equation 6.3 and displayed in Table 6.1. The same calculation is performed for the deflector plate, except the downwards velocity component, V_{py} , is extracted from the simulations. The angle the deflector plate makes with the material is 35° , ultimately finding the normal component of the velocity to the deflector plate, V_{py_n} . The same mass flow rates are found when measurements are conducted right before impact on the deflector plate.

	Impact plate		Deflector plate	
	V_{px_n} [m/s]	R_n [N]	V_{py_n} [m/s]	R_n [N]
Pellets, 800 t/h	2.19	469	4.75	738
Sinter, 800 t/h	2.10	451	4.49	698
Pellets, 1600 t/h	2.28	976	4.94	1538
Sinter, 1600 t/h	2.26	970	4.63	1440

Table 6.1: Velocities normal to impact and reaction forces from impacts

From Table 6.1 it can be seen that the higher flow rates produce higher reaction forces, as can be expected. It is noted that the reaction forces for sinter are lower than for iron ore, with an increasing difference between them from impact plate to deflector plate.

6.3.3. Bulk density along material trajectory

Several bulk density sensors are positioned along the material stream at locations of interest. These locations are displayed in Figure 6.6 marked A to G. The sensors are small cubes with 70 mm sides, placed inside the material stream, ensuring they are completely engulfed by the stream. The locations are chosen right before and after free fall of material or before and after an impact.

A large decrease of over 60% bulk density is observed from the discharge to the impact plate, whereas the bulk density when the material slides alongside the impact plate is measured around 15%. It is also found that the bulk density increases shortly after the material impacts the impact plate and the deflector plate, with a noticeable difference between sinter and iron ore pellets for both flow rates, where sinter has a bigger bulk density increase.

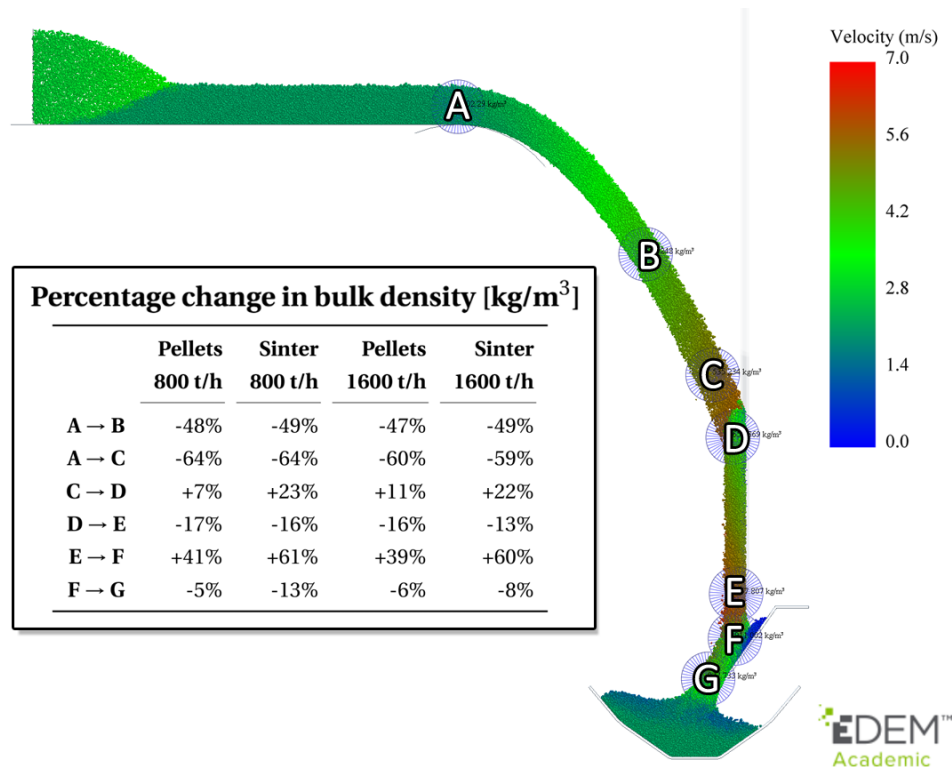


Figure 6.6: Results of bulk density variations along the material trajectory

6.3.4. Belt loading and segregation

To measure the extend of off-center loading in the simulations, the flow over the bottom belt is split through the middle using two bins (indicated in blue in Figure 6.7) and their mass over time is traced. The bins are placed as far away from the loading point as possible, to avoid interference of the loading phase on the measurement of the loaded belt further downstream. After steady, continuous flow is reached in the simulations, the average of the measured mass in that phase is recorded. The results, alongside side view images of each simulation configuration are presented in Table 6.2 and Figure 6.7.

Looking at the material on the bottom belt, it can be seen that the color of the material corresponds with the belt speed of 2.19 m/s. Figure 6.7 indicates that there is a significant off-center belt loading present in the simulations. This is corroborated and quantified by the ratios in Table 6.2, showing a big increase in off-center belt loading with 800 t/h simulations as opposed to the higher flow rate, while only a very minor increase in iron ore as opposed to sinter.

The same bins are also used to measure the average particle mass in each bin over time. The average of the continuous flow phase is taken for each result. The results are presented in Table 6.3.

	Ratio left : right
Iron ore, 800 t/h	2.69 : 1
Sinter, 800 t/h	2.58 : 1
Iron ore, 1600 t/h	1.76 : 1
Sinter, 1600 t/h	1.42 : 1

Table 6.2: Mass distribution ratio of left to right bin

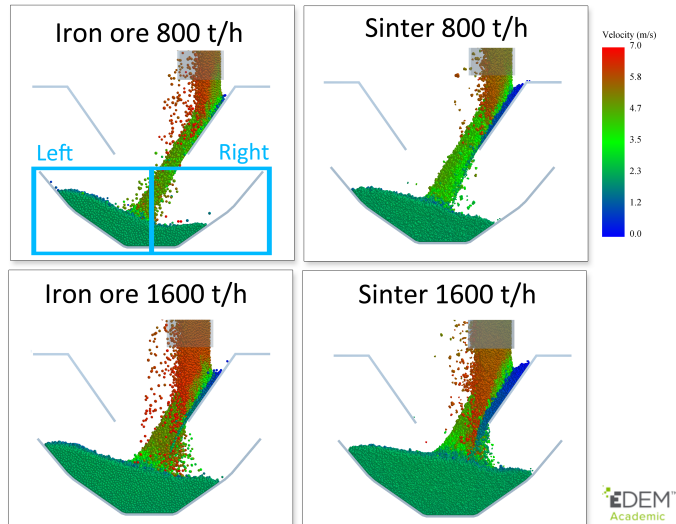


Figure 6.7: Comparison of belt loading of each simulation

	Left bin	Right bin
Pellets, 800 t/h	51.8%	48.2%
Sinter, 800 t/h	51.5%	48.5%
Pellets, 1600 t/h	50.0%	50.0%
Sinter, 1600 t/h	49.9%	50.1%

Table 6.3: Percentage of average particle mass, segregation results

6.3.5. Chute wear

Using the Hertz-Mindlin geometry contact model with archard wear provides a relative measurement of the archard wear on the chute geometry. The geometries that are checked for wear are meshed in ANSYS using CFD-fluent mesh with high smooth sizing and a max face size of 6 mm [12]. The archard equation for the volume of material removed, Q is defined as [45]

$$Q = W F_n d_t \quad (6.4)$$

Where F_n is the normal force, d_t is the tangential distance moved and W is a wear constant, which is equal to a dimensionless constant divided by a hardness measure of the softest surface. W is the input for EDEM and is kept constant for both materials at 1 Pa^{-1} , since the wear results will only be used as an indication of wear locations and for relative quantification. The normal force F_n is a function of the overlap δ_n and is calculated by the Hertz-Mindlin contact model in EDEM along with a corresponding damping force F_n^d using

$$F_n = \frac{4}{3} E^* \sqrt{R^*} \delta_n^{\frac{3}{2}} \quad (6.5)$$

$$F_n^d = -2 \sqrt{\frac{5}{6}} \beta \sqrt{S_n m^*} v_n^{rel} \quad (6.6)$$

Where E^* is the equivalent Young's Modulus given by $1/E^* = (1 - \nu_i^2)/E_i + (1 - \nu_j^2)/E_j$, R^* is the equivalent radius which is equal to $1/R^* = 1/R_i + 1/R_j$, and $m^* = (1/m_i + 1/m_j)^{-1}$ is the equivalent particle mass, where E_i , ν_i , R_i , m_i and E_j , ν_j , R_j , m_j are the Young's Modulus, Poisson ratio, radius and mass of each sphere in contact with another respectively. When a particle-wall interaction is calculated, the wall radius becomes $R_j = \infty$ and therefore $R^* = R_i$, which similarly makes $m^* = m_i$ the equivalent mass. v_n^{rel} is the normal component of the relative velocity and β and the normal stiffness S_n are given by

$$\beta = \frac{-\ln C_R}{\sqrt{\ln^2 C_R + \pi^2}} \quad (6.7)$$

$$S_n = 2E^* \sqrt{R^* \delta_n} \quad (6.8)$$

With C_R being the coefficient of restitution between the interacting entities.

