Improving Dust Control at a Bulk Terminal

Development and Implementation of a Dust Control Strategy

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by

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Abstract

Dust emissions developed during the handling of dry bulk products pose increased risks for health, safety and the environment. Legislation drives bulk handling facilities to face the challenge of maintaining dust emissions within limitations. At the bulk terminal of Verbrugge multiple bulk products are handled, making the dust control problem even more difficult. The aim of this research is to improve the dust control methods of bulk handling equipment handling various dry bulk products to further reduce the dust emissions.

A dust control strategy is developed based on the knowledge gathered through theoretical and practical research concerning the formation and control of dust emissions. The strategy provides a structural approach to identify the most suitable dust control methods, applicable for all types of bulk handling operations and bulk products. It incorporates the specifications of the dust source, investigates the feasibility of dust control measures, and creates and evaluates combinations through a weighted multi-criteria analysis.

The decision-making tool is implemented at three dust sources at Verbrugge and proposes dust control methods to improve the reduction of dust emissions. The strategy suggests providing transfer chutes between two conveyor belts with a flex-flap system to avoid dust dispersion within the installation. The proposed method offers a safer, more reliable, less expensive, and maintenance-friendly solution as opposed to the currently applied dust collector. The implementation of the dust control strategy at the transfer between a grab and hopper offers the valuable insight that the design of wind screens need to be optimised in order to improve the extent of dust control. The ship loader is best equipped with a cascade chute and dust skirt, as suggested by the strategy.

This study shows the developed dust control strategy not only substantively proposes the most suitable dust control methods, but also offers valuable insights into potential issues, provides possible solutions or improvements, and significantly reduces the time and effort invested in the decision-making process. To further enhance the findings of this research, it is recommended to include the effects of organisational dust control measures and a design aspect in the dust control strategy. Additionally, a more reliable assessment of dust control measures can be achieved by quantifying the generation and control of dust emissions.

Nomenclature

List of Abbreviations

AB	Activities Decree
AoR	Angle or Repose
APPA	All-in-one Permit for Physical Aspects
BAT	Best Available Technique
BOR	Decree on Environmental Law
DSH	Dust Suppression Hopper
ELV	Emission Limit Value
MSDS	Material Safety Data Sheet
PM	Particulate Matter
PSD	Particle Size Distribution
RIE	Industrial Emissions Directive
RM	rail-mounted
WM	Environmental Management Act

List of Symbols

β	Half-angle of liquid bridge
γ	Liquid surface tension
ρ_{air}	Air density
σ_w	Normal stress
τ_w	Shear stress
φ_x	Angle of wall friction
A	Projected area
a	Acceleration
c	Distance between center of particles
C_D	Drag coefficient
d	Distance between particles
F_B	Buoyant force
F_c	Capillary force
F_D	Drag force
F_E	Electrostatic force

F_G	Gravitational force
F_i	Inertial force
F_{vdW}	Van der Waals force
ff_c	Flow factor
g	Gravitational constant
H	Hamaker constant
m	Mass of the particle
Q_p	Electrical charge of particles
R	Radius of the particle
U	Relative velocity between particle and air flow
V	Volume of the particle
ϵ_0	Relative permittivity
ϵ_r	Free space permittivity
σ_1	Consolidation stress
σ_c	Unconfined yield strength

Contents

1 Introduction

The bulk department of Verbrugge International B.V. (hereafter: Verbrugge) is specialized in the storage and transshipment of multiple dry bulk materials. At the bulk terminal in Terneuzen, the Netherlands (Figure 1.1), the bulk products are distributed through road, rail, and water transport. Currently, Verbrugge is transitioning its emphasis to soda as its primary handled product in response to a new client with high demand for transporting soda. However, handling soda in addition to numerous other dry bulk products entails some concerning challenges.

Figure 1.1: Bird's-eye view of the bulk terminal of Verbrugge in Terneuzen. Source: Verbrugge International B.V. (n.d.)

1.1. Problem statement

A well-known issue of handling soda is the formation of dust emissions. Air pollution in the form of fine particles, also called particulate matter (PM), is a serious hazard for health, safety, and the environment. Moreover, dust emissions may adversely affect handling operations. The consequences of dust emissions are not limited to the workplace, but may also have impact on surrounding residents. According to RIVM (2019), exposure to PM polluted air can be linked to various respiratory diseases, cardiovascular diseases, lung cancer, birth defects, and shortened lifespan. World Health Organization (2021) states that the contribution to diseases and mortality along with the associated economical impact makes air pollution "the single largest environmental threat to human health and well-being" (p. 12). Moreover, the dust emissions may lead to nuisance in the neighborhood, such as dust settlement on people's properties, which could result in complaints.

Swinderman et al. (2009) describe several safety hazards posed by dust liberation for employees. Fugitive dust particles may lead to impaired visibility, which increases the risk of accidents. Furthermore, the accumulation of dust particles on surfaces may cause slippery walkways and requires frequent cleaning and maintenance, resulting in employees working close to equipment and increasing the risk of injuries. These issues create an unpleasant workplace, reducing employees' diligence and productivity.

Besides the health and safety risks, dust also forms various problems in the handling process (Swinderman et al., 2009). The performances of monitoring sensors and instruments may be affected by dust settlement on the equipment. Additionally, dust generated by corrosive products can cause damage to the equipment material. Both issues increase the demand for maintenance, which induces not only safety risks, but also requires more time of employees and decreases equipment availability. Furthermore, the generated dust equals product loss.

Due to the health, safety, environmental, and nuisance risks, regulations are imposed on bulk handling facilities, which drives companies to incorporated measures to keep dust emissions within limits. Although legislation proposes various dust control measures, the dust emissions limitations are regularly exceeded. Insufficient *dust control* is also an issue at some installation at the bulk terminal of Verbrugge. An additional challenge is the handling of multiple dry bulk products, besides soda. The bulk handling installations and operations must take various bulk characteristics into account, restricting the possible dust control measures. A structural approach to determine the most suitable dust control method and further reduce dust emissions is desired.

Dust control

In this study, dust control is considered preventive or suppressive ways to reduce dust emissions.

1.2. Research goal and questions

This research aims to address the challenge of reducing dust emissions formed during handling different dry bulk products. Reducing dust emissions contributes to reducing the health, safety, and environmental impact of bulk handling facilities. Furthermore, it enhances operational efficiency, reduces costs and avoids nuisance in the surrounding area.

Based on the problem statement and research goal, the main question addressed by this research is formulated as:

How can the dust control methods of bulk handling equipment processing various dry bulk products be improved in order to further reduce dust emissions?

The following subquestions are addressed in this study to derive an answer to the main question.

1. How is bulk handling influenced by the properties of different bulk products?
2. How are dust emissions generated during bulk handling?
3. What dust control measures reduce the dust emissions?
4. To what extend are dust emissions reduced by the applied dust control techniques at Verbrugge?
5. What strategy can be used to select the most suitable dust control method?
6. What dust control methods are proposed by implementing the developed strategy to further reduce dust emissions at Verbrugge?

1.3. Research methodology and scope

The objective of this research is to address the dust emissions generated during bulk handling of various dry bulk products. First, a literature study is conducted to acquire a better understanding of the theory behind the control of dust emissions. This literature study concerns the influence of bulk properties, the principles of dust generation, and dust control measures. Practical approaches are used to obtain an indication of the contribution of different dust generation principles and to qualitatively determine the performances of applied dust control techniques. The theoretical and practical knowledge is incorporated in the development of a dust control strategy, providing a structural approach to determine the most suitable dust control methods. The developed strategy is implemented at three dust sources at Verbrugge to verify its applicability and to propose dust control methods to further reduce dust emissions. The methodology of this research is graphically presented in Figure 1.2.

This study aims to improve dust control at all types of bulk handling facilities. This study uses a general approach, allowing a wide application of the findings of this research. Yet, the hands-on experience at the bulk terminal of Verbrugge is incorporated to serve a verification role. Hence, this study considers the bulk products, bulk handling operations and dust control equipment at Verbrugge.

Bulk properties may influence the operations and design of bulk handling equipment and need to be investigated. The bulk terminal at Verbrugge enables handling of numerous dry bulk products. To narrow down the scope of this study, small selection of the bulk products handled at Verbrugge is considered: soda, phosphate, and urea. These three bulk products contain characteristics covering most of the materials handled at Verbrugge.

The regulations concerning dust emissions may vary among different countries and type of facilities. Therefore, only the regulations imposed by the Dutch government and the permits that apply to Verbrugge are considered in this research. Regulations regarding other subjects, such as safety, are not considered in the scope of this research.

In order to enable dust control, it is essential to first understand the causes of dust emissions, and the trajectories of airborne dust particles. The dust generation principles may not equally contribute to the formation of dust emissions. Experiments are conducted to analyze the influence of each dust generation mechanism. Yet, due to limited workspace conditions and equipment, the results are indicative and not quantified.

Based on the mechanisms of dust generation, the principles to prevent the development and dispersion of dust emissions can be established. Specific dust control techniques, both preventive and suppressive, are investigated. Techniques applied at Verbrugge are evaluated to establish whether their performances, concerning both dust control and general functionality, correspond to the expectations based on the theoretical information. The performances are qualitatively described based on observations of the equipment during operations and interviews of operational involved employees.

A dust control strategy is developed to obtain a structural approach for addressing dust emissions during bulk handling. The strategy extends the regulations and is a general method, applicable for all types of bulk handling operations and bulk products. The knowledge gained during the literature study and practical approaches in this research are incorporated in the dust control strategy. It takes the characteristics of the dust source, bulk materials, and dust control measures into account. A weighted multi-criteria analysis aims to identify the most suitable dust control method.

The developed dust control strategy is utilized to implement dust control methods at three different types of dust sources at Verbrugge. Since the organisational measures are operator-dependent, and their influence on dust control are not considered in this research, only technical measures are taken into account. The results of the implementation of the strategy are used for verification and proposing three methods to improve dust control at Verbrugge.

1.4. Report structure

The outline of the report is structured as follows. The situation at Verbrugge, including the bulk materials, legislation, and bulk terminal equipment and operations, is outlined in Chapter 2. Chapter 3 investigates the influence of bulk properties of different dry bulk products on bulk handling. Chapter 4 studies the generation and dispersion of dust emissions during handling dry bulk products and what bulk properties are related to the dustiness of a material. The mechanisms and techniques to control dust emissions are examined in Chapter 5. In Chapter 6 the performances of the dust control techniques applied at Verbrugge are evaluated. A dust control strategy is developed to obtain a structural approach for selecting the most suitable dust control method in Chapter 7. In Chapter 8, the dust control strategy is implemented by three dust sources at Verbrugge to review the strategy and propose dust control methods at Verbrugge. The discussion of this research is addressed in Chapter 9. Finally, Chapter 10 concludes the report by providing an answer to the main question and providing recommendations for further research.

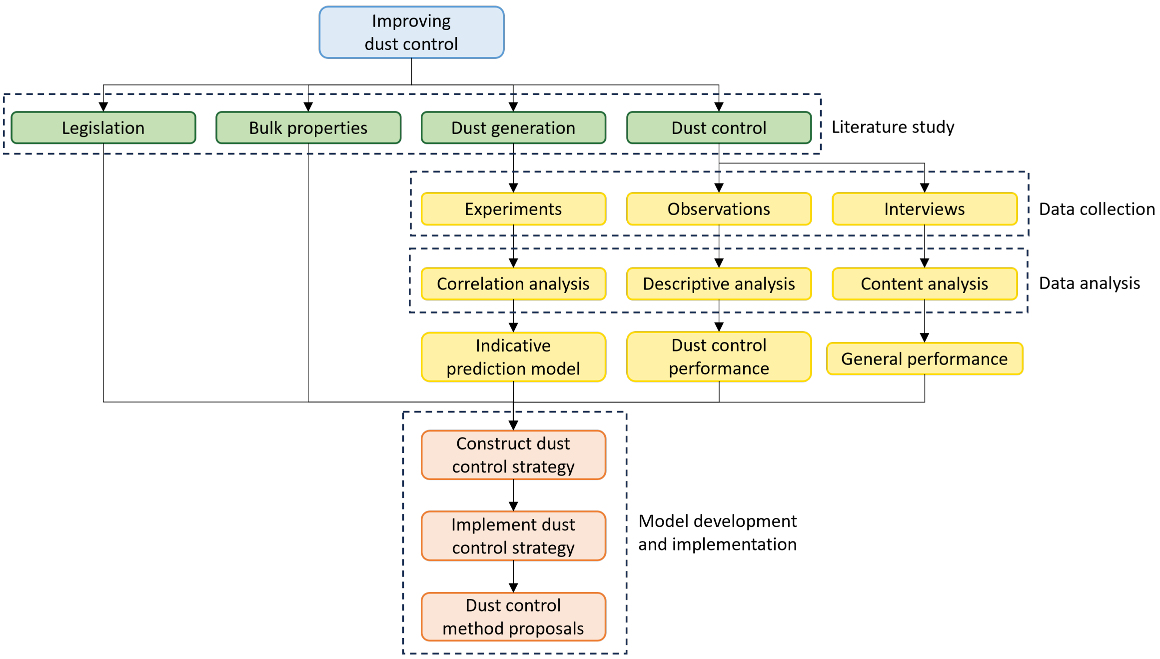


Figure 1.2: Methodology utilized in this research

2

Bulk terminal at Verbrugge

Although this research aims to improve dust control for bulk handling facilities in general, the bulk terminal at Verbrugge serves as the foundation for this research. In this chapter, the situation at the bulk terminal of Verbrugge is outlined. First, the dry bulk products handled by Verbrugge are discussed. Next, the regulations that apply to Verbrugge are investigated. Lastly, the layout of the bulk terminal is described.

2.1. Bulk products

Numerous dry bulk products are handled at the bulk terminal at Verbrugge. Besides soda, the primary bulk product, most materials handled have a fertilizing purpose. Examining each bulk product is not be feasible within the available time for this research. Therefore, a small selection of the bulk products handled at Verbrugge is taken into account. The considered bulk products in this study are soda, phosphate, and urea. The selection, presented in Table 2.1, was made with the intention of including materials with as many different bulk properties as possible. Soda, the primary bulk product handled at Verbrugge, is perceived as one of the most challenging materials with regard to dust control at Verbrugge. Phosphate, also highly sensitive to dust generation, has the tendency to adhere to equipment surfaces, which may lead to flow problems. Lastly, urea contains corrosive properties, like most fertilizing materials. Moreover, urea is handled in granular form as opposed to soda and phosphate, which are powders. Other relevant bulk properties of these bulk products are addressed in Chapter 3.

Table 2.1: The materials and their physical state handled at Verbrugge

Product	Physical state	Throughput percentage
Soda	Powder	67%
Phosphate	Powder	33%
Urea	Granulated	

2.2. Legislation

The bulk terminal at Verbrugge needs to be in compliance with the Dutch legislation. This section investigates what laws and regulations apply to Verbrugge with regard to dust emissions.

Figure 2.1 presents an overview of the regulations, the sources, and their relations to each other. Kenniscentrum InfoMil (2012) provides an instruction manual for determining the applicable regulations for companies contributing to air emissions. The following regulations need to be considered: the Activities Decree (Activiteitenbesluit milieubeheer (2023), hereafter: AB), the Environmental Management Act (Wet milieubeheer (2023), hereafter: WM), the Industrial Emissions Directive (Richtlijn

Industriële Emissies (2010), hereafter: RIE), and the Decree on Environmental Law (Besluit omgevingsrecht (2023), hereafter: BOR). The AB contains regulations concerning air emissions of companies and aims to reduce the emission freight and to provide measures to tackle emission sources. The WM specifies the requirements for good air quality, based on the RIE. The RIE present European guidelines for environmental polluting companies and demands an All-in-one Permit for Physical Aspects (Omgevingsvergunning, hereafter: APPA) before operations may commence. The BOR describes which activities require an APPA and determines what needs to be incorporated in its content.

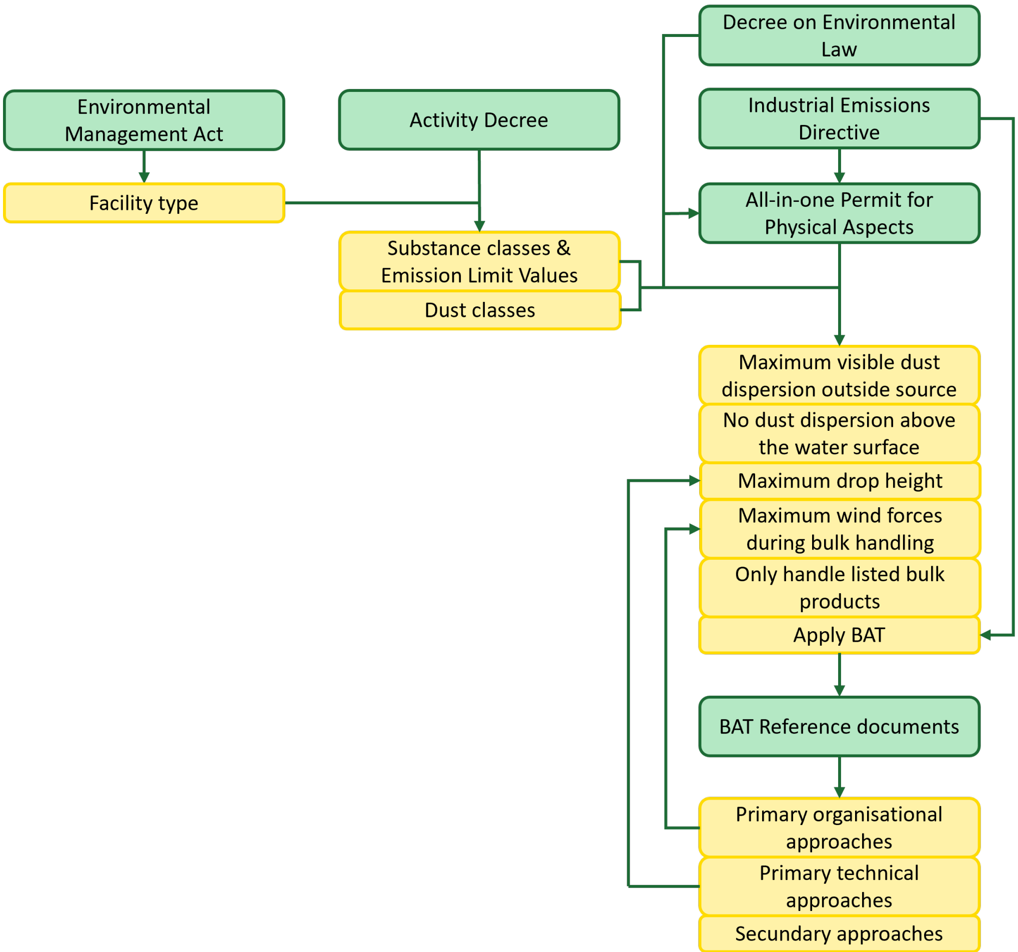


Figure 2.1: Relations between dust emission legislation

Based on these pieces of legislation, the applicable regulations for Verbrugge are determined. First, the type of facility needs to be determined. Three types of facilities can be distinguished: A, B, and C. Type C facilities can be further divided into companies with and without IPPC-installations. For the full descriptions of each facility type is referred to Kenniscentrum InfoMil (2012). According to the WM, Verbrugge can be considered a facility of type C without IPPC installations. Based on the facility type and the AB, the Emission Limit Values (ELV) for particulate matter are specified. The ELV for particulate matter is 5 mg/m^3 for a mass flow equal to or larger than 200 g/h, and 20 mg/m^3 for a mass flow below 200 g/h. Furthermore, the AB presents the dust classification of bulk materials (Table 2.2). The dust classes are distinguished by the sensitivity to generate dust emissions and whether the bulk product is wettable or not. Using moisture to reduce dust emissions is a common and effective method. However, due to the quality deterioration of some bulk products when adding moisture, many materials are not wettable. Such bulk products are categorised as S1 or S3 and must be stored in an enclosed storage facility. Yet, the ‘dustiness’ of bulk materials is not quantitatively defined by the dust classification. It is unclear how the sensitivity of dust generation is determined and what are the ranges of each dust class. Therefore, the dust classification may not be accurately representative and is only indicative. Since some regulations are based on the dust classification, the dust classes are still used in this study.