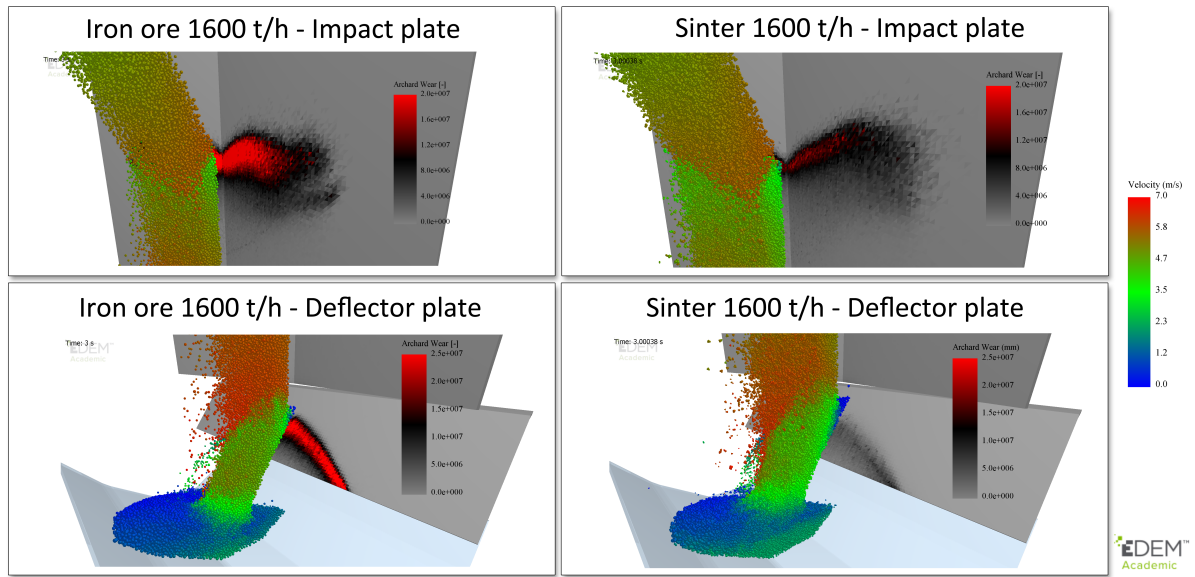


Figure 6.8: Relative archard wear comparison of the chute's impact plate and deflector plate, with a cross-section view of the material stream

	Impact plate	Deflector plate	Bottom belt
Pellets, 800 t/h	2.30	1.53	0.53
Sinter, 800 t/h	1.38	0.52	0.17
Pellets, 1600 t/h	3.33	1.88	0.76
Sinter, 1600 t/h	1.83	0.52	0.20

Table 6.4: Normalized wear gradients

The wear that results from these calculations in EDEM is depicted in Figure 6.8 as a comparison between iron ore and sinter. Surprisingly the relative wear in iron ore appears more pronounced than its sinter counterpart, which is contradictory to what is experienced in the industry. From the impact plate wear, it is noted that the wear pattern is thicker in the flow direction. The cross-section of material on the deflector plate shows that there is a layer of sinter particles in contact with the plate that is not moving (blue particles), an effect that is much less pronounced in iron ore, if present at all.

To compare all configurations in regards to wear, the graphs for archard wear are studied. When graphed, the archard wear progresses in a linear fashion. The gradient of this linear path is extracted and presented in Table 6.4. The wear increases with increased flow rates, except for sinter on the deflector plate and bottom belt, the latter showing only a very minute increase.

6.4. Discussion

This section discusses the KPI results and their validity, while trying to understand what happens in the simulations.

- The results suggest that the modeled sinter tends to build up material at impact zones, where iron ore flows more fluidly. This is evidenced by the higher deceleration of sinter at the impact plate and deflector plate as compared to iron, as well as double the bulk density increase at these locations. The explanation for this speed decrease and compacting can be the higher friction coefficients sinter has to steel. Another reason can be the irregular particle shape of sinter particles that causes them to bounce away from the bulk stream direction, creating more inter-particle bounces that obstruct the steady material stream as well as slow the particles down by loss of energy.
- At the deflector plate the brunt of the impact shifts from particle-to-wall towards particle-to-particle, since a stagnant layer of sinter particles resides on top of the deflector plate (shown in Figure 6.8), protecting the plate from archard wear.
- The analytical calculation for the impact forces on the impact plate and deflector plate show that the deflector plate suffers around 2.7 times the impact force compared to the impact plate, due to the higher angle it makes with the material stream and the much larger impact velocity the material has at that area. Only at the deflector plate in sinter at 1600 t/h this is less extreme, due to the relatively low incoming velocity of the material caused by the impact at the impact plate discussed in the first point.
- The wear results at the impact plate are much lower for sinter than for iron ore, which does not reflect reality. This seems strange, since the higher friction coefficients for sinter and the irregular particle shape should cause more sliding along steel plates compared to the spherical pellets. Tests with one particle show that the irregular shape of sinter lowers the wear results significantly when compared to a spherical model of sinter. From Equation 6.5 this relationship shows a higher R^* leading to a higher F_n , which increases wear. The much higher density of iron ore pellets in the model also contribute to the higher wear, looking at the m^* in Equation 6.6. A final contributor can be the bulk behavior of sinter, which slows down upon impact and could therefore have a slightly different particle trajectory with less tangential distance moved along the impact plate (d_t in Equation 6.4). This is a minor contribution however, if at all, considering this altered trajectory is not seen in the vector plots in Figure 6.4.
- wear at deflector plate has an even larger decrease in wear in sinter compared to iron ore, especially in the higher flow rates. This increase in difference is caused by the bulk behavior of sinter, that has a layer of particles that almost completely stop flowing on the surface of the deflector plate. This significantly reduces the wear, since there is less sliding per time step over the deflector plate.
- The material trajectory modeled only takes into account inter-particles forces and gravity, while ignoring other influencing forces such as air resistance [34], which can lead to discrepancies between the model and reality.
- The higher flow rate configurations cause less velocity fluctuations in belt loading, which is caused by a higher pile of material on the belt, making the free fall of material very short.
- The wear pattern as well as the stagnation of particle velocity on the deflector plates reflects the wear and material residu found at Tata Steel. The particle residu can be seen in Figure 6.1. The off-center belt loading is far less pronounced in real life. This is most likely caused by
 - Material buildup and wear deformation of geometry elements
 - Unknown exact dimensions of this section of the chute geometry
 - The material settles further along the bottom belt trajectory due to belt vibrations
 - Calibration of material and/or rubber could be inaccurate due to their unrealistic particle shape or properties
- The segregation in the model is also less pronounced when compared to reality (for reference, see Figure 2.5, top right), which can be caused by discrepancies between PSDs in the model compared to reality, the (three-)spherical particle shape of iron ore and sinter behaving different from reality, or a slight difference in material stream from anomalies in the geometry

6.5. Conclusions

This chapter answers the following research question:

- ***Where along the material stream in a transfer chute at Tata Steel is potential dust creation and liberation and what is the influence of different materials and mass flow rates in DEM software on this problem?***

In this chapter simulations on the case study chute at Tata Steel have been performed with iron ore pellets and sinter of 800 and 1600 t/h. Results of three KPIs that indicate either air entrainment or dust liberation have been analyzed, leading to the following conclusions:

- Three impact zones that have potential dust liberation, with the material impacting the impact plate, the deflector plate underneath the impact plate and the receiving belt.
- Free fall sections from discharge till impact plate and from impact plate till deflector plate show a lowering of bulk density of the material stream, suggesting potential air entrainment.
- Simulations show highest material velocity fluctuation and highest bulk density change at the deflector plate impact, making it the most problematic area for dust liberation according to the simulation.
- The DEM model for sinter shows more compacting of material in comparison to iron ore pellets, likely due to higher friction coefficients with the steel chute and an irregular particle shape hampering sliding and rolling.
- A higher flow rate softens the material impact at the bottom belt due to the higher material bed on the belt, preventing the material to speed up and spread in free fall.

With the identification of problem areas in regards to the dust liberation problem at the A317 chute at Tata Steel using DEM simulations, the next step is to design a new chute configuration where these problems are addressed.

7

Redesign proposals

In this chapter all the knowledge gathered from the literature study on chute design is combined with the findings from the existing transfer chute into redesign proposals for the case study chute. Three conceptual designs are proposed and analyzed to make a preliminary selection on a conceptual redesign.

These new designs are tested for the same performance indicators as the existing chute to compare their performance. This will result in recommendations for the redesign of the case study chute at Tata Steel. The research question that this chapter answers is therefore:

- *What does a redesign for a Tata Steel transfer chute to minimize dust creation and liberation look like and what can be the quantifiable improvements to the original design?*

7.1. Conceptual redesign proposals

From the analysis of the current case study transfer chute at Tata Steel in Chapter 6, the design objectives of the redesign are summarized as follows:

- Minimize the number of impacts and impact forces
- Minimize the amount free fall in the material stream
- Improve center belt loading at the bottom belt
- Lower chute wear

The case study chute has many complicating factors in its requirements, of which most notable:

- Multi-material chute with large lump size difference
- Two different mass flow rates of 800 and 1600 t/h
- Movable top part of chute to load different bottom belts
- Bottom belts with different directions are to be loaded
- Limited space available

Using these design objectives and considerations, three concept proposals are made. Substantiated by analytical findings, one concept is chosen for a simulation to compare with the current case study chute. Sinter at 800 t/h and 1600 t/h is chosen for the simulation, considering the greater differences in flowability compared to iron ore pellets, which resulted in higher bulk density and velocity fluctuations. While the simulation time for sinter at 1600 t/h is the highest, it is also the most critical when it comes to ensuring flowability. Convergence in hood and spoon need to be validated along the most volumetric condition. Also the significant velocity difference between the bottom belt speed and the material stream when guided on this belt needs to be checked for potential spillage. The same KPIs will be used to evaluate the redesign and to compare them to the current chute. A schematic drawing of the three concept proposals is illustrated in Figure 7.1, which are explained in detail in the next subsections.

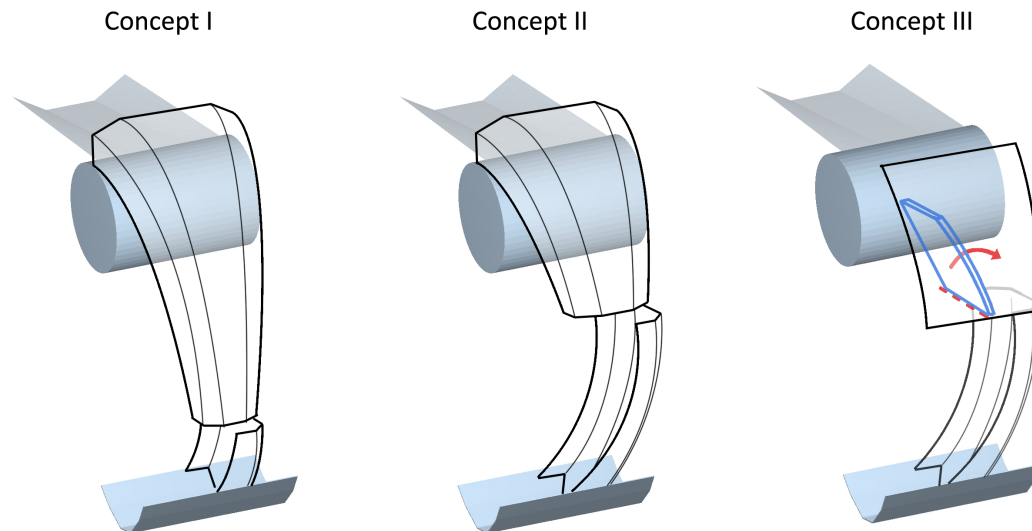


Figure 7.1: Schematic drawing of the three redesign proposal concepts

7.1.1. Redesign proposal I

Concept The first proposal that is made for the redesign is a hood and spoon concept. The hood is positioned on the movable top chute, whereas stationary spoons are fitted as a replacement for the deflector plate. The orientation of the spoons is in the direction of belt travel, which is different for one of the three bottom belts.

Dimensional constraints The current movable top chute has a height of 2.19m counting from the top of the discharging belt pulley downwards and one part with a height of 0.86m, taken from the bottom belt upwards, as seen in Figure 6.1. Also the space for a spoon along the bottom belt is limited to 1.98m, seen in the top view in the same figure. Hood and spoon designs generally have more available space [18][23], especially the spoon section.

Material trajectory Roberts' theory for transfer chute design [8][26], as laid out in Section 2.6, is used to calculate the characteristics of the hood and spoon.

Some validation calculations on the observations of the simulations are performed following Section 2.6, of which the results are presented in Table 7.1.

Description	Symbol	Value	Source
Material cross-sectional area	A	0.062 m ²	Equation 2.4
Material cross-section mean height	h	101 mm	Figure 2.15
Actual material height on belt	H	120 mm	Figure 2.15 & DEM simulations
Height to width ratio material cross-section	H/B	0.24	Section 2.6.2
Angle of discharge	θ	0	Figure 2.16 & DEM simulations

Table 7.1: Analytical calculation results pertaining the material trajectory

With a straight discharge, the material trajectory formula from Equation 2.6 is only dependent on the discharge velocity of 2.19 m/s. This is the material trajectory for the bottom of the stream, as seen in Figure 7.2 on the left, which is almost identical to the material stream found in DEM simulations. The simulated trajectory is slightly lower, which is most likely due to energy dissipation from inter-particle effects [34]. The top of the trajectory for sinter at 800 t/h is found by trial and error fitting the curve with the simulation. The resulting trajectories are presented in Figure 7.2 (left), along with their corresponding radii of curvature (right).

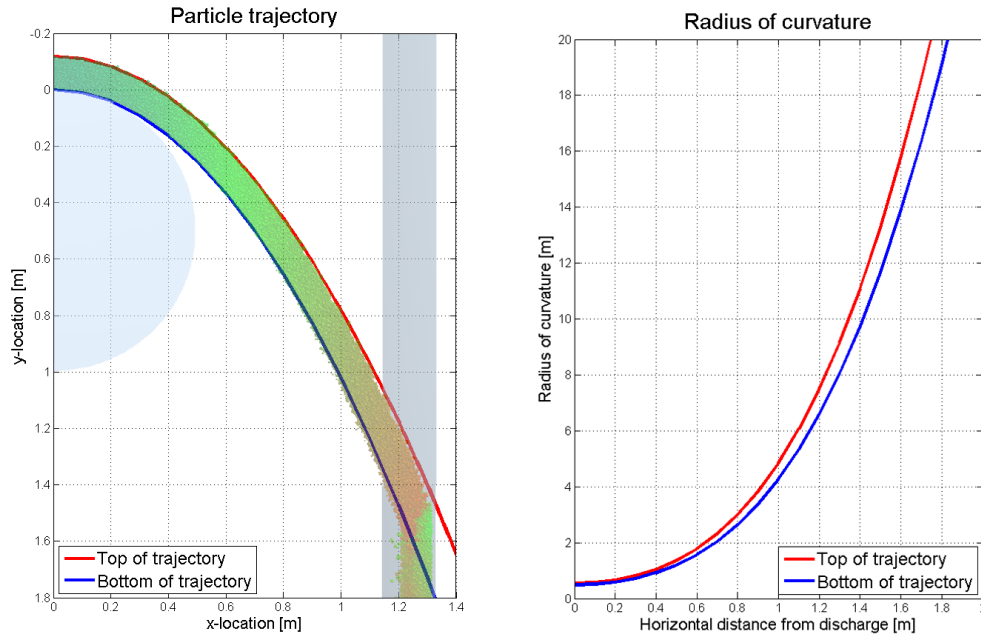


Figure 7.2: Calculated and simulation material trajectory (left), with corresponding radii of curvature (right)

It is noted that the radii of curvature become relatively high after only a short horizontal distance, which is due to the relatively low discharge speed.

Hood design The trajectories of all four simulation configurations in Chapter 6 are the same, apart from the cross-sectional material height. Therefore the hood shape calculation is applicable in all situations, provided that the hood needs to be adjustable in horizontal distance from the drive pulley to ensure no spillage occurs from materials flowing over the hood. This is already present in the case study chute with a manual lever, except this process will have to be automated given to frequency of different flow rates and materials transported through the chute. Considering cokes have the highest lump sizes, the minimum chute opening area is calculated for cokes from the equation in Figure 2.3, resulting in $A_{min} = 0.39 \text{ m}^2$. The main goal of the hood is

- To redirect the material stream straight downwards at the bottom for the spoon to catch
- To provide a minimal impact angle between material and chute
- To keep the stream compact for the perpendicularly orientated spoon to be able to catch all the material

The vertical space available for the hood is 2.19 m. Using this, combined with the radius of curvature and Equations 2.9 - 2.11, the radius size and x-position of a radius of curvature that has a y-position of 2.19 m is found, resulting in $R = 2.84 \text{ m}$, an x-position of the radius center at $x_c = -1.54 \text{ m}$. The x-position and the angle at point of contact are $x = 0.8 \text{ m}$ and $\theta_c = 35.5^\circ$ respectively. The minimum chute opening is met with these hood dimensions, but due to the low discharge speed, the chute hood still is relatively close to the drive pulley, making an adjustable hood an absolute necessity to prevent blockage for different flow rates and materials.

Since the spoon is orientated perpendicular to the material stream, it is important that the hood has some convergence to ensure the stream stays compact and all particles can land on the spoon. Simultaneously, the amount of convergence is limited due to the potential threat of pluggage. The next paragraph addresses this issue. The cross-sectional shape of the hood is chosen with a typical sharp-edged inward curve on the sides, which ensures the material stream stays compact and is still realistic to be constructed.

Spoon design and conclusion The self-cleaning check for the spoon yields $\Psi > 32^\circ$. Given limited vertical space for the spoon, the main problem is to ensure all the material from the hood exit will land on the spoon and not directly onto the bottom belt, as can be seen from the schematic drawing in Figure 7.1 on the left illustration. Considering only 0.86m is available, this is not possible in this design concept, even with an extreme convergence of the hood shape. Therefore this concept is not chosen and options involving a higher cut-off of the movable chute will need to be considered.

7.1.2. Redesign proposal II

Concept For the second design proposal, the possibility of a larger height for the spoon is investigated. Spoons are again fixed on top of the bottom belts, just as the current deflector plates, but are now higher than the rail of the movable chute (see Figure 6.1). The pink line in the side view and the hashed pink area in the front view picture indicates the area that is altered to ensure free movement of the chute. This metal plate is cut and outfitted with rubber flaps to keep the enclosure closed off while allowing the chute to move into position above a spoon. This metal plate does not compromise the structural integrity of the chute, as long as the horizontal I-beam right above this plate is left intact.

Hood design The hood height has to be shortened for this concept, where the cut-off is possible between 0.93 m and about 1.4 m from the discharge point, to ensure enough space for a spoon. The hood radius of 2.84 m from Concept I is used, but a straight vertical cut-off of the hood is not possible when the hood needs to be shorter. Therefore after the material is caught at $x = 0.8$ m, the hood bends along a second, smaller radius. A radius of $R_2 = 1.35$ m is chosen, which is the curvature of the material trajectory at $x = 0.5$ m. When the hood is pointing the material straight downwards, this radius is cut off, which is at a height of 1.27 m from the discharge point. It is noted that this multi-radius hood curvature will be difficult to implement in real life due to the difficulties in manufacturing these shapes, which needs to be taken into account in the assessment of the results compared to real life. A slight convergence of the hood shape is chosen to ensure the material stream stays compact and will be properly guided onto the spoon. The transfer rate of 800 t/h is not influenced by this convergence, since it is not more compact than the material on the top belt. To investigate if the convergence is of influence on sinter at 1600 t/h will have to be investigated.

Spoon design The vertical space left for the spoons is 1.76 m, accounting for a 10 mm gap between hood and spoon. Adhering to the self-cleaning spoon exit angle of 55° , trigonometry dictates a spoon radius of $R = 2.15$ m. Larger radii are not chosen, due to the relative short height of the spoon (despite its height increase for this concept) which will otherwise cause the material to barely touch the spoon and have a significant free fall height on one side. The width between the rails of 1.98 m (see Figure 6.1, top view) is another space constraint. The length of the spoon in bottom belt direction is 0.88 m, which is well within this space, since it is placed almost directly underneath the pulley to catch all the material from the hood. The spoon exit velocity will be much higher than the bottom belt velocity, which is similar to the current design. Simulations and verification and validation will have to be performed to ensure no spillage will occur from high flow rates and anomalies like surge flows. To prevent this phenomenon, a convergence in the spoon should be incorporated. In this design, a very minor convergence is implemented, with the spoon exit width of 0.8 m, which is still larger than the width of sinter at 1600 t/h on the top belt.