Table 2.2: Dutch dust classification

	Dust sensitive	Mildly dust sensitive	Not dust sensitive
Not wettable	S1	S3	S5
Wettable	S2	S4	

The APPA imposes the following regulations regarding dust emissions:

- Bulk materials are loaded, unloaded, transported, transferred and stored within the facility in the open air in such a way that visible dust dispersion 2 meters outside the source is prevented.
- Dust dispersion may not occur above the water surface.
- The unloading, loading and transshipment of bulk material must be stopped when this leads to visible dust dispersion 2 meters outside the source and/or spillage of bulk goods, but also in case of:
  - wind force 4 (8 m/s) or higher for bulk materials belonging to dust classes S1 and S2
  - wind force 6 (14 m/s) or higher for bulk material belonging to dust classes S3
  - wind force 8 (20 m/s) or higher for bulk materials belonging to dust classes S4 and S5
- The drop height of bulk materials from grabs, buckets, loading shovels and conveyor belts is kept as small as possible, but with a maximum of 1 meter
- The facility applies eligible Best Available Techniques (BAT). The relevant BREF (BAT Reference document) is: BREF Emissions from Storage

The first two regulations pose limitations on the (visible) dispersion of dust emissions. The following two regulations are measures that must be taken to contribute to the reduction of dust emissions. The last item imposes additional dust control measures to be incorporated to further reduce dust emissions. The BREF for Emissions from Storage presents the BAT for storage, transfer and handling of liquids, liquefied gases, and solids (European Commission, 2006). These are common measures and techniques to reduce dust emissions and can be divided into primary approaches and secondary approaches. Primary measures prevent the generation of dust emissions during the storage and handling of the materials and can be further categorised into organisational approaches, which regard the actions of operators, and technical approaches, which present specific equipment. Secondary approaches reduce the distribution of emitted dust. In this research primary and secondary measures will be referred to as preventive and suppressive measures, respectively. Generally, the prevention of dust generation is preferred over dealing with liberated dust emissions. Since completely preventing dust emissions is often not achievable, both preventive and suppressive measures should be implemented to minimise the dust emissions. The categories and associated BAT are presented in Table 2.3.

The BAT distinguishes organisational measures as dependent on the implementation by (the employees of) Verbrugge. Yet, some organisational measures may be enforced by the design of equipment. For example, the drives of the conveyor belts may be limited to a maximum conveyor speed. Therefore, the term ‘organisational’ may not be completely accurate. To avoid confusion, this research will keep the term organisational measures.

2.3. Bulk terminal layout

The bulk terminal at Verbrugge consists of various storage facilities, transport systems, and equipment. Bulk handling operations at the terminal can be divided into five categories: loading, unloading, transferring, conveying, and storage. The five types of bulk operations are illustrated in Figure 2.2. This example shows the import of bulk materials. Loading entails the discharge of bulk material into a transportation mode or storage facility, whereas retrieving the material is considered as an unloading operation. In between transshipment, bulk products are stockpiled in enclosed storage facilities. The transportation of bulk products between the various modes of transport and/or storage facilities consist

Table 2.3: Best Available Techniques for reducing dust emissions

Approaches and techniques to reduce dust emission from the storage and handling of solids		
Primary	Organisational	Weather conditions
		Monitoring
		Maintenance
		Measures (for the crane operator) when using a grab: - reduction of the drop height when the material is discharged - total closing of the grab/jaws after material pick-up - leaving the grab in the hoppers for a sufficient time after discharge
		Measures (for the operator) when using a belt conveyor: - suitable conveyor speed - avoiding loading the belt up to its edges.
		Measures (for the operator) when using a mechanical shovel: - reducing the drop height when the material is discharged - choosing the right position during discharging into a truck.
		Layout and operation of storage sites (by the planner and the operating personnel) - reduction of transport distances - adjusting the speed of vehicles - roads with hard surfaces - reduction of wind attack areas
	Technical	Use of wind protection
		Covering of open storage
		Moistening of open storage
		Optimised grabs
		Use of closed conveyors (e.g. tube belt conveyors, screw conveyors)
		Conveyor belt without support pulleys
		Primary measures on conventional conveyor belts
		Primary measures on transfer chutes
		Minimising speed of descent
		Minimisation of free fall heights (e.g. cascade hoppers)
		Use of dust barriers on dump pits and hoppers
		Low dust bunker
		Chassis of vehicles with round tops
Secondary	Screens for open conveyor belts	
	Housing or covering of the emission sources	
	Applying covers, aprons or cones on fill tubes	
	Extraction systems	
	Filter systems for pneumatic conveyors	
	Dump pits with suction equipment, housing and dust barriers	
	Optimised discharge hoppers (in ports)	
	The techniques of water spraying/water curtains and jet spraying	
	Cleaning conveyor belts	
	Fitting trucks with mechanical/hydraulic flaps	
	Cleaning of roads	
	Cleaning of vehicle tyres	

primarily of conveying the bulk products, commonly through conveyor belts. Transferring bulk products occurs at points where material is exchanged between two pieces of equipment. The layout of the bulk terminal of Verbrugge is shown in Figure 2.6.

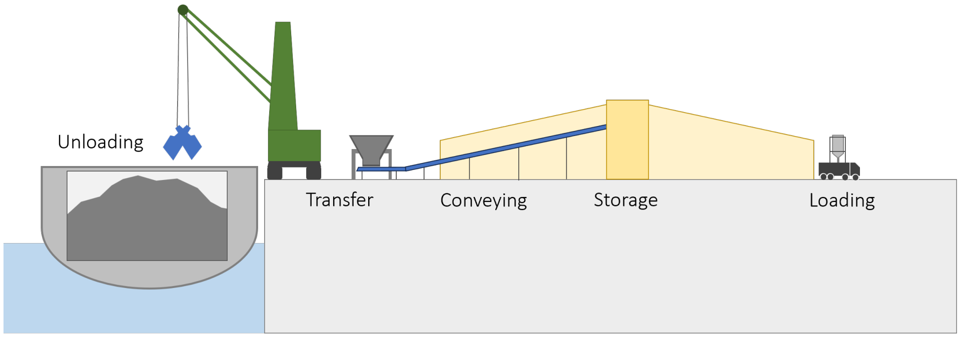


Figure 2.2: Illustration of typical operations at a bulk terminal

Infrastructure

The bulk terminal at Verbrugge enables import through road, rail, and water transport. The location of the terminal at the water gives Verbrugge the possibility for import and export by vessels. The quay is equipped with rails for travelling (un)loading equipment. The length of over 500 meters enables multiple (smaller) vessels to be (un)loaded simultaneously. The bulk terminal is also connected to the railway system for freight trains. Transport by trains is only used for the import of soda. Several routes allow accessibility to multiple (un)loading locations across the terminal for road transport.

Storage

Since most bulk materials handled at Verbrugge are categorised as dust class S1 or S3, the products are stored in enclosed facilities. The bulk terminal of Verbrugge consists of six warehouses designated for handling dry bulk. Three warehouses are utilized for the storage of soda, one warehouse is used for nepheline (a rock-formed mineral), and one warehouse is designated for various types of fertilizers, such as phosphate and urea. Warehouse 18 is not connected to the continuous transport systems, but soda is imported packed in big bags. In the warehouse the big bags are cut and emptied and the soda is transferred to and stored in silos. The soda from warehouse 18 is exported by road transport. Warehouses 42 and 48 stores soda imported by vessels and trains. Nepheline and fertilizers are only imported by vessels and stored in warehouse 43 and warehouses 35 and 36, respectively.

Table 2.4: Storage facilities

Warehouse	Capacity (m^3)	Products
18	27.296	Soda
35/36	180.000	Fertilizers
43	50.000	Nepheline
42	50.000	Soda
48	55.000	Soda

Transportation systems

Verbrugge has various types of equipment and numerous conveyor belt systems. The equipment functions can be divided into loading, unloading, transferring, and conveying. Loading techniques are deployed for the export of bulk products through water and road transport and for discharging bulk products into storage facilities. Unloading techniques are used to import bulk materials from the cargo hold of the vessels or vehicles, and gather stockpiled bulk products from storage facilities. Transferring equipment is used to pass bulk materials from one piece of equipment to another. Transport of the bulk products over large distances, between (un)loading and transfer equipment, is mainly carried out by conveyor belts.

Bulk products imported by vessels can be unloaded by various quay equipment. The main equipment deployed at the quay are a mobile crane (Figure 2.3), a rail-mounted (RM) gantry crane (Figure 2.4) and a RM hopper (Figure 2.5). The mobile crane and the RM crane, both provided with a grab, are utilized for unloading vessels. The mobile crane deposits the bulk material into the RM hopper by the grab, whereas the RM crane is equipped with its own hopper to receive the material. Both hoppers are fed bulk materials by the grab and have the capability to either transfer the bulk material to the conveyor belt system or redirect it to a loading chute attached at the bottom of the bunker. The loading chute can directly load open trucks. In addition to these primary quay equipment, several smaller mobile grab cranes can be used for unloading the vessel. These are mostly deployed for direct transshipment between vessels and trucks.

The grab cranes can also be deployed to load vessels. However, due to a new client with a high demand for exporting soda, a more efficient approach for vessel loading is desired. Therefore, Verbrugge is currently engaged with the installment of a new ship loader. The ship loader will travel on the same quay tracks as the RM crane and RM hopper. Conveyor belts transport bulk materials from the warehouses to the ship loader, which then loads the vessels.

Figure 2.3: Mobile grab crane for unloading vessels. Source: Verbrugge (2020)

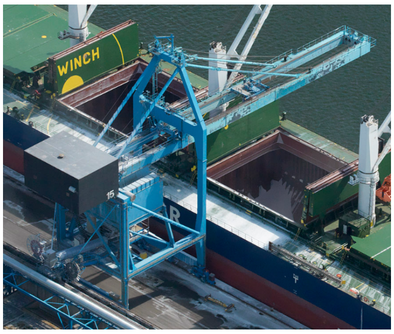


Figure 2.4: RM crane for unloading vessels. Source: Verbrugge (2024)

Figure 2.5: RM hopper for receiving bulk material discharged by grabs. Source: Verbrugge (2024)

Besides direct transshipment, trucks can also be loaded with bulk products stored in silos. Telescopic loading chutes below the silos load trucks with enclosed cargo spaces through a hatch.

Trains importing soda at Verbrugge are unloaded at the wagon unloading pit. The bulk product is discharged at the bottom of the wagon and received by a conveyor belt system.

After receiving bulk products by the quay equipment or wagon unloading pit, the conveyor belt systems transport the material to one of the warehouses. The warehouses are divided into multiple compartments, separating the different type of bulk products. In warehouses 35, 36, and 43, the bulk products are distributed by a tripper car with rotating throwing belt. The tripper car travels through the ridge of the warehouse so that it can reach all compartments. The rotating throwing belt can discharge bulk products on both sides of the warehouse and allows an evenly distribution of the material in the compartment. The bulk material is launched off the throwing belt into the compartment. No measures are taken to reduce the dust emissions generated by loading bulk products into the warehouse. Therefore, during discharge of (dust sensitive) materials, the warehouse is closed off to prevent the dust emissions from escaping. Warehouses 42 and 48 are both equipped with a tripper car and DSH travelling through the ridge. The tripper car enables a full loading range of all compartments, whereas the DSH minimises the dust liberated during discharge.

Bulk products stored in one of the warehouses are picked up by front loaders to export it. The front loader disposes the material into a reclaim bunker, which feeds the bulk product to a conveyor belt. The bulk material can be transported to a silo, where the product can be loaded into trucks, or to other conveyor belts.

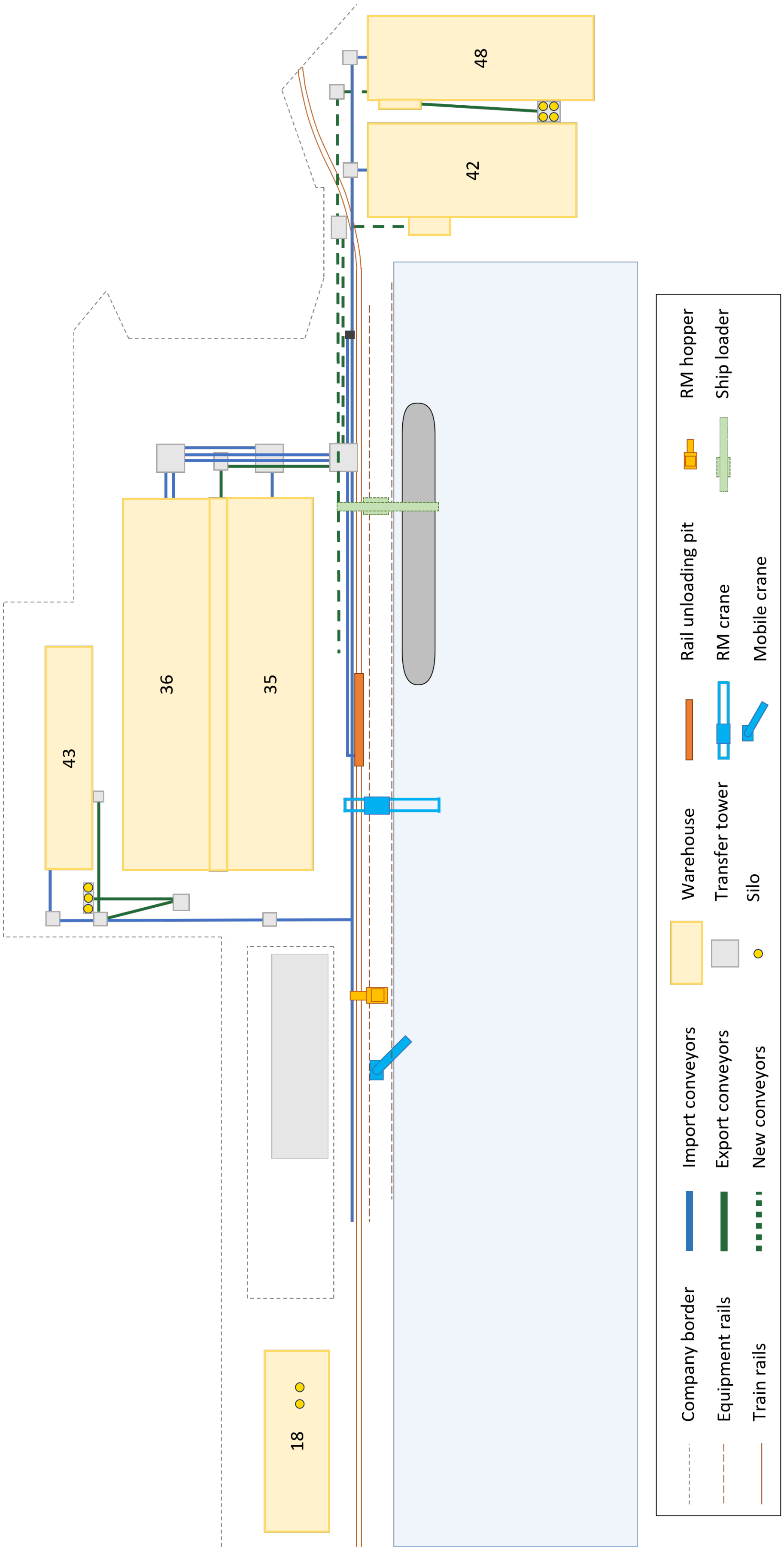


Figure 2.6: Layout of the bulk terminal at Verbrugge

3

Influence of bulk properties

Bulk handling equipment is typically designed for specific applications, including the type of bulk products they handle. This chapter explores how handling different bulk products can influence the design and operations of the bulk terminal equipment. First, the relevant bulk material characteristics and their impact on bulk handling are established. Then, the consequences of handling the specific bulk materials at Verbrugge on equipment design and operations is investigated.

3.1. Influencing bulk properties

Various bulk material characteristics are relevant for the handling process and equipment design. This section addresses which properties play a role in the handling of bulk materials and how they may influence the operations or design of bulk handling equipment. The relevant properties are categorised as the particle, flow, or strength property of the bulk materials, as presented in Table 3.1.

Table 3.1: Bulk material properties and categories

Property	Particle property	Flow property	Strength property
Particle size	x		
Particle size distribution	x		
Particle shape	x		
Particle density	x		
Bulk density		x	
Compressibility		x	
Cohesion & Adhesion		x	
Hygroscopy	x	x	
Flow function		x	
Angle of internal friction		x	
Angle of wall friction		x	
Angle of repose		x	
Abrasion			x
Friability			x
Corrosion	x		
Hazardous	x		

Particle size

The particle size plays an important role in the flowability and generation of dust emissions. The mass of a spherical particle decreases faster with the radius of the particle than its surface area. Due to the relative larger surface area, smaller particles have a decreased flowability (Ganesan et al., 2008). Moreover, the particle size is related to the dustiness of bulk material. Smaller particles require less force to be separated from the bulk stream and take more time to settle down under gravity, as will be further explained in Chapter 4. However, bulk materials often consists of a range of particles sizes, represented by the particle size distribution.

Particle size distribution

The particle size distribution (PSD) indicates the proportions of particles sizes in a bulk material (Schulze, 2008). In bulk materials with a wider PSD, smaller particles fill the gaps between larger particles, creating more contact points among particles and enhancing the cohesive strength (Ganesan et al., 2008). Therefore, the flowability generally decreases with a larger range of size distribution.

Particle shape

The flow of the bulk materials is also affected by the shapes of the particles. Whereas the flowability of coarse, smooth, spherical particles is generally better, cohesive materials might benefit from more rough, irregular-shaped particles as the inter-particle distance increases. However, a uniform relation between the particle shape and flow of the material cannot be established (Schulze, 2008).