7.1.3. Redesign proposal III

Given the main problem in the redesign is the hood and spoon being perpendicular to each other, causing material to not fully land on the spoon slope. The third concept that is considered is therefore the incorporation of a flopper gate, as seen in Figure 2.14. The flopper gate is illustrated in blue on the right image of Figure 7.1. The difficulty in this design is the forward momentum of the material stream, which requires an impact plate or hood to redirect the stream downwards. When a stationary impact plate is chosen, the likelihood of material getting stuck in the gap between the flopper gate and the impact plate is very high. Another possibility could be to fix the impact plate to the flopper gate, but the dimensions for this concept will not be able to fit inside the hood and significantly increase the power required to move the gate. The complexity of this design with many moving parts, will be costly to manufacture. This complexity makes the chute concept also vulnerable to excessive maintenance. Therefore this concept is not chosen.

7.1.4. Redesign choice

To conclude, redesign proposal II is chosen, for the following reasons:

- The current available height between the bottom belt and the movable chute is too small to properly fit a spoon. Concept I is therefore not chosen, since the hood would direct material straight onto the bottom belt, instead of over the spoon.
- Concept III is not chosen due to the complexity of the design, being vulnerable to excessive maintenance and potentially costly construction

- Concept II fits a hood and spoon design where the whole material stream will be able to flow over the spoons, due to a higher cut-off of the movable head chute. The spoons will be able to redirect and load the material into the transport direction of the bottom belts, which is an ability that is absent in the current design.

7.2. Results

Velocity fluctuations In Figure 7.3 the velocity profile of sinter at the two different flow rates are compared to the case study results. It is noted that the material is caught by the hood earlier than the current impact plate, the maximum velocities have slightly increased, but decreases in velocity are less extreme.

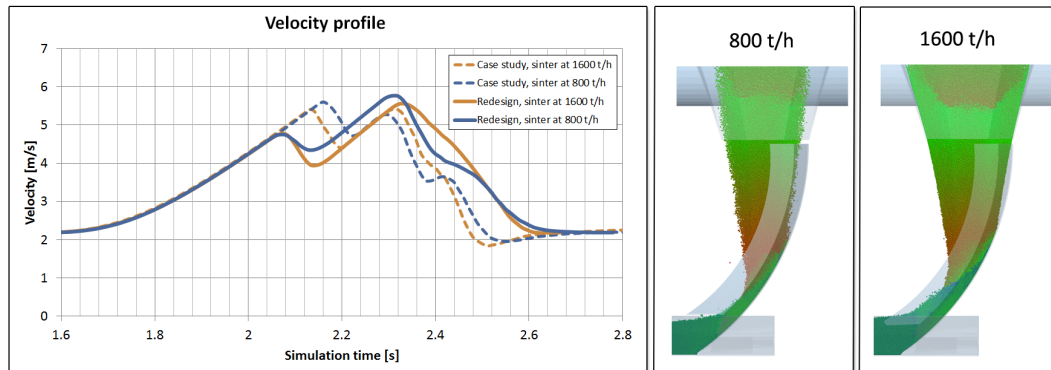


Figure 7.3: Comparison of velocity profile between current design and the redesign simulations

Impact velocity and force Due to the limited space available in the design of the A317 chute, a perfect tangent between the hood and the material was not achieved. On the middle and right in Figure 7.4, the velocities and reaction force when impulse-momentum of the impact are presented. The angle β in the figure is found by first locating the angle the material stream radius of curvature has at the impact point using the trajectory equations. This is then subtracted from the angle the hood radius curvature has at the same point. The impact point is approximated from the simulations, where conservative values are used in the calculations. Finally, the total particle velocity before impact, V_p , is used in conjunction with β and the mass flow rate to find the reaction force, R_n .

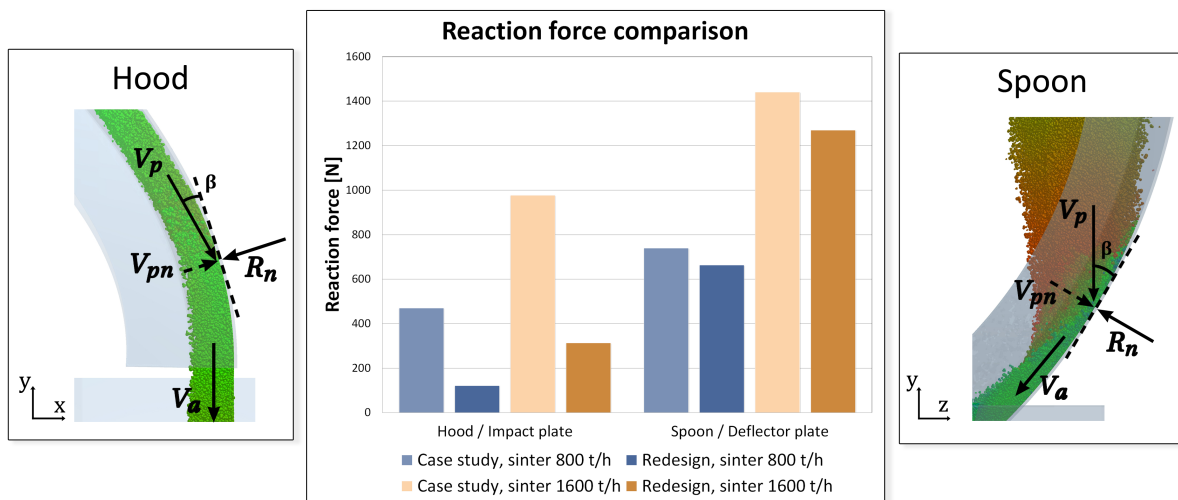


Figure 7.4: Comparison of reaction forces between current design and the redesign simulations (middle) and schematic of forces at impact on hood (left) and spoon (right)

As can be seen from the results on the right in Figure 7.4, the hood proves an extremely significant improvement in the reduction of the impact force, whereas the spoon provides a smaller impact reduction.

Bulk density Using bulk density bins in EDEM, an overview can be made of the change in bulk density along the material stream in the simulations. The results are presented in comparison with the sinter simulations of the case study chute in Figure 7.5

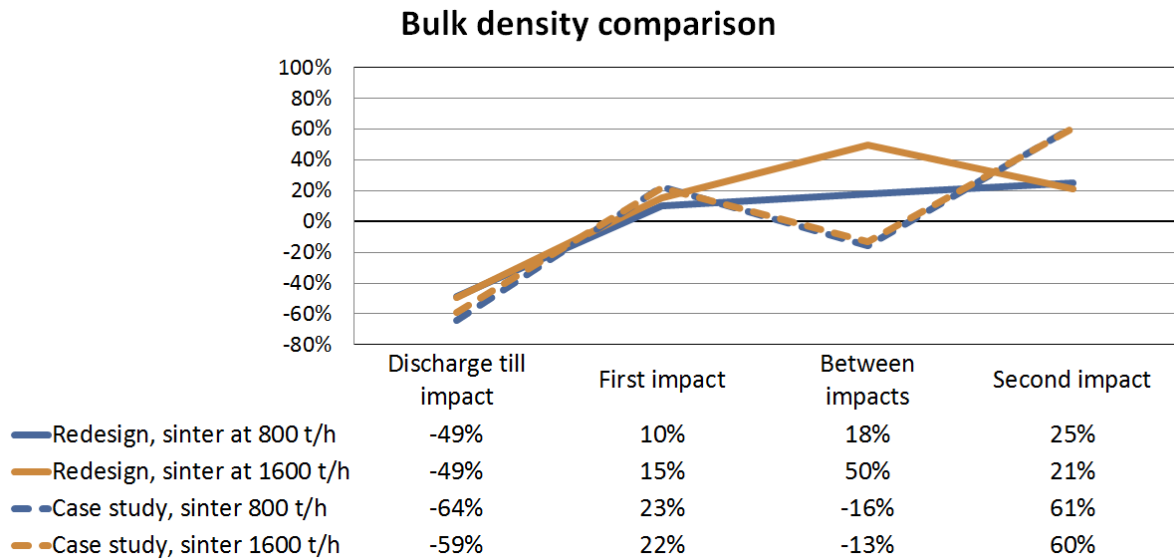


Figure 7.5: Comparison of bulk density percentage changes along the material stream

Belt loading and segregation The results of the KPIs to check the level of center belt loading and segregation are shown in Table 7.2, alongside Figure 7.6, which gives an impression of the belt loading of the redesign.

Table 7.2: Comparison of center belt loading and segregation

Case study	Total mass	Average particle mass	
	ratio left:right	Left bin	Right bin
800 t/h	2.58:1	51.5%	48.5%
1600 t/h	1.42:1	49.9%	50.1%
Redesign			
800 t/h	0.70:1	51.8%	48.2%
1600 t/h	0.89:1	50.3%	49.7%

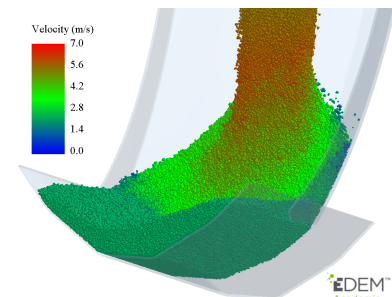


Figure 7.6: Isentropic view of 1600 t/h belt loading

Chute wear The normalized wear gradients are extracted in the same manner as the case study chute analysis and presented in Table 7.3

	Hood / Impact plate	Spoon / Deflector plate	Bottom belt
Case study, sinter 800 t/h	1.38	0.52	0.17
Redesign, sinter 800 t/h	1.38	5.1	0.042
Case study, sinter 1600 t/h	1.83	0.52	0.20
Redesign, sinter 1600 t/h	1.38	6.1	0.027

Table 7.3: Normalized wear gradients

7.3. Discussion

Analyzing the results of the redesign in comparison with the case study chute provides the following insights based on the KPIs:

- The hood is effective in decelerating the material more gently than the impact plate, judging from the less steep decline in the first 'hill' in Figure 7.3. This is much more prominent in the low flow rate simulation. The explanation to this is two-fold. The convergence of the hood causes the material to compact in the high flow rate simulation, affecting the flow speed to some degree. Also, a miscalculation caused the hood placement to be slightly too far away from the pulley in the high flow rate simulation, making the impact angle higher and the impact point lower.
- The reaction forces on the hood are significantly reduced compared to the impact plate (Figure 7.4), due to a much lower impact normal velocity. This is because the impact angle is significantly reduced, and also the material stream velocity is lower since the stream is 'caught' earlier.
- The convergence of the hood is extremely effective in compacting the material in free fall between hood and spoon. The bulk density increases up to 50% for the high flow rate, instead of the decrease experienced in the case study simulation after the impact plate is hit (Figure 7.5). The wider material stream of the 1600 t/h simulation benefits more from this convergence than the 800 t/h simulation. This effect also leads to a much higher bulk density increase at spoon impact for the 800 t/h stream compared to its higher flow rate counterpart.
- The converging free fall of material causes it to be caught by the spoon lower than intended, making the impact far from tangent and therefore only a slight decrease in reaction force is found as compared to the case study simulations (Figure 7.4). This decrease is larger for 1600 t/h, since the converging of material after the hood causes a relatively slightly lower velocity at spoon impact.
- The spoon is more effective in gently decelerating the material compared to the case study for the high flow rate case, whereas with low flow rates the velocity profile looks similar to the deflector plate impact of the case study chute. This is seen in the decline rates of the graphs between 2.3 s and 2.4 s in Figure 7.3. The spoon exit onto the receiving belt is also much smoother in deceleration (see 2.4 s - 2.6 s in Figure 7.3). In the case study, the material even decelerated to below the belt speed, forcing the belt to speed up the material again. The elimination of this phenomenon can potentially decrease the power consumption of the bottom belt pulley system.
- The center belt loading is significantly improved when comparing the mass ratios at the bottom belt from Table 7.2. However, the velocity difference between the spoon exit velocity and the bottom belt speed causes the material to spread out wide over the belt, as can be seen in Figure 7.6. In this simulation it causes no spillage, but for the actual implementation of the design, a narrower spoon exit is advised to be implemented after testing, verification and validation.
- The segregation results are almost identical to the case study results, where no more than 2% difference in average particle mass is found between the left and right side of the bottom belt. It is unclear what the reason for this is, since some segregation is expected when the material is transferred, as observed at Tata Steel. Further investigation is required to analyze segregation in the transfer chute, but this is outside the scope of this research.
- The downside of a redirection of flow over a smooth surface is the chute wear that is increased enormously in the simulation results. The hood vs impact plate show little difference, whereas the spoon vs deflector plate has a wear gradient of up to 10 times higher.
 - The hood wear is similar most likely because although the impact is decreased, the amount of sliding of particles along the hood metal surface is increased.
 - The wear increase in the spoon has multiple reasons. The decrease in impact angle causes material to slide more; the downwards velocity before impact is larger; and finally because the archard wear is the total wear calculated over the entire geometry surface, which is significantly larger for the spoon compared to the deflector plate. The latter reason makes a proper comparison in total archard wear between the case study deflector plate and the spoon in the redesign not possible.

- The already small belt wear is decreased a lot more in the hood and spoon simulations. This is most likely explained by two reasons. The first reason is a reduction of direct belt impact and the second reason is that the spoon directs the material in the belt travel direction instead of the belt needing to create that momentum for the particle stream. The latter will likely cause more sliding of particles on the belt, increasing wear.

7.4. Conclusions

The research question that was answered in this chapter is:

- ***What does a redesign for a Tata Steel transfer chute to minimize dust creation and liberation look like and what can be the quantifiable improvements to the original design?***

From the results of the redesign simulations and their resulting analysis, the following can be concluded:

- The current dimensions of the movable chute show that a hood and spoon concept for a chute with a material direction change of 90° will not suffice in a working chute as the concept intends. The spoon will be too short to catch the wide material stream and material will fall directly onto the belt, even with a significant convergence in the hood.
- A higher cut-off of the movable chute is conceptualized and simulations with sinter at 800 t/h and 1600 t/h are performed. The simulations of this hood and spoon design show signs of decreased dust liberation potential, being:
 - A lower deceleration and reaction force in the hood compared to the impact plate (especially for 800 t/h), which suggests a lower impact and therefore less risk of dust liberation.
 - The hood catches the free falling material earlier, and after it leaves the hood the material stream is more compact, which suggest less dust liberation potential according to literature[1][4]. This compacting is much more significant in the higher flow rate simulation which makes sense considering the same hood convergent shape and a much wider material stream at 1600 t/h. The results of this compacting propagates to the spoon impact, which again is positive regarding dust liberation.
- However, despite the lower reaction force of the 800 t/h simulation, this configuration shows a higher increase in bulk density at the spoon and the stream's downwards velocity at this point is higher than in the case study. Therefore it is unclear if the cumulative benefit regarding dust liberation for this configuration is positive for the redesign.
- Center belt loading is significantly improved with a spoon design as compared to deflector plates as in the case study simulations, although care much be taken to make the spoon convergence sufficient to avoid spillage, due to the velocity difference between stream velocity at the spoon exit and the bottom belt speed. Segregation is almost completely non-existent in the simulations, which requires further investigation to analyze.
- Quantification is hard to compare with radically different designs, but a strong indication is shown towards a significant increase in archard wear in the hood and spoon design, which is conform to experience in the industry with metal plates deliberately allowing sliding of ore materials over its surface.

8

Conclusions and recommendations

In this chapter all the conclusions that are drawn from this research are collected and presented, as well as recommendations for further research or further improvement of the redesign.

8.1. Conclusions

The main research question that is answered in this report is

What are the causes and solution methods in minimizing dust creation and liberation at transfer chutes and how can these be applied in the redesign of a multi-material Tata Steel transfer chute with differing flow rates?

In order to answer this question, several smaller research questions are answered in the previous chapters, of which an overview is presented below:

- *What is known in literature on the influencing factors on the creation and liberation of dust in transfer chutes and what are known transfer chute design considerations that provide solutions to these problems?*
 - Dust liberation is a result of air displacement of the material stream and is minimized in transfer chutes by minimizing material impact, minimizing free fall of material and a compact containment of the flow stream.
 - Air control through filtration systems or using water curtains have all been tried, but usually with only minor improvements, if any.
- *What are suitable assessment methodologies for identifying transfer chute problems at Tata Steel that involve dust creation and liberation?*
 - Measuring methodologies of direct dust measurements have many disadvantages regarding accuracy of source location, therefore other methods such as air or material degradation or numerical modeling techniques such as DEM, CFD, and the coupling of the two can be employed as a substitution for the identification and quantification of dust liberation.
 - For this research material degradation through sampling is performed. This is chosen for a multitude of reasons, like the availability of measurement tools and level of identification and quantification. DEM is chosen as numerical modeling tool, due to its material-equipment interaction modeling capabilities and the level of applicability time-wise compared to CFD-DEM coupling techniques.
- *What is the extend of material degradation at a Tata Steel transfer chute?*
 - Insufficient samples are performed in this research to answer this question to a satisfactory degree.
 - Stopped-belt sampling according to ISO3082-2009 is possible for iron ore pellets and sinter, but not for cokes. The penetration of the material with the sampling tool is not possible due to the large lump size of cokes.

- *How to calibrate bulk materials for dynamic simulations like transfer chutes?*
 - The inclined surface wear tester is used as a dynamic calibration test setup. The setup is capable of providing both static indicators, like angles of repose, as well as dynamic indicators.
 - Verification of the simulations was done by comparing results of three repeated simulations.
 - The trial and error methodology used leaves sensitivity analyses and the level of influence each parameter has out of the calibration process, which is a strong recommendation for future research.
 - Eight performance indicators are used in combination with six calibration parameters, and while good agreement was found between experimental and simulation results, not all parameters are calibrated within the experimental range of results.
- *Where along the material stream in a transfer chute at Tata Steel is potential dust creation and liberation and what is the influence of different materials and mass flow rates in DEM software on this problem?*
 - Three impact zones are found that have potential dust liberation, at the impact plate, the deflector plate underneath the impact plate and the bottom belt.
 - Free fall sections from discharge till impact plate and from impact plate till deflector plate show a lowering of bulk density of the material stream, suggesting potential air entrainment.
 - Simulations show that the highest reaction forces and highest bulk density change is at the deflector plate impact, making it the most problematic area for dust liberation according to the simulation.
 - The DEM model for sinter shows more compacting of material in comparison to iron ore pellets, likely due to higher friction coefficients with the steel chute and an irregular particle shape hampering sliding and rolling.
 - A higher flow rate softens the material impact at the bottom belt due to the higher material bed on the belt, preventing the material to speed up and spread in free fall.
- *What does a redesign for a Tata Steel transfer chute to minimize dust creation and liberation look like and what can be the quantifiable improvements to the original design?*
 - A hood and spoon concept is a potentially improved design with regard to dust liberation, among other factors.
 - A cut-off of the movable top chute in the case study at Tata Steel needs to be adjusted in order to fit a hood and spoon design that is simulated.
 - Simulations show potential for dust liberation minimization due to:
 - ◊ Less and softer impacts, as shown by velocity profiles, reaction force calculations and bulk density differences
 - ◊ Compacting of material by hood convergence, as shown visually and through bulk density measurements
 - ◊ Earlier catching of material from discharge improves free fall time, with the free fall after the hood being more compact
 - Off-center belt loading is significantly improved, while archard chute wear is increased.

8.2. Recommendations

Many recommendations for further research are to be made from this research, which are listed in this section, separated in several categories for clarity.

Design

- The incorporation of a honeycomb in the hood and spoon is recommended, since the amount of wear will most likely be a more significant problem in the implementation of the redesign than dust liberation. A drawback is the contamination of materials in these multi-material chutes.
- The redesign is potentially difficult to manufacture, so approximation of the curves with tiles are a compromise.