Particle density

The particle density equals the mass of particles per unit volume. Barbosa-Cánovas et al. (2005) describe three definitions of the particle density: true density, apparent density, and effective density. The true particle density divides the particle mass by the volume excluding any pores. Hence, it denotes the density of solely the solid material. The apparent density only excludes the open pores for the volume, and can be determined by gas or liquid displacement methods. The effective density includes both open and closed pores in the volume. The particle density is useful for determining the weight of particles and certain forces acting on the particle, such as gravity and buoyancy.

Bulk density

The bulk density is defined as the mass per unit of volume occupied by the material (Abdullah and Geldart, 1999). This volume includes the voids in between particles, in addition to the volume of the material particles. However, the bulk density is not an intrinsic property and depends on the packing of the material particles. Therefore, the value for bulk density may vary between a certain range. Two ways of packing can be distinguished: random loose packing and random dense packing. Random loose packing creates an aerated bulk density by releasing particles into a container and letting it settle by gravity. Frictional forces between particles provide resistance against compression of the bulk material, resulting in loose bulk density. Tapping the container containing the loosely packed material temporarily reduces the frictional forces between particles, allowing the collapse of the material. The volume occupied by the material decreases as the voids are filled by particles. Hence, the bulk density increases as the mass of the particles remain while the volume is reduced. Figure 3.1 illustrates the bulk density of a loose and dense packed bulk material. The state of compaction relates to the cohesion of the bulk material, and thus also influences the flowability and dust generation. The bulk density is mainly important to determine dimensions of the bulk handling equipment in order to obtain the desired flow rate in the bulk handling processes.

Compressibility

The tapping of a contained bulk material decreases the material volume. After a certain amount of tapping, the material cannot be compressed any further. The ratio between the original volume (V_0) and compressed volume (V_n) is called the Hausner ratio (H_R), which denotes the compressibility of the material. Barbosa-Cánovas et al. (2005) describes the equation of the Hausner ratio, given by:

$$H_R = \frac{V_0}{V_n} \tag{3.1}$$

The Hausner ratio is an indication of the flowability of the bulk material, as presented in Figure 3.2.

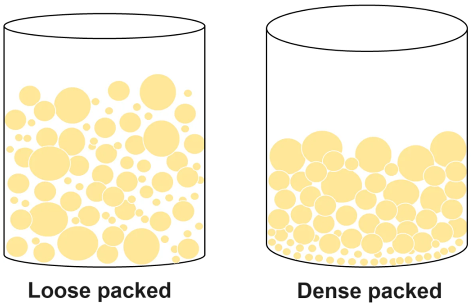


Figure 3.1: The bulk density of loose packed and dense packed bulk material. Adapted from Bettersize Instruments Ltd. (2022)

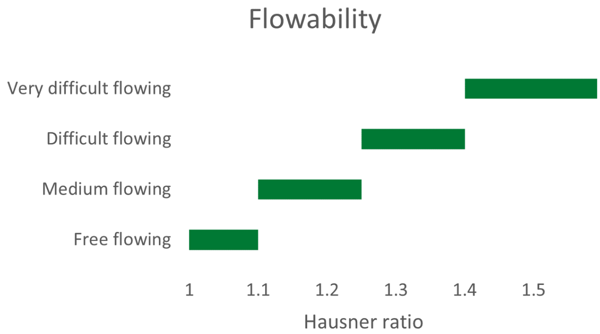


Figure 3.2: The flowability indication based on the Hausner ratio.

Cohesion and adhesion

Cohesion and adhesion represent the attraction forces among particles and between the bulk material and other surfaces, respectively (Barbosa-Cánovas et al., 2005). The binding forces depend on the PSD, other forces acting on the bulk material, such as compression or gravity, and the moisture content, as will be further explained in Chapter 4. Larger cohesive forces require larger separation forces to liberate dust particles, but also reduce the flowability. Adhesivity may contribute to material build-up on equipment surfaces.

Hygroscopy

The moisture content plays an important role in the cohesion and flowability of the bulk material. The extent to which a material absorbs moisture depends on the hygroscopic property and the humidity level. A common issue with hygroscopic bulk materials is caking. By absorbing moisture, the formation of liquid bridges increases and the material becomes more cohesive. Particles agglomerate and form solid clumps. The increased cohesion and formation of clumps decrease the flowability, increase the risk of clogging, and contribute to faster wear of the equipment (Borax, 2017).

Figure 3.3: The formation of clumps due to the absorption of moisture

Measures have to be taken in order to increase the flowability and prevent clogging by clumps of a hygroscopic bulk material. A primary means to shield bulk products against external influences like weather conditions is to incorporate enclosures. However, this method may not be entirely effective, especially in high-humidity environments, where some absorption of moisture by the bulk products can still occur. Hence, lump breakers and sieves can be additionally deployed to break down the agglomerates and filter out clump sizes above certain dimensions.

Flow function

The flow function shows the relation between the unconfined yield strength and the consolidation stress. The unconfined yield strength (σ_c) represents the stress required to cause bulk material to flow after consolidation. The unconfined yield strength can be determined by a uniaxial compression test, as described by Schulze (2008). Bulk material contained in a cylinder is loaded with a consolidation stress (σ_1). Subsequently, the consolidation stress and the cylindrical container are removed. The bulk material is loaded until failure, which results in flow of the material. The stress required to cause the bulk material to flow is the unconfined yield strength. The flow factor (ff_c) of a bulk material is the slope of the flow function, which is defined as:

$$ff_c = \frac{\sigma_1}{\sigma_c} \tag{3.2}$$

A larger flowability ratio signifies a better flowing bulk material, as illustrated in Figure 3.6.

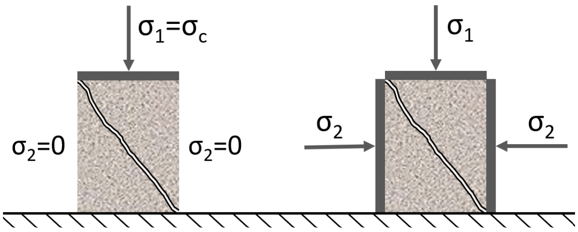


Figure 3.4: Incipient flow before and after consolidation

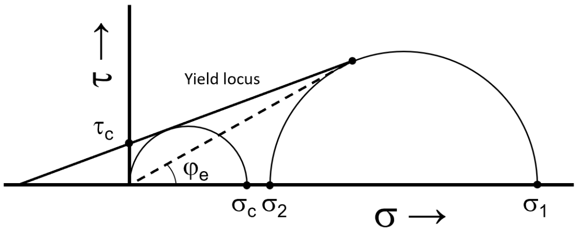


Figure 3.5: Yield locus

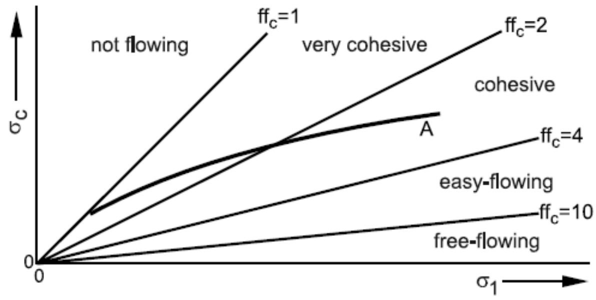


Figure 3.6: Flowability as a function of the consolidation stress and unconfined yield strength. Source: Schulze (2008)

Angle of internal friction

The effective angle of internal friction relates to the friction between particles of the bulk material (Schulze, 2008). A higher internal friction angle requires a larger force to move the material. The effective angle of internal friction, φ_e, can be determined by the following relation between the major and minor principle stresses, σ_1 and σ_2:

$$sin\varphi_e = \frac{\sigma_1 - \sigma_2}{\sigma_1 + \sigma_2} \tag{3.3}$$

Angle of repose

The state of compression, cohesion, moisture content, and internal friction all play a role in the flowability of a bulk product. A convenient way to achieve an indication of the flowability of a bulk material is to determine the angle or repose (AoR). The AoR is defined as the angle between the slope of a heap of bulk material and the horizontal. Materials experiencing a smaller AoR denote a better flowability than materials with a larger angle, as shown by Table 3.2 (Akhand et al., 2013). Rhodes (2008) describes three common ways to determine the AoR, which are through either pouring, draining, or rotating the material (Figure 3.7). The pouring method creates a pile on a flat surface through discharging the bulk material through a funnel. This method is not applicable for cohesive materials, as it could obstruct the funnel (Barbosa-Cánovas et al., 2005). The drained AoR is obtained by draining bulk material contained in a cylinder through a central outlet. The draining method usually achieves a larger AoR. When the AoR of a bulk material in motion is desired, the dynamic AoR can be determined by the rotating method. The bulk material in a cylinder container is rotated and shows, dependent on the rotating speed, the AoR.

Angle of wall friction

The angle of wall friction concerns the friction between the bulk material and a solid wall material (Schulze, 2008). Therefore, it is of importance for designs of silos and chutes, where a bulk material

Table 3.2: Relation between the flowability and AoR

AoR	Flowability
< 25°	Excellent
25°- 30°	Good
30°- 40°	Passable
> 40°	Poor

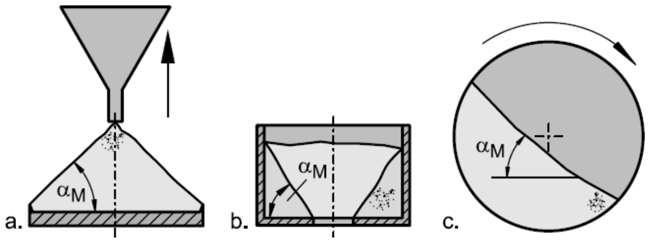


Figure 3.7: Three methods to measure the angle of repose; a) pouring, b) draining, c) rotating. Source: Rhodes (2008)

flows across a wall. Since the wall shear stress depends on the normal stress, the angle of wall friction is introduced, which is determined by the following equation:

$$\varphi_x = arctan\left(\frac{\tau_w}{\sigma_w}\right) \tag{3.4}$$

In this equation, φ_x is the angle of wall friction, τ_w the shear stress, and σ_w the normal stress.

Abrasion

Abrasion is the wear of equipment as the bulk material comes in contact with the surface of the equipment material (Barbosa-Cánovas et al., 2005). The abrasiveness of a material is related to the hardness of the particles. The hardness of a material is measured relatively to other materials and can be defined as the resistance of a material to plastic deformation caused by another material. There are various methods and scales to measure the hardness. Mohs hardness scale is commonly used measure of the hardness of a bulk material, where materials are denoted an index between 1 (soft) and 10 (hard) (Figure 3.8). The following rule of thumb can be used to indicate the hardness:

- index between 1 and 3: soft
- index between 3.5 and 5: medium
- index between 5 and 10: hard

Material wear contributes to the formation of small particles, potential dust particles. The influence of abrasion to dust generation is further discussed in Chapter 4.

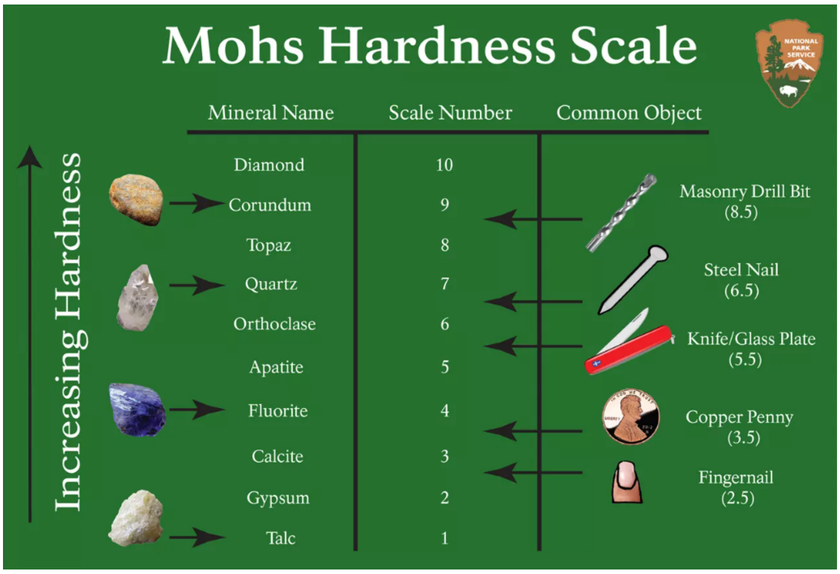


Figure 3.8: Mohs hardness scale. Source: National Park Service, 2023

Friability

The friability of materials indicates the tendency of breakdown of particles into smaller pieces (Barbosa-Cánovas et al., 2005). Friable bulk material require gentle handling to avoid generation of fine particles, which is a source of dust. Since dust emissions are related to several properties and handling conditions, the friability is not a good indicator of the dustiness of a bulk material. The categorisation of the dust classes gives a more representative indication of the dustiness of the bulk material.

Corrosivity

Corrosive materials cause damage to other materials, such as living tissue and metals, due to a chemical reaction when they come into contact (EcoOnline, n.d.). Therefore, corrosives can be very harmful for people, equipment, and the environment. Figure 3.9 shows an example of corrosion at an installation of Verbrugge. An important indicator of the corrosiveness of a material is the pH level. The corrosivity generally increases with more acidic (lower pH) or basic (higher pH) materials. Furthermore, materials considered as oxidizing or dehydrating agents can also have corrosive properties (EnviroServe, 2021). The level of corrosivity is based on the experiences with the material.

Due to the harmfulness for people and materials, corrosive products require safe storage and handling. According to Martinelli (2018), corrosives should be stored separately from other materials, especially if they are incompatible. The storage facility should also be well ventilated, constructed from corrosive resistant materials, be provided with suitable cleaning and firefighting equipment, store only below eye level, and maintain an appropriate temperature. Employees working with corrosive materials should wear Personal Protective Equipment (PPE), such as gloves, goggles, boots, and protective clothing. Equipment that comes into contact with corrosive materials should be thoroughly cleaned to avoid hazardous reactions with other materials.

Hazardous properties

If bulk products contain hazardous characteristics those materials need to be stored and handled with extra care. Most hazardous properties derive from the ignitability, reactivity, or toxicity of the product (US EPA, 2015). The ignitability of a material could because of a flash point below 60 °C, or the ability to ignite a fire through friction, moisture, chemical changes or process heat. Hazardous reactive threats can be initiated by unstable materials subjected to chemical changes, products dangerously reacting with water and possibly forming an explosive substance or toxic fumes, or materials able to detonate or explode at normal temperatures and pressures (Figure 3.10). Health or environmental harm can be a consequence of ingestion or absorption of a toxic product. Although non-hazardous products may not impose direct health or safety risks, it is always recommended to avoid eye and skin contact, inhalation, and ingestion.

Figure 3.9: Corrosion at an old installation at Verbrugge

Figure 3.10: Dust explosion. Source: Price (2020)

Overview

The descriptions of the bulk properties show most bulk properties are related to or dependent of each other. Figure 3.11 shows an overview of the relations between the bulk properties, and how it influences the equipment design. The moisture content depends on the hygroscopy of the material and the humidity level. Cohesion is related to the particle size and distribution, moisture content, and the handling conditions of the bulk material. The particle shape, internal friction, and cohesion influence the flowability of a bulk material. The influence on the equipment design follows from both the regulations as the bulk properties like the flowability. Some regulations depend on the dust classification of bulk materials. Abrasion, dependent on the hardness of materials, the wall friction, and corrosivity may influence the material selection bulk handling equipment. The bulk density and flowability are important properties of the dimensions, design, and operations of the bulk handling equipment.

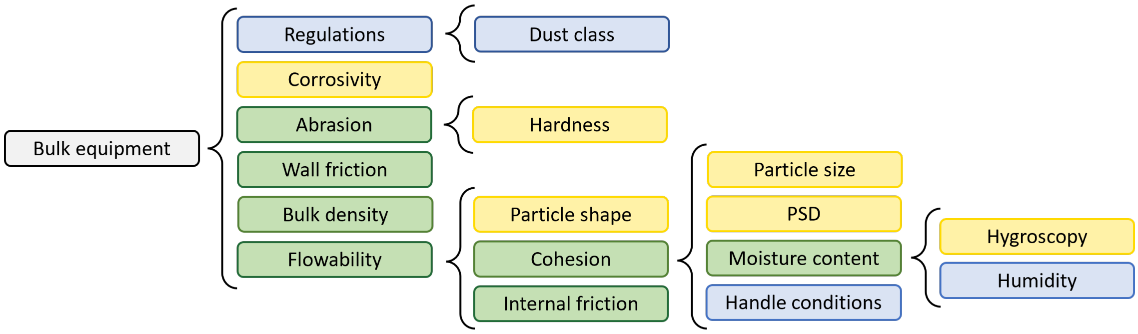


Figure 3.11: Relation between various bulk properties and the equipment design

3.2. Bulk product properties

The investigated materials at Verbrugge are: soda, phosphate, and urea. This section looks into the bulk material properties of these materials. As described in the previous section, many properties are related and often dependent on each other. Therefore, it is redundant to establish each bulk property separately. Table 3.4 summarizes which bulk properties should at least be considered. The bulk properties are based on online available data and Material Safety Data Sheets (MSDS). However, data for some properties may show some variations among the different sources. A reasonable explanation for these differences are that bulk products often have some varying characteristics based on the origin of the product, the gathering method, and the way the material is handled. Therefore, some bulk properties are experimentally tested to compare the characteristics of these materials with the findings in literature.

3.2.1. Tested bulk properties

Bulk density

The bulk density is determined by collecting a sample of the bulk product with a volume of 400 cm^3, and measuring the mass. By dividing the mass by the volume the bulk density is achieved. The measurement is repeated five times and the average value is taken.

Angle of Repose

The AoR is an important and frequently used indicator of the flowability due the relatively simple determination methods. The pouring method is used to obtain a heap of bulk material. Then, the AoR (α) is determined by measuring the width (w) and the height (h) of the heap with the equation:

$$\alpha = tan^{-1}\frac{2h}{w} \tag{3.5}$$

The measurement is repeated five times and the average value is taken.

3.2.2. Bulk products

The characteristics and uses of the considered bulk products are described in this section. The results of the bulk properties are summarized in Table 3.3.

Soda

Soda, also referred to as soda ash or sodium carbonate, is the main product handled at the bulk terminal. Therefore, soda is considered the key factor in the bulk handling equipment at Verbrugge, and plays the decisive role if conflicting design considerations regarding different products occur.

Ansac (n.d.) describes four main uses of soda. The most common application of soda is in the glass production industry. Soda enables a lower furnace temperature as it reduces the melting point of silica, thus saving on the required energy of glass production. An expanding application for soda is the manufacturing of lithium batteries, where it is used to produce lithium carbonate. A generally well-known field utilizing soda is in household products purposed for cleaning. It can be used to remove grease or alcohol stains, or to aid the distribution of the cleaning products. Moreover, soda is widely used in the chemical industry. The applications range from pH neutralizing to the production of sodium chemicals, and from the synthetic detergent industry to the petroleum industry.

Soda is a white, odourless bulk material with the chemical formula Na_2CO_3. Soda is a powdery substance and is at Verbrugge mostly known for its dustiness. Although the official dust class for soda is S3, experience at Verbrugge indicates otherwise. The dustiness of soda is assumed to be influenced by the origin and production process of the bulk product. The soda handled at Verbrugge is highly prone to liberate dust emissions and considered as an ‘S1’ bulk product. Contact with moisture should be avoided, as soda is a hygroscopic material and forms solid clumps when exposed to humid conditions. Soda is quite harmless for people and the environment. It may cause some eye irritation and it is mildly corrosive, but does not pose any hazards otherwise. Hence, the most challenging of handling soda is the dust formation and preventing contact with moisture.

Phosphate

Processed phosphate rock, rich of phosphorus, is used in the production of many fertilizers (HandyBulk, n.d.). After mining phosphate rock, also called phosphorite, it is crushed and grounded into a powdery form. The powder is used to produce various types of phosphate fertilizers, such as diammonium phosphate, monoammonium phosphate, and triple superphosphate. Verbrugge currently handles mostly raw phosphate rock powder, which will hereafter be referred to as ‘phosphate’. Besides fertilization, phosphate is used in food, beverages, treatment of drinking water, and various industrial applications.

Phosphate is a very fine powder with a relative high particle density, as compared to soda and urea. The AoR found in literature is significantly larger than the experimentally tested AoR. The difference could be a result of variations in moisture content or handling conditions. It is recommended to further investigate the flowability of phosphate for more reliable results. In this research, the least favorable AoR is considered to account for the ’worst case’ scenario, assuming that phosphate has poor flowability. At Verbrugge, phosphate is known as a bulk product that adheres easily to the equipment. Large inclination angles of equipment surfaces are required to prevent the product to remain behind. With a score of H=5 on Mohs hardness scale, phosphate is harder than the other two bulk materials, which suggests a more abrasive material. Similar to soda, phosphate is highly sensitive to generating dust and caking with an increasing moisture content. Therefore, phosphate is also classified as dust class S1. Further, phosphate may cause irritation to skin, lungs and eyes, but is relatively harmless otherwise. The most considerable bulk properties to take into account for handling phosphate is the flowability, adhesion, and dust generation.

Urea

The most common application of urea is fertilization (The Chemical Company, 2022). An important feature of urea is the high nitrogen content in comparison to other fertilizers. In the chemical industry, urea is used in the manufacturing of several plastics, adhesives, and urea nitrate (explosives). Another field of application is in automotive systems, to decrease the NOx concentration in exhaust gases. In addition, there are many more applications for urea.

The chemical formula of urea is $CO(NH_2)_2$ and it is handled in a granular form. It is less likely to generate dust emissions compared to soda and phosphate, classified as S3. An important characteristic of urea is its corrosivity to non-ferrous metals. Due to the location near sea water and the maritime climate, Verbrugge already contends with a higher level of corrosion. Therefore, handling urea and other fertilizers necessitates careful consideration in selecting materials for the bulk equipment. Furthermore, explosion hazards may be posed when mixed with strong acids or nitrates. Therefore, it is important to thoroughly clean the equipment when switching between bulk products.

Figure 3.12: Soda

Figure 3.13: Phosphate

Figure 3.14: Urea

Table 3.3: Bulk properties of soda, phosphate and urea

Property	Soda	Phosphate	Urea
PSD	280 +/- 50 μm[1]	10 - 250 μm[2]	1851 +/- 406 μm[3]
Particle density	2,52 g/cm^3[1]	3,12 g/cm^3[2]	1,33 g/cm^3[4]
Bulk density	950-1100 kg/m^3[1] / 1304 kg/m^3[0]	794-1563 kg/m^3[5] / 1909 kg/m^3[0]	700-780 kg/m^3[4] / 871 kg/m^3[0]
Angle of repose	32°[6] / 24.9°[0]	40°[6] / 25.5°[0]	34°[6] / 28.0°[0]
Hygroscopy	Hygroscopic[1]	Hygroscopic[2]	Hygroscopic[3]
Mohs hardness	H=1.3[7]	H=5[8]	H=1.5-3.5[9]
Corrosivity	Mildly corrosive[10]	Not corrosive[2]	Corrosive to non-ferrous metals[3]
Hazards	May cause eye irritation[1]	May cause skin, lung, and eye irritation[2]	May be explosive when mixed with strong acids or nitrate[4]
Dust class	S1	S1[11]	S3[11]

[0] Tested
[1] Tata Chemicals Europe (2023)
[2] OCP (2017)
[3] BASF (2019)
[4] AOA (2015)
[5] BiMCO (2018)
[6] Bureau of Indian Standards (2002)
[7] Patnaik (2003)
[8] Johnson et al. (2017)
[9] Donghai ranlu New Material Co., Ltd (2020)
[10] Ansac (n.d.)
[11] Activiteitenbesluit milieubeheer (2023)

3.3. Conclusions

The bulk handling equipment is influenced by several bulk properties and needs to be in accordance with the regulations regarding dust emission. The most relevant regulations are:

- A maximum dust dispersion of 2 meters outside the source in the open air.
- Handling of bulk products is stopped if the wind force is equal to or higher than 4 for dust classes S1 and S2, 6 for dust class S3, or 8 for dust classes S4 and S5.
- Dust dispersion is not allowed above water surface.
- A maximum drop height of 1 meter.
- Apply the BAT for handling bulk materials.

The influence of bulk products on bulk handling can mainly be attributed to the corrosivity, abrasion, wall friction, bulk density, and the flowability. The first three may affect the material selection of bulk equipment. The bulk density and flowability are mostly relevant for the equipment design and dimensions.

The bulk handling equipment needs to take the adhesiveness of phosphate into account. It is more likely to form obstructions and leave residues in the equipment. Moreover, the equipment material is influenced by the corrosivity of urea, and the hardness of phosphate. Further, all three bulk products are not wettable. The bulk products need to be enclosed in order to protect against moisture by external conditions, such as rain and high humidity levels. Lastly, soda and phosphate are both highly sensitive to dust generation. Hence, incorporating measures preventing and reducing dust emissions is required. In order to effectively reduce dust emissions, it is necessary to investigate the causes of dust generation.

Table 3.4: Influencing factors and their relevance in bulk handling

Bulk property	Relevance
PSD	The PSD is an important factor as it plays a role in the cohesion, flowability, and dust generation. The PSD presents both the range of particle sizes and their relative concentrations.
Particle density	The particle density is not directly relevant for the bulk handling equipment, but is used to determine the mass of (dust) particles.
Bulk density	The bulk density indicates the throughput of the bulk material and is an essential factor in determining the equipment dimensions.
AoR	The flowability of a bulk material is an important factor in the design of handling equipment. Kalman (2021) investigated methods to estimate the flowability of bulk materials, and concluded AoR to be the most accurate method.
Hygroscopy	Hygroscopic bulk material are prone to absorbing moisture in a humid environment. The moisture content influences the cohesion, but also contributes to the formation of clumps.
Abrasion	The wear of the bulk handling equipment is related to the hardness of a material. Mohs hardness scale is used to determine the relative hardness.
Corrosivity	The corrosivity of a bulk material plays a role in the material selection of the bulk handling equipment.
Hazards	Hazardous properties need to be taken into account in the operations and design of bulk handling equipment.

4

Generation of dust emissions

Dust emissions occur at various points in a bulk terminal. It is important to identify the main causes of dust formation at a bulk terminal. This chapter investigates the principles of dust development, the influences of material characteristics on the dustiness of a bulk product, and the trajectories of dust particles after liberation. Further, the contribution of the dust generation mechanisms are experimentally tested.

4.1. Dust development

This section addresses the definition of dust, the main principles of how dust emissions are generated, and what bulk properties are related to the dustiness of a material.

4.1.1. Definition of dust

There is no exact definition for ‘dust’ or the particle size range of dust, as it is usually varies with the field of application. In terms of air pollution, primarily fine dust particles up to 10 μm are considered. The particulate matter can be divided into PM10 for particles up to 10 μm, and PM2.5 for particles up to 2.5 μm (US EPA, 2016). Fine dust is not visible to the human eye and is considered more hazardous, as it can travel further and penetrate deeper into the respiratory system. Coarser dust particles cause more nuisance in the surroundings due to the settlement of dust. In the dry bulk handling industry, dust is generally considered as small solid particles that can either become or already are airborne. Rijkswaterstaat (2020) considers dust as all airborne particles, independent of the particle size. The regulations for Verbrugge consider visible dust clouds, without specifications about particle sizes. Hence, in this research dust will not be defined by dimensions, but by a particle’s ability to become airborne.

4.1.2. Dust emissions principles

Chakravarty et al. (2019) describe three mechanisms occurring in bulk handling that contribute to dust generation: free fall, forced elevation, and attrition. Free fall generally occurs during bulk material transfers, like the exchange between conveyor belts or loading of a vessel. During free fall, the bulk material accelerates through the air, which induces aerodynamic forces that separate dust particles from the falling stream. Additionally, when the bulk product lands on a surface or pile of material, dust particles are released by the impact. During forced elevation, the bulk material is transferred pneumatically, causing dust particles to be lifted by aerodynamic forces. Attrition generates dust as individual particles experience friction and collisions, leading to the breakdown into smaller particles, which are more prone to be liberated into the air.

These three mechanisms represent the occurrences of dust generation rather than the actual causes. Based on the descriptions, three main principles of generating dust emissions are established: particle breakdown, impact, and aerodynamic forces. The development of dust emissions is be subdivided into dust particle formation and dust liberation.

Particle breakdown

Particle breakdown is caused by collisions and frictional forces of individual particles, resulting in not only attrition, but also fracture and abrasion, as graphically presented in Figure 4.1 (Daouadji and Hicher, 2010). Fracture causes a particle to break down into several smaller pieces, each roughly the same size. With attrition, several small pieces are created, whereas a large part of the particle remains intact. Abrasion creates very fine particles due to the separation of small imperfections on the surface of the particle. The primary causes of particle breakdown and creating dust particles are inter-particle forces such as friction and collisions. Although the particle size for dust is not specified, smaller particles are more likely to become airborne, as will be elaborated in Section 4.1.3. Hence, the generation of smaller particles is considered as dust particle formation.

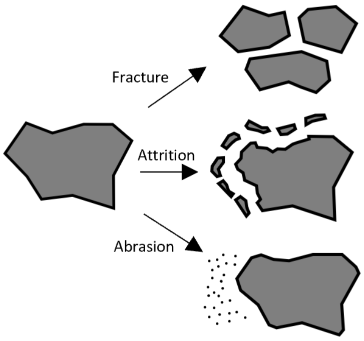


Figure 4.1: Particle breakdown by fracture, attrition, or abrasion.

Impact

Bulk material enduring an impact force promotes inter-particle forces among particles, which contributes to the breakdown of particles, but also separation forces on particles in the main bulk flow. Bulk material is kept together due to cohesive forces. If an impact leads to separation forces exceeding the cohesive forces, dust particles get separated from the main bulk stream.

Dust liberation due to impact can be explained by the conversion of the kinetic energy of the bulk material into kinetic energy of the dust particles upon impact. The kinetic energy (E_k) converted at impact is determined by the equation:

$$E_k = \frac{1}{2}m(\vec{v}_2^2 - \vec{v}_1^2) \tag{4.1}$$

where m is the mass of a particle, and v_1 and v_2 are the velocities before and after impact, respectively (Figure 4.2). Hence, a larger change in velocity and direction corresponds to greater release of energy, and thus the impact.

Impact during bulk handling is caused by a physical interaction with storage and handling equipment, or bulk material with a relative difference in velocity. Such interactions may occur in the following situations:

1. At transfer and (un)loading points, where the bulk material collides with the inner surfaces of the equipment
2. After discharge, where the bulk material lands on a horizontal or inclined surface
3. After discharge, where the bulk materials lands on a pile of bulk material

Figure 4.3 presents an example of how impact is induced on bulk material in three different ways.

Aerodynamic forces

As bulk material moves relative to the air, aerodynamic forces are induced. First of all, the aerodynamic forces contribute to the generation of dust particles as the air currents promote the movements of individual particles within the bulk stream, which advances particle breakage. The separation of dust particles by the main stream occurs when aerodynamic forces exceed the cohesive forces. Moreover, a

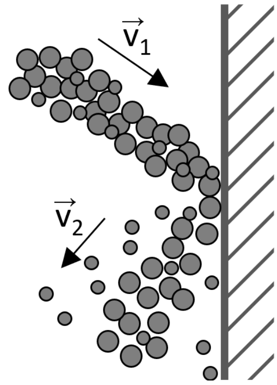


Figure 4.2: Impact causes a change in velocity and direction of the bulk material

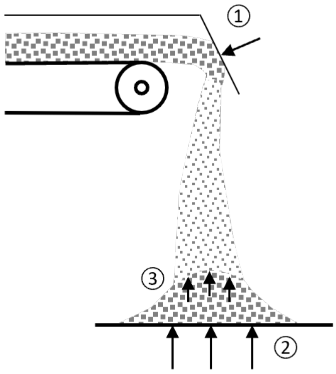


Figure 4.3: Three situations of impact induced on the bulk material

bulk product moving with a relative velocity to the air disperses and entrains surrounding air. Turbulent air flow causes the bulk particles to mix with the entrained air as the material moves. Dust particles carried by the entrained air are released from the bulk stream due to aerodynamic forces, or upon impact of a free-falling bulk product (Ansart et al., 2009). This mechanisms is usually referred to as *air entrainment*.

In general, the generation of dust emissions caused by aerodynamic forces is a result of bulk material and air flow moving relative to each other. The relative motion may present itself in three situations:

1. The bulk product is in rest ($V_{bulk} = 0$) and there is an external air flow (such as wind) ($V_{air} \neq 0$)
2. The bulk product is in motion ($V_{bulk} \neq 0$) and there is no air flow ($V_{air} = 0$)
3. The bulk product is in motion ($V_{bulk} \neq 0$) and there is an (external) air flow with a different velocity than the bulk product ($V_{air} \neq 0$)

At a bulk terminal such situations may present itself at open storage (1), transportation by conveyor belts (2), and transfer, loading and unloading operations in an enclosed environment (2) or in open air (3). Figure 4.4 shows an example where the three situations present itself.

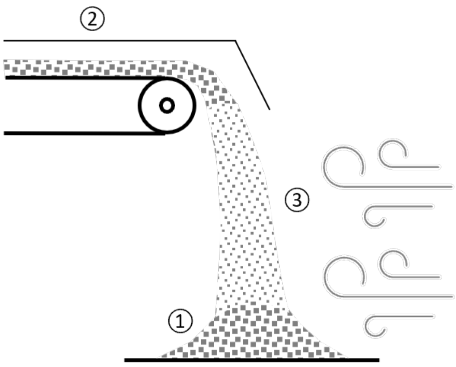


Figure 4.4: Three situations of aerodynamic forces induced on the bulk material

4.1.3. Influencing factors

The extent to which a bulk product liberates dust is influenced by several material properties. This section describes the material characteristics related to the dustiness of bulk products.

Cohesion

As stated earlier, the force required to separate dust particles from the bulk material needs to exceed the inter-particle binding forces. These binding forces mainly represent the cohesion among the product and keep the particles together. The inter-particle binding forces consist of Van der Waals forces, electrostatic forces, and capillary forces, as shown in Figure 4.5 (Chakravarty et al., 2019). Van der Waals forces are induced by the electric dipoles of atoms. The dipole moment produces an electric field, which causes the dipole moments of all atoms to align accordingly (Figure 4.5a). This causes an attraction between the dipoles, resulting in an attraction between particles (Rhodes, 2008). The Van der Waals forces, F_{vdW}, are determined by the equation

$$F_{vdW} = \frac{-HR}{12d^2} \tag{4.2}$$

where H is a Hamaker constant, which depends on the material of the particles, R is the radius of the particle, and d is the distance between the particles (Chakravarty et al., 2019). From this equation it becomes clear particles with a larger diameter experience a larger van der Waals force than smaller particles, and the van der Waals forces decreases quadratically with an increasing distance between the particles. At little to no distance between particles, van der Waals forces are one of most dominant binding forces. However, as the distance between particles increases, the van der Waals forces reduce strongly.

Electrostatic forces are caused by electric potentials of the particle surface (Figure 4.5b). Electrostatic forces are relatively small and negligible at small distances between particle in comparison to van der Waals forces. The electrostatic force, F_E, is given by

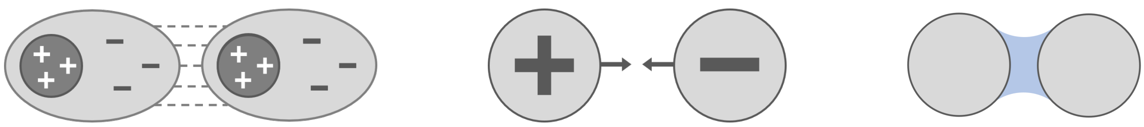
$$F_E = \frac{-Q_A Q_B}{4\pi\epsilon_r\epsilon_0 c^2} \tag{4.3}$$

where Q_A and Q_B are the electrical charges of both particles, ϵ_r and ϵ_0 are the free space and relative permittivity, respectively, and c is the distance between the centers of the particles (Chakravarty et al., 2019). Since the distance is considered between the centers of the particles, instead of the the distance between particle surfaces, the minimum distance increases proportional with the particle size. Moreover, the electrostatic forces decrease quadratically with the distance between the two particles, and with the size for particles at contact. However, the electrostatic force is significantly smaller than van der Waals forces, and can often be neglected.

Capillary forces are formed by liquid bridges caused by the surface tension between liquid layers at particle surfaces (Figure 4.5c). Chakravarty et al. (2019) states the following equation for determining the capillary force, F_c, between two particles connected by a liquid bridge:

$$F_c = 2\pi R\gamma \frac{2t^2 - t + 1}{(1 + t^2)^2} \tag{4.4}$$

with γ the liquid surface tension, $t = tan(0,5\beta)$, where β is the half-angle of the liquid bridge. The attractive forces by liquid bridges are large at small distances, decrease mildly at increasing distance, but dissolves completely at a certain distance. The condition for capillary forces is the presence of moisture, and become stronger with an increasing moisture content. This explains the relation between cohesion and the moisture content of the product (Chakravarty et al., 2019).



(a) van der Waals forces (b) Electrostatic forces (c) Liquid bridge

Figure 4.5: The three main inter-particle binding forces

In summary, both the van der Waals forces and electrostatic forces decrease quadratically with the distance. Capillary forces decrease less rapidly, but become zero if the distance is too large or if the moisture content is negligible. Hence, the cohesive forces are stronger between particles close together. Figure 4.6 graphically shows the relation between the inter-particle binding forces and distance between particles. Additionally, all three forces increase with the particle size (Figure 4.7). Hence, smaller particles are less cohesive than larger particles and need smaller separation forces to be liberated from the bulk material.