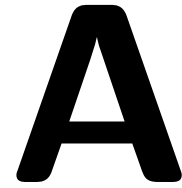
- Chute curvatures with higher radii could potentially improve flow conditions according to Roberts' theories. Testing and implementing this where possible is recommended.
- The bottom belt needs to allow material to pass along the spoon. A spoon that can rotate upwards to some degree is recommended[7].
- Make use of settling zones or 'calming tunnels' (see Section 2.4) is an alternative to minimize dust liberation if a complete redesign is unable to be performed.
- Most likely very little dust creation occurs at the case study transfer chute, since the drop height and impact forces are not very high, especially in comparison to the bunker loading that happens before the transfer chute for some materials for instance.

Measuring and modeling methodologies

- The stopped-belt method can potentially be used for the extraction of samples right before and after a transfer chute and result in PSD data within a CI of 95%, but many samples will most likely be required. Several recommendations for a successful outcome of this procedure are:
 - Since the differences in before and after samples are grouped together to obtain one average within 95% CI, ideally all samples are taken at on the same day. Differences in source material (like origin or exposure to elements) can lead to differences in breakage rates, making a CI of 95% more difficult.
 - A wider tool is recommended to minimize contamination of the samples with the insertion of the tool into the material.
 - If cokes or other large lump size materials are sampled, stopped-belt is not recommended. vibratory plates might be able to penetrate the material for sampling, but the risk of breakage contamination is likely larger than the amount of breakage occurring along the bottom belt trajectory. Therefore sampling directly from the top belt pulley discharge and from the end of the bottom belt.
- Improving flow aspects in transfer chutes using DEM has been proven to be sufficient in lowering dust liberation and solve other chute problems. Modeling dust flows with CFD-DEM coupling is only recommended if dust problems persist, but with the current lack of sufficient validated research in this area, more fundamental, experimental research in this field is needed. Also the computational power required for entire chute granular and dust flow analysis is a current hurdle that can be overcome in the future when computational power increases.

Calibration

- Sensitivity analysis on dynamic calibration using design of experiments for instance
- Calibration validation is required using other test setups
- The PSD of sinter that is measured is relatively small, which can vary much more at Tata Steel and elsewhere, depending on when samples are taken. Therefore most likely an extreme amount of samples need to be performed to get a PSD within 95% CI, and therefore an average PSD for DEM modeling of sinter can be recommended in most cases.



Research paper

A.1. Abstract

With increasingly strict restrictions on environmental pollution, dust liberation in the bulk handling industry is a problem that needs to be minimized. This research attempts to find the causes of dust liberation in a case study transfer chute at Tata Steel and test a redesign with simulations to improve the chutes' dust liberation problems, taking into account multiple materials, flow rates, and a movable head chute. Material degradation was attempted to be recorded using stopped-belt sampling, since impacts cause degradation as well as dust liberation, but no conclusive evidence was found due to a lack of samples. Iron ore pellets and sinter were dynamically calibrated for DEM software using an inclined surface wear tester. Case study simulations of these materials at 800 and 1600 t/h found three problem areas involving impacts. These were reduced in a redesign that was tested in simulations. The redesign uses a hood and spoon concept with movable hood, where the cut-off of the movable chute head needed to be heightened to fit a spoon that can improve flow conditions. Improvements in the identified problem areas were found in simulations of the redesign.

A.2. Introduction

Dust liberation in transfer chutes has been a persistent problem in the bulk handling industry, with increasing demand for solution given the tightening of environmental regulations. Besides environmental contamination and employee respiratory damage; the added costs dust liberation introduces by the loss of material; increased maintenance costs on damaged equipment; and cleanup costs can add up to an average loss of one percent per ton of throughput according to investigative reports performed in the UK[1][4]. Research into the causes and solutions for dust liberation problems at transfer chutes have

found that air flows are linked to the control of dust. Three main design objectives are found that minimize dust liberation, which are:

- Minimize material impacts
- Minimize free fall of material
- Compact containment of material flow stream

Other methods that are attempted in the industry are to minimize the air speed inside the chute using rubber flaps around the chute opening and skidboards; extension of chute enclosure over the receiving belt to calm the air flows (also called 'calming tunnels'); water curtains that contain dust; and air filtration systems. These methods however seem to be battling the symptoms rather than tackling the root causes[1][23]. Current chute configurations incorporate dead boxes or hood and spoon concepts to attempt to redirect the flow in a more controlled manner, where the latter seems more suitable for dust liberation minimization, due to the minimization of both impacts; amount of free fall; and compact containment of flow if a convergent hood and spoon is used. A novel concept of a movable hood and/or spoon has been introduced that accounts for different material flow properties, but papers on this topic as well as industry applications have been severely lacking[23].

A.3. Sampling

To assess the case study dust liberation problems, a sampling method was devised to perform on-site measurements. Direct measurement of airborne or settled dust provide a multitude of problems, among which the biggest is the problem of identifying the exact source of the airborne or settled dust that is measured. Where material impacts are both the cause of dust liberation and dust creation, material degradation can also be used as a quantifying measurement

in transfer chute problems. A sampling methodology as described in *ISO3082-2009* is used, for which a sampling tool was constructed. This standard is made for finding the PSD of big bulk material volumes, but its methodology of stopped-belt sampling is applied in this research to measure the PSD of material right before and after the chute to compare the amount of smaller particles. Samples had to be taken close together along the stream and the material had to have passed the chute at full speed to get accurate measurements, for which the following formula was devised:

$$t_{bs} = t_{su} + \frac{s_{bs} - \frac{1}{2} \cdot t_{su} \cdot v_b}{v_b} \quad (A.1)$$

where t_{su} is the start-up time, v_b is the belt speed, and s_{bs} and t_{bs} are the distance and time between the two sample locations respectively. Iron ore and sinter were possible to sample using the sampling tool, but the large lump size of cokes made it impossible to penetrate with the tool. A total of two before and after samples of sinter were extracted and found to be insufficient to provide conclusive evidence of material degradation within a 95% confidence interval.

A.4. Calibration

Iron ore pellets and sinter were dynamically calibrated on a rubber and steel surface using an inclined surface wear tester, shown in Figure A.1, for the purposes of dynamic simulations of transfer chute flow. Eight performance indicators were used, with three angles of repose and four dynamic indicators. The latter being all the inclination angles at: first material on material shift; first material on plate shift; biggest material shift; and when the top box is emptied. Normal distributions were used for the PSDs, extracted from literature for pellets and from samples for sinter. Pellet particles are modeled as single spheres and sinter as three spherical particles. From a literature based reference case, seven calibration parameters were calibrated using a trial and error method. The results are shown in Table A.1, where p-p is particle to particle and s and r stand for steel and rubber respectively. While good agreement with the experiments was found on most performance indicators, a sensitivity analysis using design of experiments is highly recommended to study the level of influence of the calibrated parameters on bulk behavior.

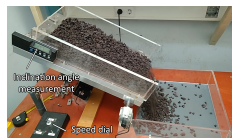


Figure A.1: Picture of inclined surface wear tester during a test with sinter

Calibration parameters	Pellets	Sinter
• Static friction p-p [-]	0.3	0.25
• Rolling friction p-p [-]	0.15	0.15
• Static friction p-s [-]	0.3	0.5
• Rolling friction p-s [-]	0.25	0.3
• Static friction p-r [-]	0.4	0.6
• Rolling friction p-r [-]	0.29	0.5
• Density [kg/m ³]	3700	2850

Table A.1: Results calibration parameters

A.5. Case study DEM analysis

Methodology

To analyze the case study chute to identify the main causes for its dust liberation as listed in the introduction and to investigate the effects of differing mass flow rates and materials, a geometry model is made and simulations are performed. The three main key performance indicators (KPIs) that are used are:

- Velocity fluctuations in material flow
- Impact velocity and reaction force
- Bulk density fluctuations along material stream

Secondary KPIs to give an indication of chute performance in other design objectives are:

- Belt center loading
- Chute wear
- Segregation

Velocity fluctuations are measured by selecting a small box of material on the top belt and extracting the average velocity. The reaction forces on the impact plate and the deflector plate are calculated from extracting the normal component of the material velocity to the geometry surface from the simulations and using the following equation:

$$R_n = m_s V_{pn} \sin \beta \quad (A.2)$$

Where m_s is the mass flow rate in kg/s, V_{pn} is the normal velocity component of the particles, and β is the angle between the material stream and the geometry. Bulk density fluctuations are measured using small, cubic, bulk density sensors with sides of 70 mm that are tucked inside the material stream along its trajectory. Center loading and segregation measurements use the same two bins that split the bottom belt in half and measure the total particle mass and average particle mass respectively. Total archard wear is measured from meshed geometries (using ANSYS to create smooth surface CFD-Fleunt meshes with 0.006 m maximum face sizes) and normalized gradients are extracted from their linear progression results.

Four simulations are performed with combinations of the calibrated sinter and iron ore pellet material models and 800 t/h and 1600 t/h mass flow rates. Figure A.2 shows the geometry as modeled in DEM, where it can be seen that the material hits a v-shaped impact plate, which is attached to the movable top part of the chute along with the top belt and pulley. Then a deflector plate that is fixed above one of three bottom belts is hit and finally the material lands on the bottom belt.

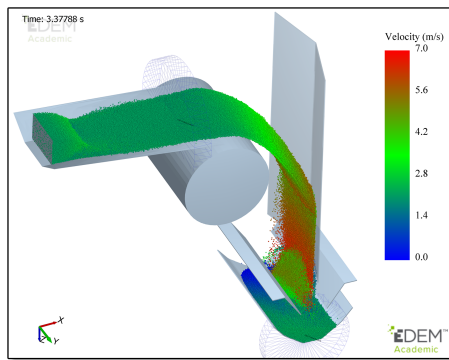


Figure A.2: Case study chute simulation of iron ore at 1600 t/h

The chute geometry model was checked for continuous flow without spillage using mass flow rate sensors before discharge and on the bottom belt. The point of impact on the impact plate and the wear and material residue found on the deflector plate were all indications of a model that represents reality to some degree.