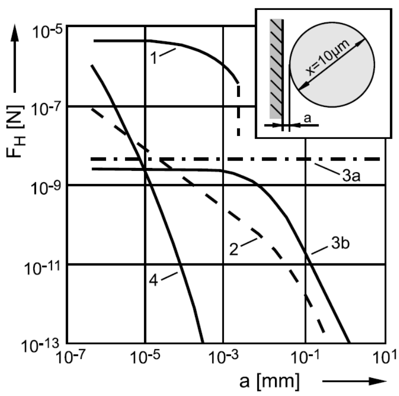


Figure 4.6: The cohesive forces based on inter-particle distance. Source: Schulze (2008)

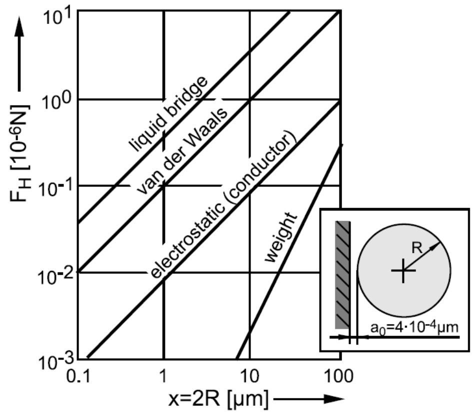


Figure 4.7: The cohesive forces based on particle size. Source: Schulze (2008)

Particle size and distribution

Both particle size and distribution influence the particle breakage (Han et al., 2021). Larger particles contain more imperfections and have higher collision energy, increasing (the risk of) particle breakage. Both a wider PSD, which contains greater strength within agglomerates, and a relatively large concentration of fine particles, which presumably provides protection for larger particles, reduce the particle breakage. Furthermore, the formulas for the cohesive forces show the role that particle size plays in cohesion. Both the van der Waals forces and capillary forces are directly proportional to the radius of the particle. The electrostatic forces are inversely proportionate to the diameter of a particle. Since the electrostatic forces are significantly smaller than the other two forces, the cohesion is generally increases with the particle size.

Particle shape

According to Chakravarty et al. (2019), various studies have found a relation between the irregularities and dust emissions. It is speculated the irregularities of particles are less resistant to particle breakdown, resulting in increased dust emissions. Particles that are more spherical have higher strength and are more likely to fracture into relatively larger fragments than irregular shaped particles. Moreover, irregular-shaped particles have larger surface areas and experience more interparticle collisions. However, a clear correlation between the 'roundness' or relative surface area was not established. Hence, although the particle shape is related to the dustiness of a bulk material, an accurate prediction of the influence on the dust emissions cannot be described.

Flowability

Although the flowability of a bulk product is not directly related to the dustiness of the material, it influences the handling processes. Free flowing materials enable gentle handling, whereas more cohesive materials are often accompanied with flow problems. Flow problems are often associated with high internal stresses within the bulk material and larger forces required in order to move the product. Since the AoR is good indicator for the flowability of a material, it is regularly used in studies to determine the relation between the flowability and the dustiness of a bulk material. Chakravarty (2018) discusses several studies where the relation between the AoR and the dustiness are researched. The considered studies showed only a poor or moderate correlation between the two. Moreover, the flowability depends on the compressed state of the bulk material. Several studies have examined the influence of compression on the dustiness, but both weak and strong correlations were established (Chakravarty et al., 2019, Shandilya et al., 2019, Lilao et al., 2017).

4.1.4. Literature review

Various studies have been executed to establish the influence of the dust mechanisms and bulk properties on the generation of dust emissions. In these studies, the correlation between the factors and the dustiness of a material were experimentally tested or computational simulated. The relations between the expected influencing factors and the dust formation vary from strong correlations to contradicting results. Table 4.1 presents an overview of the influencing factors and the results of several studies. Particle size, PSD, and the (relative) air velocity show a strong correlation with the dustiness consistently. These factors are considered to have the most influence on the dust generation of bulk materials. Cohesion, particle shape, compression, and impact are also consistently correlated, but to a lesser degree. Although in most studies the moisture content is inversely correlated to the dust emissions, there are also some uncorrelated or contradicting results. Also, the particle breakage and flowability of a bulk product showed no clear correlation.

Based on the results of these studies, the most important bulk properties are cohesion, particle size and distribution. Of the dust mechanisms, aerodynamic forces contribute most to the dust emissions, followed closely by impact force. Particle breakage is mainly relevant for bulk products with larger particle size and a wider PSD, but shows no clear correlations otherwise.

Table 4.1: Correlation between material properties and handling conditions found in literature

Influencing factor	Results	Sources
Cohesion	(Strong) inversely correlated Cohesion depends on moisture content and compression Cohesion also influences the flowability	Chakravarty et al. (2019), Shandilya et al. (2019), Plinke et al. (1995)
Moisture	Often inversely correlated Some results are contradicting or show no clear correlation	Chakravarty et al. (2019), Shandilya et al. (2019)
Particle size	Strong inversely correlated Directly correlated with particle breakage	Chakravarty et al. (2019), Jia et al. (2018), Lilao et al. (2017), Han et al. (2021)
PSD	Strong directly correlated Directly correlated with trajectory segregation Inversely correlated with particle breakage	Chakravarty et al. (2019), Derakhshani (2016), Plinke et al. (1995), Han et al. (2021)
Particle shape	Weak directly correlated with irregularities Direct correlation between irregularities and particle breakage	Chakravarty et al. (2019), Han et al. (2021)
Compression	Inversely correlated Results vary between weak and strong correlation Related to the cohesion and flowability	Chakravarty et al. (2019), Shandilya et al. (2019), Lilao et al. (2017)
Flowability	Poor correlation	Chakravarty et al. (2019)
Particle breakage	Both direct, inverse, and unclear correlations	Chakravarty et al. (2019)
Air velocity	Strong directly correlated Directly correlated with segregation Directly correlated with particle breakage	Derakhshani (2016), Jia et al. (2018), Shandilya et al. (2019), Han et al. (2021)
Impact	Directly correlated	Plinke et al. (1995)

4.1.5. Particle trajectories

Usually, a dust particle is released into the air by either an impact or aerodynamic force, then travels a certain distance, and eventually settles down. The trajectory of the airborne dust particle is determined by several forces acting on the particle.

First, the dust particle is suspended into the air with an initial velocity. The inertial force, F_i, obtained by the particle depends on the mass of the particle and is determined by

$$F_i = ma \tag{4.5}$$

where m is the mass of the particle, and a is the acceleration.

Gravity produces the primary downward force contributing to the settlement of airborne particles. The gravitational force, F_G, is given by

$$F_G = mg \tag{4.6}$$

where g is the gravitational constant ($g = 9,81 m/s^2$).

Buoyancy generates an upward force, counteracting the gravitational force, caused by the air that needs to be displaced by the volume of the particle. The buoyant force, F_B is given by

$$F_B = \rho_{air} V g \tag{4.7}$$

where V is the volume of the particle.

The drag force, F_D, is exerted by the air on the particle and is given by

$$F_D = \frac{1}{2} C_D A \rho_{air} U^2 \tag{4.8}$$

with C_D the drag coefficient, A is the projected area, ρ_{air} is the air density, and U is the velocity of the particle with respect to the air flow. The drag coefficient depends on the particle size, shape and the air viscosity. The direction of the drag force depends on the relative velocity of the air flow with respect to the particle.

Besides these four well-defined forces acting on airborne particles, there are several other forces that are less easily defined. Air flowing along a particle does not only exert a drag force, but also a lift force. The lift force acts perpendicular to the air flow, and is usually considered in an upward direction (Benson, 2021). There are several formulas presented to determine the lift force, but due to variables such as the particle size and shape, it is difficult to analytically define the lift force at all times (Ural, 2011). Moreover, the motion of the air is usually not a homogeneous, constant flow. Turbulent currents, Brownian motions, and eddies induce unpredictable forces on the particles. Therefore, in this research the trajectories of dust particles is approximated by only considering the inertial, gravitational, buoyant, and drag forces.

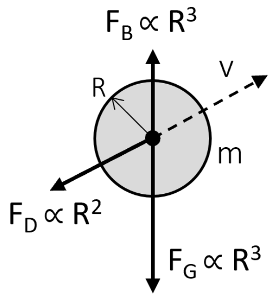


Figure 4.8: Forces acting on an airborne dust particle

These forces acting on airborne particles are presented by Figure 4.8. The gravitational and buoyant forces always act strictly vertical and act in opposite directions. The net force is given by

$$F_B - F_G = \rho_{air} V g - \rho_p V g = V g(\rho_{air} - \rho_p) \tag{4.9}$$

with ρ_p the density of the particle. Assuming the particle density is larger than the air density, this results in a net downward force.

The direction of the drag force depends on the relative velocity between the motion of the particle and the air flow. When there is no (external) air flow, the drag force acts in the opposite direction of the particle's movement.

The net downward force, caused by gravitational and buoyant forces, depends on the volume of the dust particle, whereas the drag force is proportional on the projected surface of the particle, resulting in the following relations to the particle's radii:

$$F_g, F_B \propto R^3 \qquad F_D \propto R^2 \tag{4.10}$$

These relations demonstrate that the significance of the drag force reduces with an increasing radii of a dust particle. A smaller dust particle will experience relatively more drag force, and slow down faster after liberation, assuming there is no air flow. On the other hand, an external air flow, such as wind, in the same direction could carry the small particle a lot further along, whereas larger particles will settle down faster. Figure 4.9 shows the ratio of forces on airborne particles with different sizes.

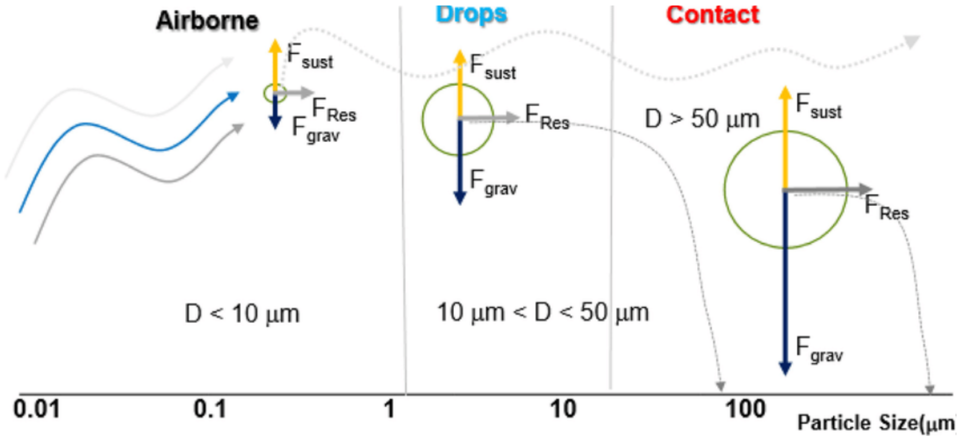


Figure 4.9: Influence of particle size on trajectories. Source: Lipinskia et al. (2020)

4.2. Contribution dust generation causes

The literature review showed that aerodynamic forces and impact play the greatest role in the formation of dust emissions. Furthermore, the particle size and distribution are strongly correlated to the dustiness of bulk materials. However, these bulk properties are intrinsic properties which cannot be altered at the bulk terminal. Therefore, the bulk properties are not further investigated. Particle breakage and the remaining bulk properties have less influence on the dust emissions of bulk materials. Hence, these influencing factors are also not further examined. To obtain a better understanding on how aerodynamic and impact forces contribute to dust formation of bulk products, some experiments are executed. Since the dust emissions usually depends on various factors besides these two dust principles, the goal of the experiments is not to attain a quantifiable prediction model, but rather an indication of the influence on dust emissions.

4.2.1. Drop tests

The contribution of the dust generation principles are explored by conducting drop tests. During a drop test, a bucket of bulk material is turned over, causing the bulk product to fall down. By varying one factor at each repetition, while keeping the other conditions constant, the influence of the factor can be determined.

The influence of the aerodynamic forces on the dust formation can be examined by varying the velocity of either the bulk product or the air flow. Increasing the velocity of the bulk product will also increase the impact force when the material lands. Therefore, the influence of aerodynamic forces is experimentally investigated at different air flow velocities.

The relation between the impact force and the dustiness of the bulk material can be established by investigating the influence of the velocity or the angle of impact. A higher velocity of bulk material also increases the aerodynamic forces, making it difficult to examine the influence of the impact individually. Therefore, the influence of the impact force is investigated at different impact angles.

Since aerodynamic forces and impact often occur together, the contribution of both forces can be tested by varying the velocity of the bulk product. An increased bulk velocity increases both the aerodynamic forces and the impact force. By varying the drop height, the velocity of the bulk material is varied.

Test 1: Aerodynamic forces

Objective

To establish the contribution of aerodynamic forces to the development of dust emissions of bulk materials.

Method

The contribution of aerodynamic forces is determined by observing the dust emissions formed at different wind speeds during a drop test (Figure 4.10). The bulk product is dropped at a fixed height, while an air flow is generated by a fan. The test is repeated at different wind velocities and recorded by a video camera. The dust emissions created by the drop tests are determined by the distance of dust settlement after dispersion.

Materials

- Bucket
- Soda
- Anemometer
- Fan
- Measuring tape
- Video camera

Procedure

1. Fill the bucket with soda
2. Measure the drop point at a height of 1.2 meters
3. Set up the fan
4. Turn the fan on
5. Measure the wind velocity at the drop point
6. Set up the video camera
7. Pour the soda from the bucket at the drop point
8. Turn the video recording off after the dust particles have settled down
9. Measure the distance of dust dispersion from the source
10. Repeat steps 1 to 9 for the wind speeds varying from 0 m/s to 5 m/s with interval steps of 1 m/s

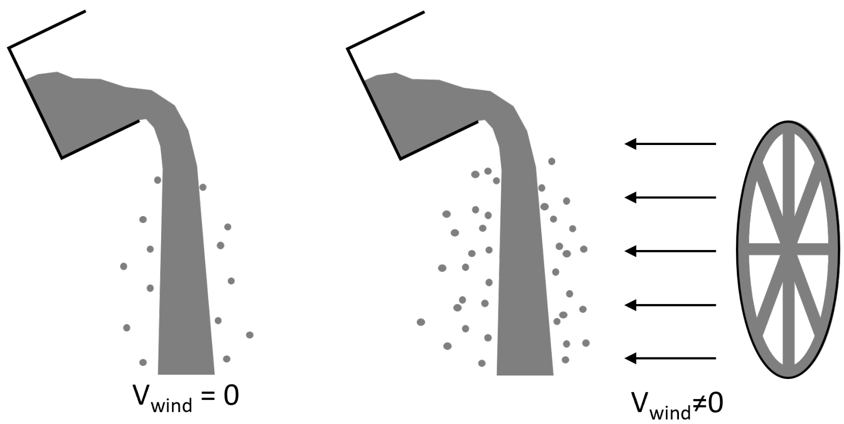


Figure 4.10: Set up of drop test 1

Test 2: Impact force

Objective

To establish the contribution of impact force to the development of dust emissions of bulk materials.

Method

The contribution of impact force to the dust emissions is determined by dropping bulk products onto an inclined surface (Figure 4.11). A smaller inclination angle results in a larger change in velocity and direction, which increases the impact force. The bulk product is dropped at a fixed height in the absence of any external air flow. The dust emissions created by the drop tests are determined by the distance of dust settlement after dispersion.

Materials

- Bucket
- Soda
- A flat surface
- Measuring tape
- Video camera

Procedure

1. Fill the bucket with soda
2. Measure the drop point at a height of 1.2 meters
3. Set up the surface below the drop point
4. Set up the video camera
5. Pour the soda from the bucket at the drop point
6. Turn the video recording off after the dust particles have settled down
7. Measure the distance of dust dispersion from the source
8. Repeat steps 1 to 7 with the inclination angles of the surface of 0°, 10°, 20°, 30°, and 40°

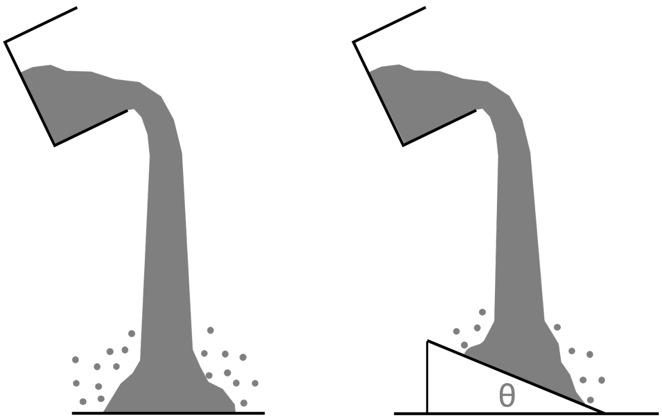


Figure 4.11: Set up of drop test 2

Test 3: Aerodynamic and impact force

Objective
To establish the contribution of both the aerodynamic and impact forces to the development of dust emissions of bulk materials.

Method
The contribution of both aerodynamic and impact forces to the dust emissions is determined by dropping bulk products from different heights (Figure 4.12). The velocity of the bulk product increases as the drop height increases. A larger velocity increases both the aerodynamic forces and the impact force. The dust emissions created by the drop tests are determined by the distance of dust settlement after dispersion.

Materials
- Bucket
- Soda
- Ladder
- Measuring tape
- Video camera

Procedure
1. Fill the bucket with soda
2. Measure the drop height (possibly using a ladder)
3. Set up the video camera
4. Pour the soda from the bucket at the drop point
5. Turn the video recording off after the dust particles have settled down
6. Measure the distance of dust dispersion from the source
7. Repeat steps 1 to 6 with the drop heights of 1 m, 2 m, and, 3 m.