Results

The velocity profiles shown in Figure A.3 of the four simulation all showed roughly the same pattern of three abrupt changes from material acceleration to deceleration, suggesting an impact.

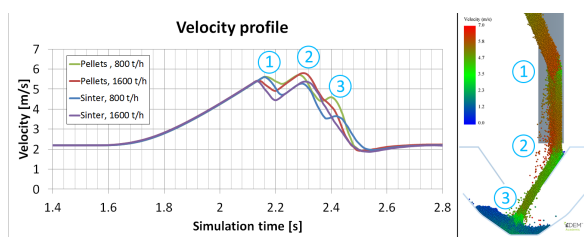


Figure A.3: Graph of average velocity profile of a small material selection (left), side view of pellets, 800 t/h (right)

These three impacts could visually be traced back to impacts on the impact plate, deflector plate and bottom belt. Iron ore showed less deceleration after hitting the impact plate than sinter, causing a higher maximum speed, which happens before the impact on the deflector plate. The higher flow rates, especially sinter, showed almost no acceleration before

the bottom belt, due to it being loaded much higher, which eliminated the possibility of material free fall. The reaction forces for the higher flow rates were more than double than the low flow rate forces, due to the higher flow rate and slightly increased normal velocity components, which was to be expected.

The bulk densities were decreased over 60% in the first free fall section, while upon impact an increase in roughly 10% was seen for pellets and 22% for sinter. This pattern repeated at the deflector plate, where pellets and sinter had around 40% and 60% bulk density increases.

The wear results at the impact plate showed higher wear in pellets than sinter. This wear difference was higher at the deflector plate. This result does not reflect reality.

Discussion

The results suggest that sinter tends to build up material at impact zones, where iron ore flows more fluidly. The reason can be the higher friction coefficients sinter has to steel, and the irregular particle shape of sinter particles cause them to bounce away from the general stream direction, creating more inter-particle bounces that obstruct the steady material flow and slow down the stream due to energy losses for collisions. The brunt of the impact is shifted from the particle-to-wall impact towards particle-to-particle impact, since it was observed that a layer of stagnant sinter particles were residing on the deflector plates' surface.

The higher wear results for sinter were not expected, since the calibrated model for sinter has a higher friction coefficient on steel than pellets and the irregular shape should encourage sliding over rolling. Tests with single particles on steel plate impact revealed that the irregular shape of sinter result in lower wear registered, which is due to the relationship between the particle radius in contact with the geometry and the normal force, of which the latter is in the equation for archard wear. A higher radius leads to a higher normal force, which in turn increases the wear. Another factor that can cause the higher wear in pellets are the much higher particle density. A final contributor can be the bulk behavior of sinter, which slows down the upon impact and could have different particle trajectories that register less tangential distance moved along a geometry. This is a minor factor if it is present, since vector plots showed no signs of altered trajectories.

The differences in bulk behavior for sinter does explain the higher wear difference at the deflector plate, considering the material stagnation found on the surface.

A.6. Redesign

Proposals

Three concept proposals were made for the redesign of the case study transfer chute, where one new concept was explored and two hood and spoon configurations were calculated. A schematic drawing of the concepts are illustrated in Figure A.4.

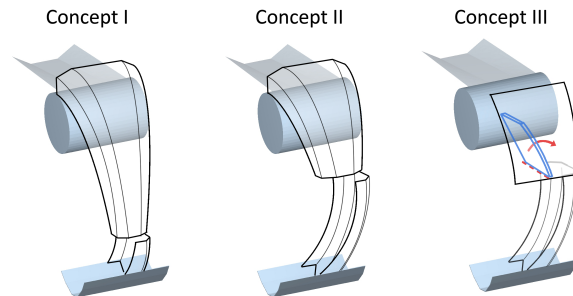


Figure A.4: Schematic drawing of the three redesign proposal concepts

The first concept was to construct a hood and spoon on the top and bottom sections of the chute respectively. To calculate the radii and location of the hood and spoon, Roberts' theory was used [26]. The trajectory was first calculated and found in accordance with the material stream modeled in DEM simulations. The hood is designed to ensure a straight downwards redirection of flow at the height of the cut-off of the top chute, which is at 2.19 m. Using the equations for radius of curvature, material trajectory and the chute position together with this constraint a resulting chute radius of 2.84 m is found. The material is then caught after 0.8 m free fall in the horizontal direction. When the spoon calculation was performed and only 0.86 m height was available, the 90° turn the material needs to make causes straight to belt loading instead of landing on the spoon for a wide section of the stream, even when a large convergence of the hood is incorporated. Therefore this proposal was dropped.

The second concept is to making the cut-off between the movable chute and the bottom section higher in order to fit a larger spoon at the bottom. The hood requires some adjustments to fit in the narrower space, curving the hood with a second, smaller radius at the bottom of 1.35 m, in accordance to the curvature radius of the material trajectory at $x = 0.5$ m. This results in a hood directing the material downwards at 1.27 m below the discharge point. A minor convergence is fitted on the hood with the exit width being 0.8 m, to ensure compact containment of the flow. The space in height left for the spoon is sufficient to fit a radius of 2.15m, where the spoon exit angle is 55° is chosen, adhering to the self-cleaning check. The spoon exit velocity of the material in belt direction can not be

lowered to the relatively low belt speed of 2.19 m/s, and therefore simulations are required to check for spillage risks and the status of belt wear.

Concept III uses an innovative new design concept of combining an impact plate with a flopper gate pressed against it, directing the flow either left or right onto a spoon below, depending on the spoons orientation (the bottom belts have different directions, so the fixed spoons above the belts have differing orientations). This ensures the material makes an s-curve from the discharge point left or right to the spoon guiding it right or left respectively. A disadvantage of this design is the high probability of material getting stuck between the movable gate and the impact plate when gaps are formed from eventual wear damage, blocking the flopper gate. Fixing the flopper gate to the impact plate raises new issues of dimensional constraints and power consumption of moving a relatively heavy gate. For these reasons, together with high maintenance and costly manufacture, this concept is not chosen.

Concept II is chosen for the redesign, circumventing the issue of straight to belt loading in concept I and risk of high maintenance and construction cost in the complexity of concept III. From the case study analysis the flowability of sinter showed more signs of pluggage or spillage risk for a redesign and due to lengthy computational times, the redesign was simulated using sinter with 800 t/h and 1600 t/h to compare with the case study results.

Simulation results

The velocity fluctuations show an earlier catch of the free falling material, where especially the 800 t/h stream showed a more gently deceleration, as seen in the gentler decline in after the first 'peak' in Figure A.5. A similar, much more gentle deceleration was found in both flow rates at the spoon exit when compared to the case study results.

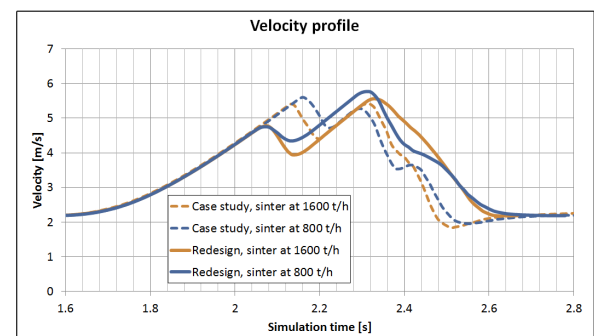


Figure A.5: Comparison of velocity profile between current design and the redesign simulations

The reaction forces are presented in Figure A.6. As can be noted, they were significantly reduced in the

first catch of material, whereas a smaller reduction in the second impact was found on the spoon/deflector plate.

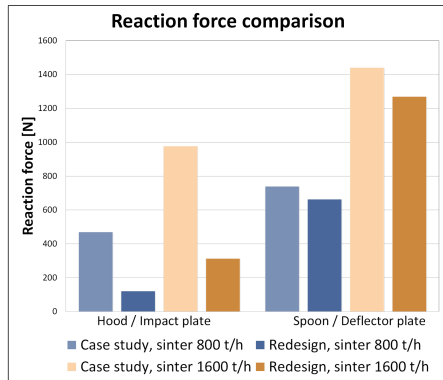


Figure A.6: Comparison of reaction forces between current design and the redesign simulations

The bulk density result data are shown in Figure A.7. At the impact plate the bulk density increase was lower, whereas in between impact the hood created a significant bulk density increase when the impact plate caused a decrease. The biggest bulk density increase was found at spoon impact for the low flow rate stream.

	Discharge till impact	First impact	Between impacts	Second impact
Redesign, sinter at 800 t/h	-49%	10%	18%	25%
Redesign, sinter at 1600 t/h	-49%	15%	50%	21%
Case study, sinter 800 t/h	-64%	23%	-16%	61%
Case study, sinter 1600 t/h	-59%	22%	-13%	60%

Figure A.7: Comparison of bulk density percentage changes along the material stream

Segregation showed almost no difference between case study and redesign, while the belt center loading was significantly increased. The total archard wear gradient results are listed in Table A.2.

	Hood / Impact plate	Spoon / Deflector plate	Bottom belt
CS, 8	1.38	0.52	0.17
R, 8	1.38	5.1	0.042
CS, 16	1.83	0.52	0.20
R, 16	1.38	6.1	0.027

Table A.2: Normalized wear gradients comparing case study (CS) with redesign (R) for 800 t/h (8) and 1600 t/h (16)

The hood showed little difference in archard wear, while the spoon has over ten times the total archard wear, which is addressed in the discussion. The bottom belt showed a significant decrease in wear for the redesign.

Discussion

The convergence of the hood was proven extremely effective compacting the material and causing a gentler deceleration. This was especially true for the high flow rate stream, since it is much wider and can therefore compact much more with the relatively tighter hood convergence. The effect of this compacting propagates in the free fall section and eventually at the spoon impact, where significantly less bulk density increase was found. This suggests less dust liberation potential in this simulation compared to the case study, since compact material containment was achieved. The fact that the lower flow rate simulation does not benefit as much from the hood compacting was seen in the very high density increase at the spoon impact, which suggests an adjustable hood convergence could significantly improve both flow rates.

The reduction in reaction forces on the hood and spoon was expected, given the very low impact angle compared to the impact plate and deflector plate. This reduction is much less at spoon impact, due to the converging flow impacting lower on the spoon than intended. This created a higher downwards velocity before impact, but the impact angle was still sufficiently reduced to yield a decrease in reaction force.

The spoon is very effective in gently decelerating the material to the belt speed, as seen in Figure A.5, between 2.3 s and 2.6 s, eliminating the third impact on the belt as seen in the case study at low flow rate in the figure. In the case study, the material even decelerated to below the belt speed, forcing the belt to speed up the material again. The elimination of this phenomenon can potentially decrease the power consumption of the bottom belt pulley system.

The center belt loading is significantly improved. However, the velocity difference between the spoon exit velocity and the bottom belt speed causes the material to spread out wide over the belt. In this simulation it causes no spillage, but for the actual implementation of the design, a narrower spoon exit is advised to be implemented after testing, verification and validation.

The hood wear is similar most likely because, although the impact is decreased, the amount of sliding of particles along the hood metal surface is increased. The spoon wear can not be compared to the case study, given the fact that the archard wear is added from the entire geometry, where the spoon is much larger than the deflector plate. The significant reduction in belt wear is likely caused by two reasons. The first being a reduction of direct belt impact and the second that the spoon directs the material in the belt travel direction instead of the belt needing to create that momentum for the particle stream. The latter

will likely cause more sliding of particles on the belt, increasing wear.

A.7. Conclusions

From this research it can be concluded that a hood and spoon concept redesign shows potential in dust liberation minimization compared to a multi-material case study chute at Tata Steel with differing flow rates. This was concluded from DEM simulations using sinter and iron ore pellets at two flow rates, 800 t/h and 1600 t/h.

More detailed conclusions from the research performed is listed below.

- Although insufficient samples were taken for conclusive material degradation evidence, the stopped-belt sampling according to *ISO3082-2009* was proven possible for iron ore pellets and sinter, but not for cokes. The penetration of the material with the sampling tool was not possible due to the large lump size of cokes.
- The inclined surface wear tester was used as a dynamic calibration test setup. The setup is capable of providing both static indicators, like angles of repose, as well as dynamic indicators. Eight performance indicators were used in combination with six calibration parameters in a trial and error calibration process, and while good agreement was found between experimental and simulation results, not all parameters are calibrated within the experimental range of results. Sensitivity analyses is highly recommended to find the level of influence each parameter has on the results.
- In the case study analysis, three impact zones are found that have potential dust liberation, which are at the impact plate, the deflector plate underneath the impact plate and the bottom belt. The deflector plate is the highest dust liberation risk, given its highest reaction forces and bulk density increase.
- The DEM model for sinter shows more compacting of material in comparison to iron ore pellets, likely due to higher friction coefficients with the steel chute and an irregular particle shape hampering sliding and rolling.
- A hood and spoon concept is a potentially improved design with regard to dust liberation, among other factors.
- A cut-off of the movable top chute in the case study at Tata Steel needs to be adjusted in order to fit a hood and spoon design that is simulated.
- Simulations show potential for dust liberation minimization due to:
 - Less and softer impacts, as shown by velocity profiles, reaction force calculations and bulk density differences
 - Compacting of material by hood convergence, as shown visually and through bulk density measurements
 - Earlier catching of material from discharge improves free fall time, with the free fall after the hood being more compact

B

Appendix

EDEM simulation settings

Calibration simulator settings

Time integration	Euler
Fixed time step	80%
Target save interval	0.01 s
Cell size	5 R min
Simulation time	35 s
Simulation computation time	7 - 12 h
Inter-particle contact model	Hertz-Mindlin (no slip) built in
Particle-geometry contact model	Hertz-Mindlin with Archard wear built in
Geometries' wear constant	1 Pa ⁻¹

Tata Steel and redesign chute simulator settings

Time integration	Euler
Fixed time step	80%
Target save interval	0.01 s
Cell size	5 R min
Simulation time	3.5-5 s
Simulation computation time	40-80 h
Inter-particle contact model	Hertz-Mindlin (no slip) built in
Particle-geometry contact model	Hertz-Mindlin with Archard wear built in
Geometries' wear constant	1 Pa ⁻¹

Material properties

	Iron ore	Sinter	Steel	Rubber	Plastic
Poisson's ratio [12][44]	0.3	0.25	0.3	0.4	0.4
Shear modulus [12][31][39][44][46]	10 GPa	13.5 GPa	78 GPa	7.1 GPa	0.96 MPa
Density [12][44]	-	-	7932 kg/m ³	950 kg/m ³	1136 kg/m ³
Coefficient of restitution with iron ore	0.45	-	0.4	0.3	0.5
Coefficient of restitution with sinter	-	0.3	0.4	0.3	0.5

C

Appendix

EDEM simulation calibration steps

Iron ore pellets - Steel

Calibration parameters		Sim 1	Sim 2	Sim 3
• Static friction particle - particle [-]		0.45	0.35	0.3
• Rolling friction particle - particle [-]		0.15	0.15	0.15
• Static friction particle - steel [-]		0.5	0.3	0.3
• Rolling friction particle - steel [-]		0.25	0.25	0.25
Performance indicators		Experiments		
• First angle of repose, Φ_1	30.9 $\pm$ 0.2	34.4	33.2	30.7 $\pm$ 0.3
• Inclination angle at first mat-mat shift	8.4 $\pm$ 0.3	13.8	9.6	9.0 $\pm$ 0.7
• Inclination angle at first mat-plate shift	11.3 $\pm$ 1.9	18.7	10.1	9.2 $\pm$ 0.6
• Inclination angle at biggest mat shift	14.3 $\pm$ 1.2	19.6	15.4	14.7 $\pm$ 0.2
• inclination angle at empty top box	22.4 $\pm$ 0.2	24.5	19.7	<u>19.7 $\pm$ 0.1</u>
• Second angle of repose, Φ_2	22.8 $\pm$ 1.6	29.5	24.6	24.6 $\pm$ 1.0
• Third angle of repose, Φ_3	32.2 $\pm$ 0.7	41.5	36.9	<u>34.2 $\pm$ 0.3</u>

Iron ore pellets - Rubber

Calibration parameters		Sim 1	Sim 2	Sim 3	Sim 4
• Static friction particle - particle [-]		0.3	0.3	0.3	0.3
• Rolling friction particle - particle [-]		0.15	0.15	0.15	0.15
• Static friction particle - rubber [-]		0.71	0.5	0.45	0.4
• Rolling friction particle - rubber [-]		0.29	0.29	0.29	0.29
Performance indicators		Experiments			
• First angle of repose, Φ_1	32.9 $\pm$ 0.3	35.4	34.4	33	32.8
• Inclination angle at first mat-mat shift	9.0 $\pm$ 0.8	14.8	13.8	11.4	9.5
• Inclination angle at first mat-plate shift	13.5 $\pm$ 2.1	14.8	13.8	13.5	13.1
• Inclination angle at biggest mat shift	14.2 $\pm$ 1.0	18.5	16.2	16.3	15.3
• inclination angle at empty top box	23.9 $\pm$ 0.6	25.7	25.6	25.5	24.2
• Second angle of repose, Φ_2	19.7 $\pm$ 1.8	23.8	25.8	26.7	<u>24.1</u>
• Third angle of repose, Φ_3	29.6 $\pm$ 1.9	32.2	33.7	33.7	<u>34.6</u>

Sinter - Steel

Calibration parameters		Sim 1	Sim 2
• Static friction particle - particle [-]		0.3	0.25
• Rolling friction particle - particle [-]		0.2	0.15
• Static friction particle - steel [-]		0.5	0.5
• Rolling friction particle - steel [-]		0.2	0.3
Performance indicators	Experiments		
• First angle of repose, Φ_1	35.9 $\pm$ 0.4	39.9	35.4
• Inclination angle at first mat-mat shift	13.8 $\pm$ 0.5	15.4	13.9
• Inclination angle at first mat-plate shift	18.2 $\pm$ 0.7	18.0	<u>20.5</u>
• Inclination angle at biggest mat shift	23.1 $\pm$ 0.7	24.6	23.0
• inclination angle at empty top box	31.3 $\pm$ 0.2	30.2	<u>30.2</u>
• Second angle of repose, Φ_2	32.1 $\pm$ 1.5	37.2	<u>38.0</u>
• Third angle of repose, Φ_3	34.9 $\pm$ 1.3	40.6	34.2

Sinter - Rubber

Calibration parameters		Sim 1	Sim 2	Sim 3	Sim 4	Sim 5
• Static friction particle - particle [-]		0.25	0.25	0.25	0.25	0.25
• Rolling friction particle - particle [-]		0.15	0.15	0.15	0.15	0.15
• Static friction particle - rubber [-]		0.5	0.5	0.5	0.65	0.6
• Rolling friction particle - rubber [-]		0.4	0.45	0.5	0.5	0.5
Performance indicators	Experiments					
• First angle of repose, Φ_1	35.2 $\pm$ 0.4	35.7	35.6	35.6	35.4	35.1
• Inclination angle at first mat-mat shift	13.3 $\pm$ 1.5	12.8	12.7	12.6	13.4	13.1
• Inclination angle at first mat-plate shift	22.2 $\pm$ 2.4	21	20.3	21	24	23.8
• Inclination angle at biggest mat shift	28.3 $\pm$ 1.8	23.6	24.2	24.2	31.2	27.1
• inclination angle at empty top box	35.1 $\pm$ 0.5	30.3	30.1	30.2	37.5	35
• Second angle of repose, Φ_2	27.8 $\pm$ 0.9	35.1	35.1	35.6	36.2	<u>36.5</u>
• Third angle of repose, Φ_3	33.6 $\pm$ 0.7	40.2	35.8	36.1	41.5	<u>41</u>

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