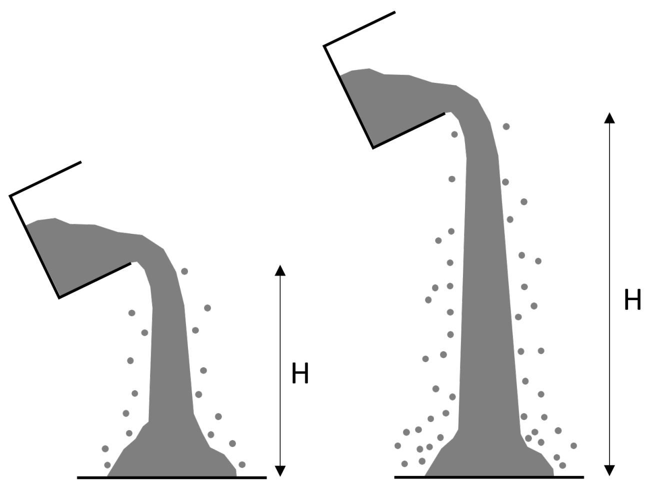


Figure 4.12: Set up of drop test 3

4.2.2. Test results

Figure 4.14 presents the results of dust dispersion for test 1. Figures 4.14a and 4.14b display the settled dust after executing drop test 1 at wind speeds $v = 1m/s$ and $v = 5m/s$, respectively. The distance of dust dispersion is measured from the center of the heap to the furthest settlement of dust. The graph in Figure 4.13 shows the distance of dust dispersion for the drop tests with wind velocity varying from $v = 0m/s$ to $v = 5m/s$. The graph clearly shows an increasing trend of dust dispersion at higher wind speeds, except between wind speeds $v = 4m/s$ and $v = 5m/s$. At both these wind speeds, the dust dispersion reached the end of the workspace, beyond which settled dust could not be observed. Hence, it is assumed the dust dispersion at $v = 5m/s$ is greater than at $v = 4m/s$. The results are in agreement with the expectations.

Figure 4.16 shows the results of drop test 2. Figures 4.16a, 4.16b, and 4.16c show the settled dust after the execution of drop test 2 at inclination angles $\theta = 0°$, $\theta = 20°$, and $\theta = 40°$. The distances of dust dispersion for drop test 2 at all inclination angles are presented in the graph in Figure 4.13. Although it is expected the dust dispersion decreases with an increasing inclination angle, the distances remain quite constant throughout all angles. A reasonable explanation could be that after impact the bulk product remains on the surface and forms a heap. Hence, the majority of the bulk product falls onto the heap instead of the inclined surface, resulting in a comparable impact force. In order to still obtain an indication of the influence of impact force on the dust dispersion otherwise, the moments right after the first bulk material reaches the surface are compared (Figure 4.17). Even though the determination of dust dispersion using this method is not very accurate, a noticeable difference is perceived from the figures.

Figure 4.18 shows the results of drop test 3. Figures 4.18a, 4.18b and 4.18c display the settled dust after executing drop test 3 at drop heights $H = 1m$, $H = 1.5m$, and $H = 2m$, respectively. The graph in Figure 4.13 shows the distance of dust dispersion for the drop tests with drop heights from $H = 1m$ to $H = 2m$. Although only few data points are determined, a clear upward trend is visible, which was also expected.

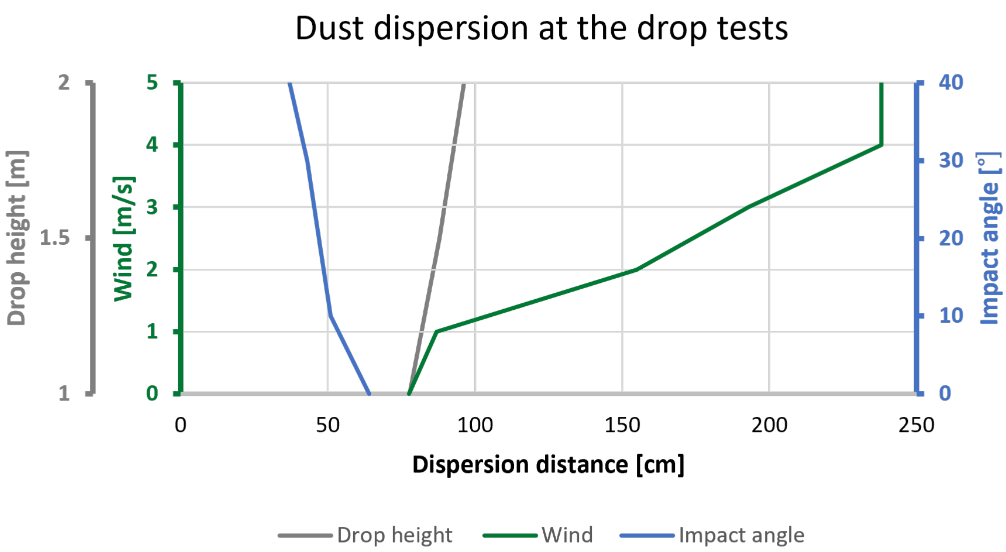


Figure 4.13: Dust dispersion of three drop tests

4.2.3. Analysis

The results of the three drop tests are combined in Figure 4.13. The graph clearly shows the great contribution of external air flow to dust dispersion in comparison to internal air flow and impact. A difference in wind velocity of 1 m/s leads to an increased dust dispersion of almost half a meter. Since the allowed dust dispersion from the source is only two meters, the contribution of wind on the dust emissions is highly significant. In Figure 4.15, the trajectories of the dust are graphically presented. With wind speeds of $v = 3m/s$ or higher, the trajectories show a dispersion even further than the settled dust measured on the blue tarp. Since the legislation allows dust dispersion of maximum two meters from the source, according to this drop test a gentle breeze already causes violations of the regulations.

The results from drop test 2 show that if the impact angle is too small for the bulk product to slide down, it will not affect the dust dispersion. However, right after impact a small difference can be detected, in accordance to the expectations.

The influence of drop height is investigated by drop test 3. The results show that a larger drop height slightly, but steadily, increases the dust dispersion. The drop height of the bulk material is of significantly less influence than the wind velocity.

The drop test are executed with only a small amount of soda and poured with an unstable flow. These conditions do not accurately represent the equipment handling situations. Therefore, the results present only an indicative influence of the aerodynamic forces and impact on dust dispersion.

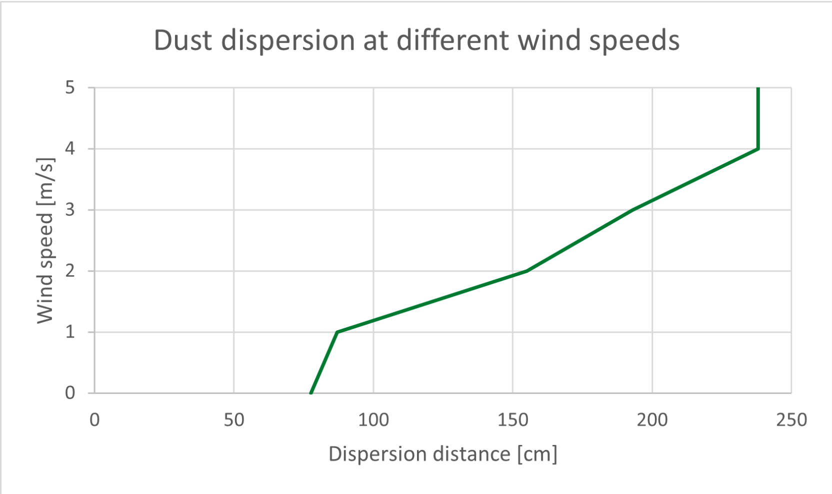
4.3. Conclusions

Three dust generation principles are established: particle breakage, impact, and aerodynamic forces. The contribution of particle breakage is negligible in comparison to the other two. Impact occurs when the bulk product endures a physical interaction causing a change in velocity and/or direction. Aerodynamic forces are induced by a relative velocity of the bulk product through the surrounding air, an external air flow, or air entrainment during free-fall of bulk material. External air flows contribute most to the development of dust emissions. The particle size and distribution are strongly correlated with the dustiness of a bulk material. Smaller particles experience less cohesion and are able to travel further when liberated in the air.

Based on the dust generation principles, dust particle trajectories, and influencing factors, measures for dust control can be established.

(a) Dust dispersion at wind speed $v = 1m/s$

(b) Dust dispersion at wind speed $v = 5m/s$



(c) Dust dispersion at wind speeds $v = 0m/s$ to $v = 5m/s$

Figure 4.14: Results of drop test 1

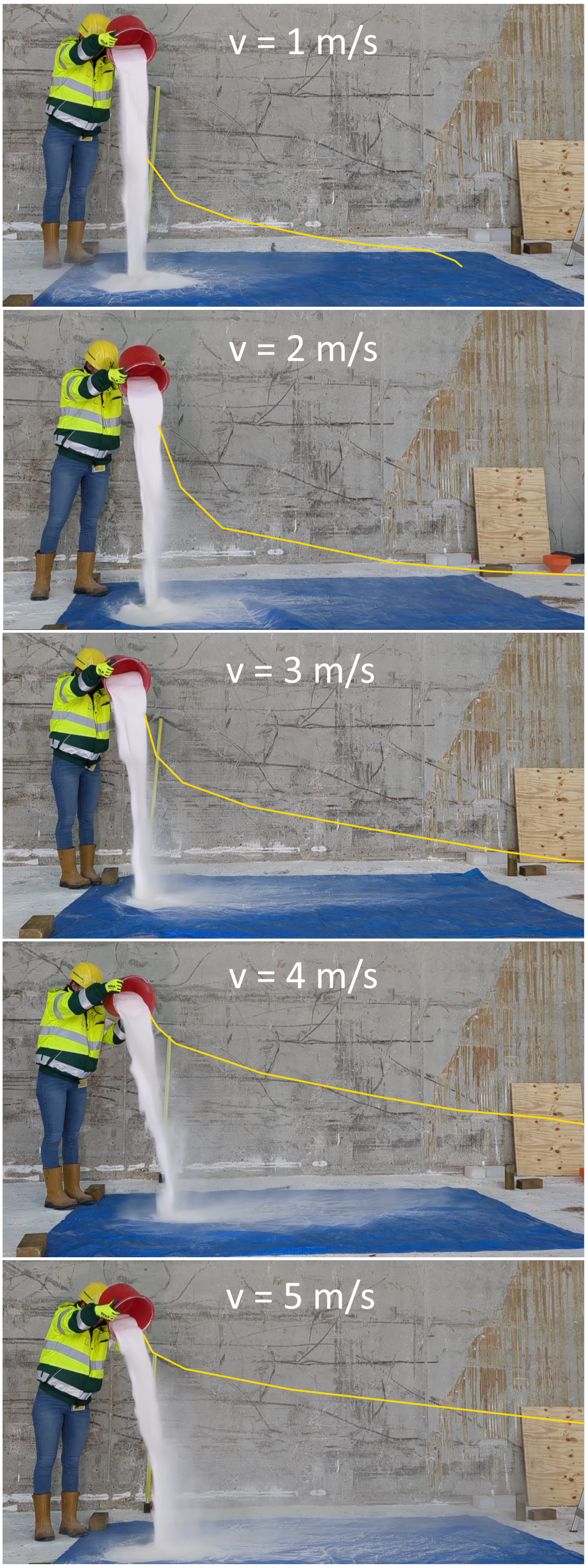
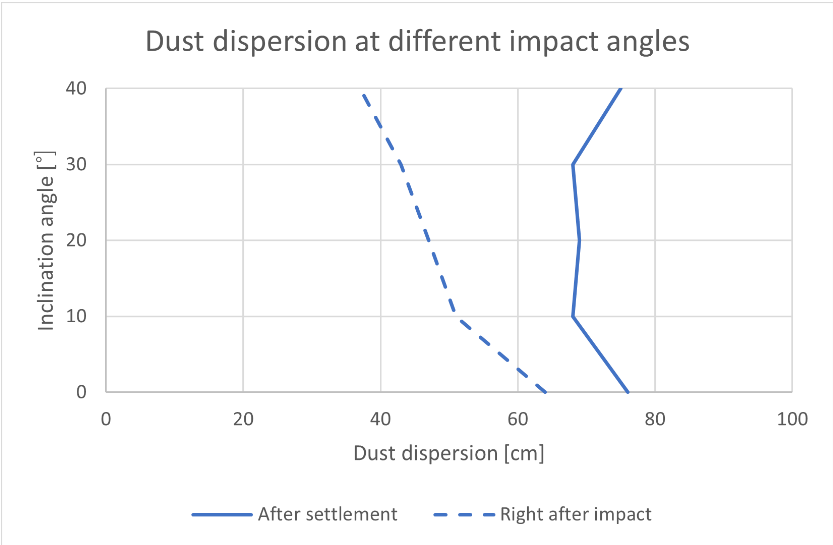


Figure 4.15: Visible dust dispersion during drop test 1

(a) Dust dispersion at inclination angle $\theta = 0^{\circ}$

(b) Dust dispersion at inclination angle $\theta = 20^{\circ}$

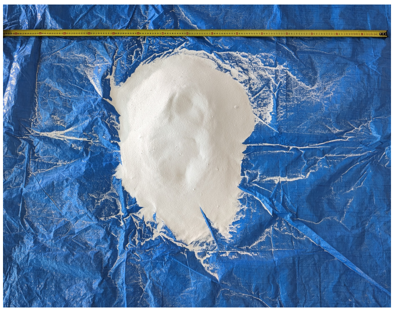
(c) Dust dispersion at inclination angle $\theta = 40^{\circ}$



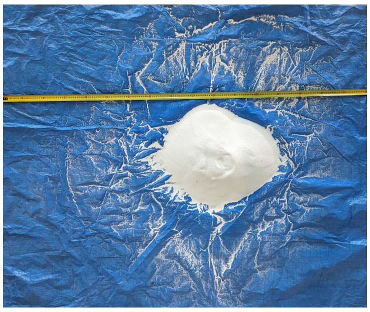
(d) Dust dispersion at inclination angles $\theta = 0^{\circ}$ to $\theta = 40^{\circ}$

Figure 4.16: Results of drop test 2

Figure 4.17: Visible dust dispersion during drop test 2



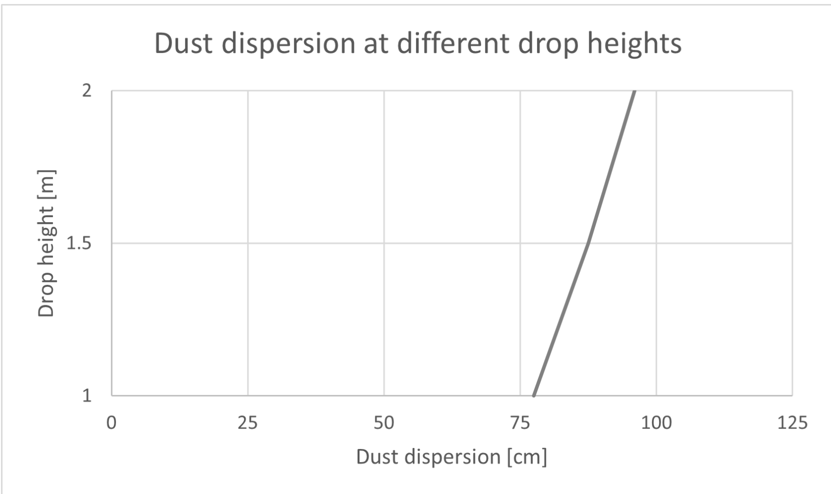
(a) Dust dispersion at drop height $H = 1m$



(b) Dust dispersion at drop height $H = 1.5m$

(c) Dust dispersion at drop height $H = 2m$

(d) Visible dust dispersion during drop test 3



(e) Dust dispersion at drop heights $H = 1m$ to $H = 2m$

Figure 4.18: Results of drop test 3

5

Dust control measures

With the understanding of how dust emissions are generated and dispersed during bulk handling, measures to reduce dust emissions can be determined. The dust generation principles established in Chapter 4 are used to determine the principles for dust control. Furthermore, common dust control techniques applied at bulk terminals are examined, which are divided into preventive and suppressive measures. Preventive dust control methods are used to avoid the generation of dust emissions, whereas suppressive techniques aim to eliminate dust particles once becoming airborne. Finally, the established dust control measures are compared to the BAT for reducing dust emissions.

5.1. Dust control principles

Dust is mainly liberated by aerodynamic and impact forces acting on the bulk material, as explained in Chapter 4. Avoiding these forces is essential to prevent the generation of dust emissions. Moreover, when the generation of dust cannot be completely prevented, it is important to restrict the dispersion of dust. This can be achieved by reducing the trajectories of dust particles after liberation.

Aerodynamic forces

Dust generation due to aerodynamic forces is a result of a velocity difference between the air flow and the bulk flow, or air entrainment. The air flow may originate from either the ambient air within the installation or from external conditions, such as wind. An external air flow can be avoided by enclosing the bulk handling equipment (Swinderman et al., 2009). Additionally, enclosures would keep the internal air flow contained within the installation and avoid airborne dust to be carried to the surrounding area.

Internal air flow is caused by the bulk material moving through the ambient air. Aerodynamic forces caused by internal air flow can be minimised by reducing the difference in velocity between air flow and bulk product. This can be achieved by either reducing the velocity of the bulk product or by equalizing the velocity of the air flow and the velocity of the bulk product.

Air entrainment occurs when the bulk product dilates as it falls. Consolidating the stream of bulk material reduces the volume of air that can be entrained. Consolidation can be achieved by increasing the cohesion or by controlling the flow of the bulk material. As described in Chapter 3, the cohesiveness can be influenced by compression or increasing the moisture content. The expansion of bulk material during free-fall depends on the drop height and, if discharged through a chute or hopper, the dimension of the outlet opening (Swinderman et al., 2009). Reducing the drop height and outlet dimensions will consolidate the bulk stream, and subsequently, restrict air entrainment.

To summarise, dust emissions caused by aerodynamic forces can be reduced by:

- minimising the velocity of air flow
- minimising the velocity of the bulk product
- minimising air entrainment

Impact

Dust emissions generated by impact are a result of a physical interaction of the bulk material, where the conversion of kinetic energy causes the suspension of dust particles. The impact force depends on the change in velocity and direction of the bulk material. Hence, the dust developed through impact can be reduced by:

- minimising the change in velocity
- minimising the change in direction

During bulk handling, impact usually occurs after a free-fall of the bulk material. Since the velocity of bulk material during free-fall depends on the drop height, the velocity at impact can be reduced by decreasing the drop height. A larger impact angle ensures that part of the velocity is retained in the direction of the bulk product's motion. Hence, both the change in velocity and direction can be reduced by using a large impact angle that gradually decreases, such that the initial velocity of the bulk material is moderately redirected in the new direction.

Dust prevention principles

Considering both aerodynamic and impact forces play the biggest role in dust generation, the following *dust prevention* principles should be taken into account in bulk handling equipment:

- enclosing the installation
- reducing drop heights
- increasing the angle of impact
- consolidating the bulk stream

Dust prevention

Dust prevention concerns avoiding or minimising the causes of dust generation.

Figure 5.1 presents a transfer point between two conveyor belts incorporating these design considerations. This example uses a so-called 'hood and spoon' design, where the hood reduces dilation of the bulk stream and the spoon gradually guides the material onto the next conveyor belt (Swinderman et al., 2009). Furthermore, the transfer point is enclosed and the drop height between the two conveyor belts is minimised.

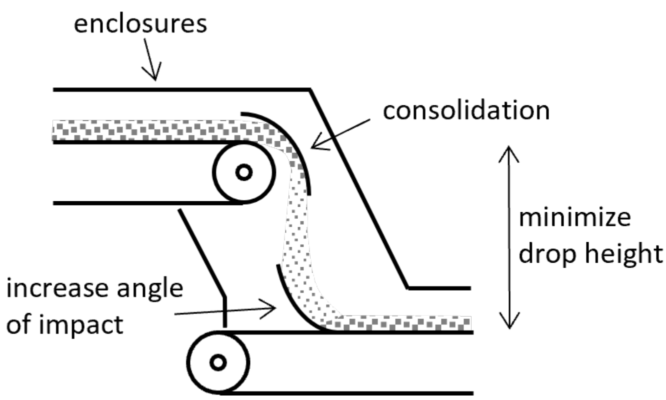


Figure 5.1: Primary design considerations to minimise the generation of dust emissions

Besides the dust generation principles, the development of dust also depends on the cohesion among particles, as described in Chapter 4. Hence, in addition to the dust prevention principles, dust emissions can be reduced by increasing the cohesive forces among dust particles.

Dust dispersion

Dust suppression

Dust suppression concerns removing dust particles suspended in the air.

It is not always possible to completely eliminate dust emissions using preventive measures. Hence, once dust particles become airborne, it is essential that the particles settle down or be extracted from the air. The trajectory of an airborne dust particle depends on the particle's volume and mass, and the forces induced by the air flow. By increasing the dimensions or weight of the particle, or using a controlled air flow, *dust suppression* can be enhanced.

The following principles should be considered to enhance dust suppression:

- enclosing the installation
- utilizing the air flow
- increasing the dimensions or weight of dust particles

5.2. Preventive dust control techniques

Preventive dust control techniques incorporate the dust control principles to reduce dust emissions. This section addresses common preventive techniques, which are a telescopic chute, a cascade chute, a dust suppression hopper, and wet spray systems.

Telescopic chute

A loading chute is used to transfer bulk material into the cargo hold of a vehicle or vessel (Cecala et al., 2019). A telescopic loading chute is composed of a series of truncated cones that can slide into each other (Figure 5.2). This allows the chute to extend or retract to obtain the optimal position for loading. Furthermore, the chute is equipped with an outer shroud that protects the bulk material against external influences, such as wind and rain. The telescopic loading chute can be lowered down and seal the hatch of an enclosed loading space, which prevents dust to escape. At an open cargo space, the chute is extended to just above the heap of bulk material in order to limit the drop height. The conical shape of the cones prevent dispersion of the bulk material during free-fall and reduces air entrainment. A telescopic chute is often combined with a dust collection system and/or an outlet skirt, which will both be addressed in Section 5.3.

Cascade chute

A cascade chute is a variant on the telescopic loading chute. The cones are placed at an angle and arranged in an alternating manner. The bulk material travels down the chute by sliding along the inclined cones, progressing from one cone to the next in a cascading manner (Figure 5.3). The cascade breaks down the total drop height of the chute into numerous smaller segments. Therefore, the bulk material obtains a lower velocity and approaches a more consolidated flow. Consequently, the reduced bulk velocity and inclination angles of the cones minimise the impact forces. The cascade chute is an effective dust control technique and can reduce the dust emissions to 5 mg/m^3, according to Cleveland Cascades Ltd (2016).

Dust Suppression Hopper

A Dust Suppression Hopper (DSH) is a bulk loading technique that reduces the formation of dust emissions after discharge. The DSH is a conical hopper suspended by springs and equipped with a fixed central plug. The plug closes off the outlet of the hopper in the absence of bulk product. When fed, the bulk material accumulates inside the DSH, which increases the weight of the hopper. The springs of the hopper extend and once enough material has built up, an opening at the outlet is formed. The bulk material flow forms a compact stream as it is pressured out of the DSH. The consolidated flow minimises air entrainment and thus reduces the liberation of dust particles. The DSH mechanism combines gravitational and elastic spring forces to create a consolidated bulk flow. The system is adjusted for optimal performance based on the bulk density of the bulk product.

According to DSH Systems (n.d.), the DSH is best compatible with dry bulk products with a good flowability. Fine powders, high cohesive, or bulk materials likely to form clumps are not suitable for a DSH as they may result in blockages or build up in the hopper. This could result in an inadequate

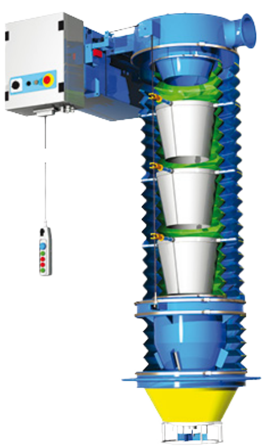


Figure 5.2: Example of a telescopic loading chute. Source: Inquip (2020)

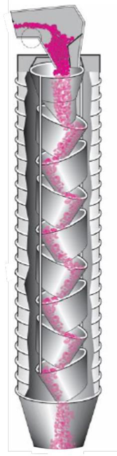


Figure 5.3: Example of a cascade loading chute. Source: Cecala et al. (2019)

outgoing flow, overflow of the hopper, or incapability to empty after the loading is finished. The system operates optimal when fed a continuous, even flow of bulk product in the centre of the hopper. Otherwise, it may lead to insufficient consolidation or other difficulties of the outgoing flow.

Wet spray systems

Wet spray systems can be used as both a preventive and suppressive method. The preventive method utilizes wet spray systems to enhance the moisture content of a bulk material, increasing the cohesion among particles (Figure 5.5). The greater cohesion results in a higher likelihood of agglomerate formation. Due to the increased cohesion, larger separation forces are required for dust particles to be liberated into the air. Wet spray systems are generally very effective methods, but are not suitable for numerous bulk products. Moreover, adding moisture to the bulk product is often undesirable for the client, as it increases the overall weight, which is costly. Another disadvantage is that the greater cohesiveness increases the tendency of bulk material to leave residues and form clumps, possibly ending up clogging the equipment.

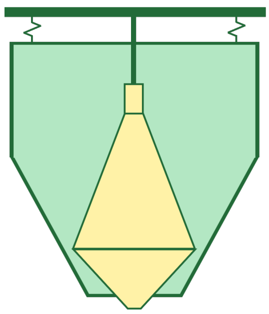


Figure 5.4: Example of a DSH

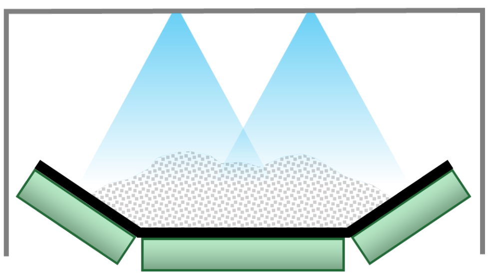


Figure 5.5: Example of a preventive wet spray system

Overview

The preventive dust control techniques incorporate one or more principles to reduce the development of dust. Table 5.1 presents an overview which principles the different techniques use. Based on the results of the drop tests, as described in Chapter 4, external air flow plays the largest role in dust generation. The most effective approach to avoid an external air flow is enclosing the installation, as incorporated by the telescopic and cascade chute. Additionally, the cascade chute incorporates three other dust prevention principles, possibly indicating a high effectiveness.

Table 5.1: Preventive dust control techniques and which design considerations they incorporate

	Telescopic chute	Cascade chute	DSH	Wet spray system
Enclosing bulk product	✓	✓		
Reduce drop height		✓		
Increase impact angle		✓		
Consolidating bulk stream	✓	✓	✓	
Increase cohesion				✓

5.3. Suppressive dust control techniques

Applying preventive dust control measures is the primary approach to minimise dust emissions. However, the generation of dust cannot be completely avoided. Therefore, it is important to also minimise the spreading of liberated dust particles. Suppressive dust control techniques are utilized to advance the removal of airborne dust particles. Suppressive methods applied in bulk handling are enclosures, outlet skirts, flex-flaps, wet spray systems, dust collection systems, and dust bags.

Enclosures

Enclosing the bulk handling equipment does not only reduces the air flow, but also prevents airborne dust to escape and spread into the environment. Moreover, enclosures protect the bulk products from environmental influences, like wind and rain. Without significant air flow, airborne dust particles will eventually settle down. A settling zone is an enclosed space after a loading or transfer point at belt conveyors. The enlarged zone uses Bernoulli's Principle to slow down the air, which is an opportunity for dust particles to settle down. At some points it may be difficult to completely enclose an installation. A simple technique, such as dust curtains (Figure 5.6), can partly enclose the system and contribute to the reduction of air flow. Other partial enclosing techniques are dust skirts and flex-flaps.

Dust skirt

Loading chutes may reduce dust emissions in the chute itself, but have little influence on the bulk material after it is discharged. One commonly applied technique is the attachment of a dust skirt below the outlet of the loading chute (Figure 5.7). The skirt, often made from some sort of fabric, lays on top of the heap of bulk product during loading. The skirt encloses the dust created by impact as the bulk product lands on the heap. The enclosure allows the dust particle to settle down before the loading chute is lifted. It is a simple, yet effective, dust suppression technique.

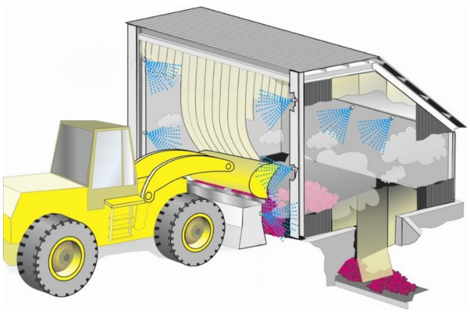


Figure 5.6: Dust curtain at a loading dump. Source: Reed et al. (2012)

Figure 5.7: A dust skirt at the outlet of a loading chute. Source: Vortex (2022)

Flex-flaps

When bulk material is loaded into an open-top unit, the developed dust can escape at the top. The flex-flap technique prevents the dust to escape by forming a one-way passage for the bulk material (Figure 5.8). The system consists of flexible 'flaps' sealing off the top. When bulk material is loaded on top of the system, the flex-flaps bend under the weight of bulk material and allow the material to flow through (Figure 5.9). The design prevents airborne dust particles to escape out. Moreover, the inclined walls reduce impact as the bulk product is loaded onto the flex-flaps.

Due to the physical contact of the bulk material with the rubber flaps, a good flowability is desirable. Abrasive materials will have a high contribution to wear of the rubber flaps. Additionally, adhesive properties may cause the material to accumulate at the the flaps, leading to a blockage of the passage. The risk of blockage also increases in the presence of clumps in the bulk material.

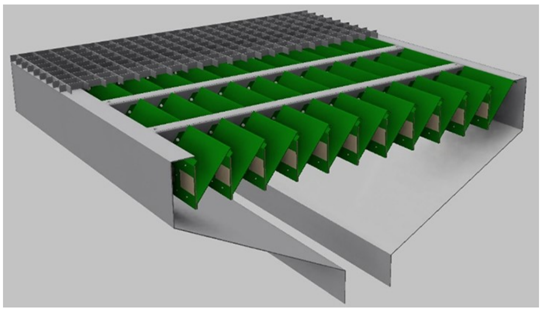


Figure 5.8: The flex-flap system. Source: I-kos (2022)

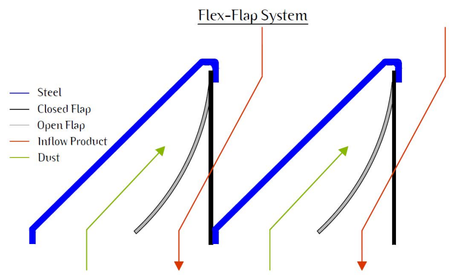


Figure 5.9: The working principle of the flex-flap technique. Source: Docksolid (2015)

Wet spray systems

Wet spray systems as a suppressive method uses the principle of increasing the particle weight to accelerate the settlement of airborne dust particles. Small water droplets are sprayed into the air near the dust source. The droplets bind to dust particles, advancing them to agglomerate and fall down due to the increased gravitational forces. The technique performs most effectively when the droplets have a similar size as the dust particles (Cecala et al., 2019). For bulk materials with hydrophobic properties, the binding of droplets with dust particles may need to be enhanced for a more effective application (Swinderman et al., 2009). The surface tension of the water droplets can be reduced by adding surfactants to the system. The surfactants increase the tendency of hydrophobic dust particles to bind with the droplets.

As explained earlier, wet spray systems may not be compatible with all bulk materials or may be undesirable for clients.

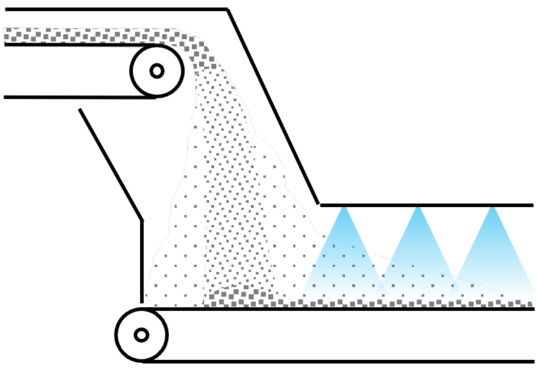


Figure 5.10: Wet spray systems as a suppressive dust control technique

Dust collection systems

A dust collection system draws air away from the dust source and filters the dust particles. Swinderman et al. (2009) describe five types of dust collection systems.

Inertial separator. The various types of inertial separators are based on inertial, gravitational and centrifugal forces. The most common applied inertial separators are cyclones. The extracted air is redirected into a separate chamber, where a vortex is created. The centrifugal forces acting on the dust particles in the extracted air push the particles out of the whirl onto the chamber's walls. Dust particles agglomerate at these walls and fall down after gravitational forces exceed the adhesive forces, and may be collected or redirected to the main stream.
Wet scrubber. This technique is a combination of a dust collection system and wet spray system. After the extracted air has entered a separate chamber, water is sprayed into the air. Water droplets bind with the dust particles and fall down due to the increased weight. A mixture of water and dust particles is discharged by the chamber and is directed to a clarification systems to extract the dust particles. Wet scrubbers are expensive techniques that require high power, and requires measures against corrosion. Moreover, the system is not applicable for bulk products that may not be wetted.
Electrostatic precipitator. The dust particles in the extracted air are ionized with a negative electrical charge upon entering a separate chamber. Electrode collection plates in the chamber are positively charged and capture the negatively charged dust particles. Vibrations allow the collected particles to be released and fall down due to gravity. Although the technique is highly effective, it is less compatible with materials with a high electrical resistance. Moreover, materials generated combustible dust clouds should be avoided due to the risk of explosion.
Cartridge filter collector. A pleated filter inside a cartridge provides a large surface area to collect dust particles, which allows the size of the system to decrease. The pleats tend to clog when the material contains a high moisture content and require high maintenance.
Fabric dust collector. The most commonly applied dust collection system is the fabric dust collector, due to its high efficiency and affordability (Figure 5.11). The technique comprises of baghouses containing a fabric filter that captures dust particles as the extracted air flows through. The collected dust particles form a cake on the surface of the filter, which needs to be cleaned regularly to avoid clogging of the system. The dust cakes can be removed through:

- Mechanical shaking: the bag is shaken by the top mount.
- Reversing the air flow: the air flow through the bag is reversed, such that the bag collapses and the dust cakes fall off.
- Reverse jet: a pulse of compressed air is injected into the bag, causing a flex in the filter, which releases the dust cake.

There is also a passive dust collecting technique for capturing dust particles from the air. A dust bag uses the build-up air pressure induced by bulk material loading into and moving through an enclosed space (Swinderman et al., 2009). The installation contains a hatch equipped with a dust bag, which acts as a dust collecting filter (Figure 5.12). The positive air pressure forces the contaminated air out, while the dust particles are captured by the dust bag. This technique is less expensive as it requires no power to extract the dust particles from the air.

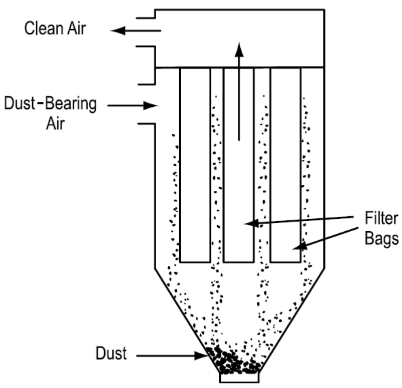


Figure 5.11: Fabric dust collector. Source: Swinderman et al. (2009)

Figure 5.12: Dust bag. Source: Swinderman et al. (2009)

A disadvantage of dust collection systems is the cleaning of the filters. Dust filters with residues of hygroscopic materials cannot be cleaned with water, as the product will cake. Due to the difficulty of cleaning the filters, some product will often remain behind. To avoid contamination of the bulk materials, the dust collection system can be used for only one bulk product.

Overview

The suppressive dust control techniques incorporate one or more dust suppression principles. Table 5.2 presents an overview which principles the different techniques use. Besides dust collection systems and wet spray systems, most techniques provide a (partial) enclosure.

Table 5.2: Suppressive dust control techniques and which design considerations they incorporate

	Enclosures	Dust skirt	Flex-flaps	Dust collection system	Wet spray system
Enclosing the installation	✓	✓	✓	✓	
Utilizing air flow				✓	
Increase particle size or weight					✓

5.4. Best Available Techniques

In Chapter 2, the BAT to reduce dust emissions were described. In this section, the BAT are compared to the established dust control principles and techniques.

5.4.1. Primary organisational measures

The measure 'Weather conditions' relate to terminating handling operations above a wind speed of 8 m/s (S1 and S2), 14 m/s (S3), and 20 m/s (S4 and S5). In Chapter 4, experiments showed that for soda visible dust trajectories already exceed the 2 meters with a wind speed of 2 m/s. Moreover, the travel distance increases rapidly with higher wind speeds. Hence, stopping the operations at wind speeds higher than 8 m/s for an S1 product would seem not very effective. However, the average wind speed in Terneuzen measured over one year (2023) is 4.5 m/s (Meteostat, 2023). Figure 5.13 shows the number of days with a minimum daily average wind speed in 2023. For 338 days, the daily average wind speed was 2 m/s or higher, in comparison to 43 days with a wind speed of 8 m/s or higher. The downtime for Verbrugge would be far too high if operations would stop at wind speeds of 2 m/s. Moreover, it may be assumed that most equipment handling dust sensitive products are (partially) enclosed to reduce external air flows.

The measures for operators of a grab, conveyor belt, or mechanical shovel concern minimising the drop height, reducing operating speed, and avoiding spillage. A reduced drop height is established as one of the main prevention principles, as it reduces both impact and aerodynamic forces. A lower operating speed reduces the generation of air flow and allows more time for dust particles to settle down. The measure can be seen as both a preventive and suppressive method. In Chapter 4, spillage was not considered as a cause of dust emissions. However, since aerodynamic and impact forces have free play on spilled bulk material, it is likely as source of dust emissions. All three operator measures are likely to contribute to a reduction of the generation of dust emissions. The measures regarding the layout and operation of the bulk terminal site may be effective, but often infeasible. Usually, bulk terminals already exist for decades and have been developed over the years. Changing the layout of the site to reduce transport distances is a drastic and costly measure. The purpose of reduced driving speeds and hard road surfaces is to prevent liberation of dust emissions from bulk material that was settled down on the road. Although the measures may prevent further distribution of dust particles, dust should be addresses dust at the source.

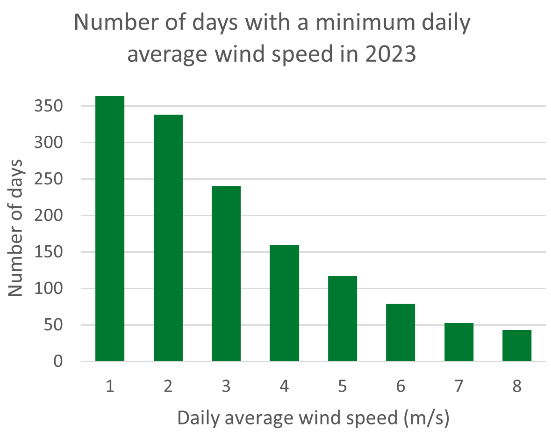


Figure 5.13: Number of days with a minimum daily average wind speed in 2023 in Terneuzen. The data is derived from Meteostat (2023)

5.4.2. Primary technical measures

Most of the primary technical measures aim to minimise the drop height, to enclose the installation to protect against wind flow, and to prevent spillage. These measures are in agreement with the established dust prevention principles. The approaches considering optimising grabs and transfer chutes also include the advancement of flowability. As discussed in Chapter 4, a clear correlation between the flowability and dust generation was not established in the literature. However, a good flowability usually reduces the risk at other problems.

5.4.3. Secondary measures

Most secondary measures comprise of (partially) enclosing the equipment or extracting particles with a dust collecting system. Other approaches concern spillage avoiding methods, such as cleaning the conveyor belts, roads, and vehicle tyres.

In general, the measures proposed by the BAT are in agreement with the dust control principles. In addition, several methods involve the prevention of spillage. Yet, these approaches actually aim to avoid dust source, instead of dust causes.

5.5. Conclusions

Bulk handling equipment should consider the main principles to prevent dust liberation and to enhance dust suppression.

- The installation should be enclosed as much as possible. Enclosures shield the bulk materials from external air flow and precipitation, slows the air flow inside the installation, and avoids airborne dust particles to be released into the environment.
- Drop heights should be minimised. This reduces the bulk velocity, restricting both impact after landing and aerodynamic forces during the free-fall of the bulk material.
- An increased angle of impact reduces the change in velocity and direction, and therefore, reduces the impact force.
- A stream of bulk material should be consolidated to minimise air entrainment.
- Air flow is not only a cause of dust generation, but can also be utilized to suppress or extract airborne dust particles.
- Increasing the weight of dust particles decreases the likelihood of dust particle to be released into the air, and enhances the settlement of already airborne dust particles.

Dust control techniques are based on these design principles, and can be categorised as preventive or suppressive methods. Preventive dust control techniques are telescopic chutes, cascade chutes, DSHs, and wet spray systems. Suppressive dust control techniques are enclosures, outlet skirts, flex-flaps, wet spray systems, and dust collection systems.

In theory, each technique contributes to the reduction of dust emissions. However, in practice, some measures may be more effective than others.

6 Evaluation of dust control techniques

The bulk terminal at Verbrugge consists of several bulk handling installations, as described in Chapter 2, posing potential dust sources. Various dust control techniques are implemented with the aim to reduce the liberation of dust. The *dust control and overall performances* of the techniques are not always the same in practice as expected by theory. This chapter aims to establish the extent of dust control, occurring problems, and considerations of the applied techniques at Verbrugge. These hands-on experiences provide practical insights in enhancing dust control and prevent unforeseen problems. First, the potential dust sources and applied dust control measures at Verbrugge are established. Then, through observations and interviews with operationally involved employees the dust control and overall performances are qualitatively determined, respectively.

Dust control performance

The dust control performance refers to the extent of a technique's ability to reduce dust emissions.

Overall performance

The overall performance refers to the functionality of a technique beyond dust control, including factors such as material flow, maintenance requirements, and operational efficiency.

6.1. Dust control at Verbrugge

The dust sources at Verbrugge are provided with both preventive and suppressive dust control techniques, as provided by the BAT. Employees at Verbrugge (are expected to) apply the relevant organisational measures. However, the effect of applying organisational measures is often not constant, which makes it difficult to examine their influences on dust control. Therefore, this chapter focuses on the technical measures. The preventive techniques are telescopic chutes and DSH. Suppressive dust control techniques incorporated are the outlet dust skirt, flex-flaps, and dust collection systems. Moreover, most installations are (partially) enclosed, which acts as both a preventive and suppressive measure. This section addresses the potential dust sources, and the application and expectations of each technique.

Dust sources and applied measures

As described in Chapter 4, dust is typically generated when aerodynamic or impact forces act on the bulk material. At a bulk terminal, this can be translated to operations where the bulk material is loaded, unloaded, transferred, conveyed, or stored in open space. Table 6.1 presents various operations at Verbrugge considered as potential dust sources, the corresponding equipment, and the currently applied dust control techniques. The bulk materials stored in warehouses at Verbrugge are fully enclosed and do not experience aerodynamic or impact forces. Therefore, the storage of bulk products is not addressed in this chapter.

Enclosed telescopic chute

Telescopic chutes are used to load trucks with soda stored in silos. The system is used in an enclosed environment, so the primary cause of dust would be impact. The chute is lowered and the outlet is connected to the hatch of the loading space by the operator. The loading route is completely enclosed

Table 6.1: Typical dust sources and applied dust control techniques at Verbrugge

Operation	Equipment	Dust control techniques
Vessel unloading	Grab, RM hopper	Flex-flaps, dust collector
Vessel loading	Grab	-
Open truck loading	Grab, telescopic chute	Telescopic chute, dust skirt, dust collector
Enclosed truck loading	Telescopic chute	Telescopic chute, dust collector
Train unloading	Wagon unloading pit	Flex-flaps, dust collector
Warehouse loading	DSH, throwing belt	DSH
Warehouse unloading	Front loader, reclaim	Dust collector, dust curtain
Conveyance	Conveyor belts	Enclosure
Conveyor transfer	Transfer chute	Enclosure, dust collector

and prevents the liberation of dust emissions during loading. Furthermore, the chutes are equipped with additional dust collection systems to extract generated dust. The remaining dust is only to escape when the chute is disconnected by the hatch. Hence, the dust emissions mainly depend on the speed of disconnection from the hatch, determined by the operator. It is expected the dust emissions are minimal. Problems that may occur are product build-up and abrasion of the cones. The build-up could result in spillage during retraction of the telescopic chute.

Telescopic chute with dust skirt

A telescopic chute is installed below the bunker of the RM hopper at the quay and can be used to directly load open trucks. The outlet of the telescopic chute is equipped with a dust skirt. In contrast to the telescopic chutes that attach to the hatch, this system does not provide a fully enclosed loading method. However, the dust outlet skirt is expected to counter for the majority of the generated dust. On the other hand, the open loading space of the truck allows wind to liberate dust particles from loaded bulk material. Therefore, it is expected a telescopic chute with a dust skirt significantly reduces dust liberation, but some dust emissions may still occur, especially with higher wind speeds. Other possible problems are similar to the enclosed telescopic chutes. In addition to the build-up of bulk materials and abrasion of the cones, the wear of the dust skirt may need to be considered.

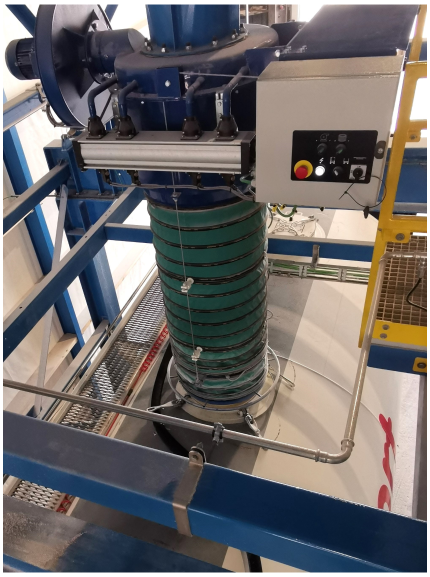


Figure 6.1: Telescopic chute attached to hatch of a truck

Figure 6.2: Telescopic chute with outlet dust skirt. Source: Verbrugge (2024)

DSH

The DSH is utilized to load soda into the warehouse. To distribute the bulk product into different compartments, the DSH is able to travel in the roof ridge along the length of the warehouse.

As described in Chapter 5, the DSH is most suited for good flowing dry bulk products. Although soda has a good flowability, it is also prone to clump formation in humid conditions. Large clumps are filtered out at the start of a transportation line, yet, the presence of smaller clumps may still lead to blockages in the DSH. If the moisture content of the soda is controlled, the DSH is expected to perform properly. Furthermore, the DSH is positioned at a height of over 16 meters above the ground. Hence, before landing the bulk product will have gained a high velocity after free-falling over a large distance. Although the DSH will expectedly provide a consolidated stream, resistant to air entrainment, the high velocity will result in a high impact force, which likely generates a lot of dust. During loading of bulk product, the warehouse is closed off, which prevents dust emissions to be released into the environment. So even though the limits imposed by the regulations are not exceeded, liberated dust inside the warehouse will settle down on the walkways and equipment, posing safety and economical risks.

Overall, the expectation is that the DSH performs well with soda, provided that the moisture content is limited. It will effectively reduce the dust liberation in the bulk stream discharged by the hopper, but cannot avoid dust generated by impact when the product lands. The generated dust emissions will not exceed the limitations imposed by the regulations, but likely causes other issues within the warehouse.

Figure 6.3: Dust suppression hopper at the warehouse

Flex-flaps

The flex-flap technique is used in multiple installations. At both the RM hopper and crane, the flex-flaps are installed at the top of a bunker. At the wagon unloading pit, the bulk product is loaded onto the flex-flaps before being fed to the conveyor belt. At each installation, the flex-flaps are deployed to suppress liberated dust. The one-way passage of the flex-flaps prevent the dust to escape by forming an enclosed system. Assuming the rubber flaps open and close effectively, dust liberation is expected to be minimal. However, during discharge of the bulk product above the flex-flaps, impact and aerodynamic forces still play a role in the generation of dust emissions. Hence, dust emissions deriving from the installation are more likely due to impact and aerodynamic forces above the flex-flap system, than dust escaping through the rubber flaps. So at the current applications, unless the flex-flap system is combined with a method to prevent dust generation during discharge of the bulk product, it is expected dust emissions are still formed.

The flex-flap system operates under the weight of the bulk product. An issue that could be expected with this system is that the volume of bulk product under which the flaps bend open differ with different bulk densities. A relative light bulk material will presumably accumulate more on top of the flex-flaps until the flaps bend and the product can flow through. This gives the bulk product more time to develop dust emissions. Moreover, the adhesive property of phosphate may cause the bulk material to accumulate at the inclined surfaces, posing a risk to obstructing the flow. The possibility of blockage due to clumps in the bulk products is eliminated by the installation of a grid above the flex-flap system.

Figure 6.4: Rail-mounted hopper

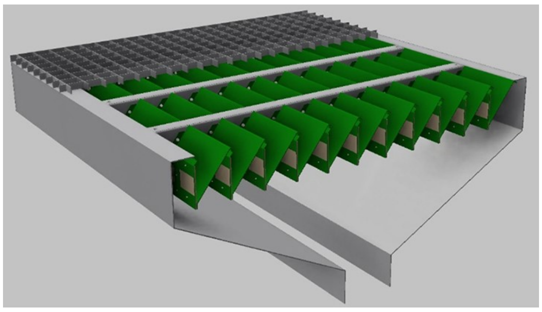


Figure 6.5: The flex-flap system at the RM hopper

Dust collection system

Dust collection systems are often used in combination with one or more dust control techniques. At several reclaim points, dust collection is the main technique for suppressing dust emissions. The reclaim collects the bulk products that is fed by a loader, and discharges the material onto a conveyor belt. The reclaim has a large opening through which the loader can supply the bulk material. To reduce dust emissions, the reclaim is equipped with fabric dust collectors on top and dust curtains to partially enclose the installation. The majority of the captured dust is released back to the main flow through reverse jet.

Dust collection systems are generally effective methods and applied in enclosed spaces. Inside the installation, it will expectedly reduce the dust emissions significantly. At the reclaim, considering that the loading space is not fully enclosed, it is expected that the dust collectors are unable to extract all dust particles. As the reclaim is positioned within the storage facility, the dust emissions mostly impact the employees and equipment. Although the dust collection systems are usually provided with a cleaning mechanism, they presumably still require frequent maintenance. Moreover, the filters may need replacement after regular utilization. Another challenge is posed when the dust collector is applied for handling multiple bulk product. The filters may contain residues from one bulk product and pose the risk of contamination if used with another material. Hence, even though dust collection systems are generally effective for dust control, they are accompanied with some challenges.

Transfer chutes

Due to the many bulk products at Verbrugge that may not be wetted, the conveying installations are enclosed. During transportation, the main dust sources are the transfer points between two conveyors. At Verbrugge, these points consist of an enclosed transfer chute placed at an inclination, and equipped with a dust collection system. Due to the enclosures, dust particles cannot escape the installation. Moreover, most of the generated dust is extracted by the dust collection system. Therefore, dust emissions may only escape with improper sealing. Problems that may arise with using a transfer chute are material residues, abrasion, and clumps obstructing the flow. The presence of large clumps are eliminated at the start of the transportation system. The risk of any issues is low. So, the transfer chute is generally a reliable and effective dust control technique.

6.2. Evaluations

The performances of the dust control techniques are established by both observations of the equipment during operations and conducting interviews with employees involved with the operations. Observations can disclose the dust emissions that are not prevented by the equipment and indicate the performance regarding dust control. The interviews indicate the general performance of the equipment,

Figure 6.6: Reclaim with fabric dust collectors and dust curtain. Source: Verbrugge (2024)

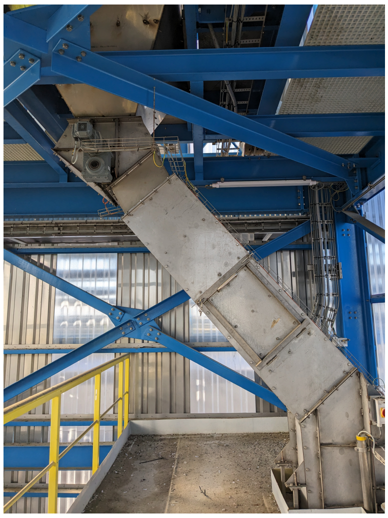


Figure 6.7: Transfer chute between conveyor belts

problems that may occur, and considerations to take into account with such installations. This section presents the results of the observations and interviews.

Enclosed telescopic chute

The telescopic chute is connected to the hatch of a truck and thus forms a fully enclosed system. As expected, during loading there are no dust emissions. When the chute detaches from the hatch, a little bit of dust from inside the truck escapes. The extent of dust liberation largely depends on the retraction rate of the chute, since more dust particles will settle down with time. In terms of dust reduction, this technique is very effective and largely operator-dependent. One precondition for good performance of this technique is the alignment of the truck with the respect to the chute. If the chute is not positioned straight down, high forces act on the chute and the cones will experience more wear due to the increased friction by the bulk product. However, due to relatively small volumes being discharged at a time, this only becomes a significant issue at frequent misalignment. The application of a dust collector ensures an increased level of required maintenance. Provided that the chute will usually be utilized correctly, this technique has an overall good performance.

Telescopic chute with dust skirt

During the loading of a truck with this chute, large dust clouds were observed (Figure 6.8). However, a considerable amount of these dust emissions did not derive from the chute, but from spillage above the chute. Nonetheless, the majority of the dust emissions were generated by the loading with the chute. The visible dust dispersion clearly exceed the two meters imposed by the regulations.

The insufficiency of dust control is believed to be caused by improper design of the dust skirt, which is presumably too short and too light. When a truck is empty, the skirt does not reach the bottom of the storage space, and can therefore not provide an enclosed space for the discharged bulk product. Due to the impact, dust will be generated and escape beyond the skirt. When there is already some product in the cargo hold such that the skirt lays on the heap of bulk material, the skirt flares up due to the flow of product and excess air that tries to escape. Increasing the weight of the skirt materials should reduce the flaring and retain the dust better. The expectations are that replacing the skirt will enhance the performance of dust control.

DSH

The DSH fulfills the expectations of its performance and effectively reduces dust during discharge. However, lots of dust, dependent on the drop height, is still generated on impact as the bulk product lands in the warehouse. This dust rises up into the gallery, where the dust settles on the pathways and equipment (Figure 6.9). This affects the life span of some equipment components, such as the conveyor rolls, bearings, drives, and other (moving) parts. Although the dust emissions remain inside the warehouse, it still poses health and safety risks, and requires regular cleaning and maintenance. Moreover, the settled dust cannot be used and is loss of product. Due to the dust emissions that are generated at impact, it is recommended to only apply this technique in enclosed spaces.

In a previous DSH installation, a problem that sometimes occurred was blockage and overflow due to clumps in the bulk product. In the current installation, the bulk product first goes through a lump breaker before it goes to the DSH. Furthermore, assuming clumps in the bulk product are filtered before entering the DSH, no performance issues are anticipated. For enhanced dust control, the DSH should be implementing in combination with an impact reducing technique. This would address the dust generation by both aerodynamic forces as by impact. Although the DSH does not violate the regulations due to the indoor utilization, it would lower the health, safety, and economical risks posed by dust settlement. It is recommended to only use the DSH in enclosed spaces, and preferably including a dust collection system to suppress the liberated dust.

Figure 6.8: Observation of telescopic chute with dust skirt during loading of an open truck

Figure 6.9: Dust settled on pathways and equipment surrounding the DSH used for warehouse loading

Flex-flaps

Incorporating flex-flaps is a simple yet effective method for preventing dust to escape the bunker. Despite its good performance regarding dust suppression, it does not affect the dust emissions generated above the flex-flaps, mostly caused by aerodynamic forces. Therefore, installations implemented with the flex-flap system are often still a source of significant dust emissions. The flex-flaps have barely posed any other issues at Verbrugge. An issue that presented itself with this technique is the accumulation of dust under the closing plates, causing the rubber flaps to not fully close. Changing the design of these plates resolved this issue. Overall, the technique effectively serves its purpose.

Important considerations in the design of the flex-flap system are the material and thickness of the flaps. Furthermore, the advise is to incorporate other dust control techniques to address the dust above the flex-flaps.

Dust collection system

The observations of the dust collection system as a primary dust control approach are in agreement with the expectations. The dust collectors in combination with dust curtains at the reclaim effectively reduce the dust emissions, but cannot completely prevent it. Moreover, the system is provided with a heating system to limit the humidity and risk of caking. The dust emissions largely depend on the proper functioning of the heating system, volume of the disposed bulk product and the operator. The main disadvantage of this method is the demand for frequent maintenance of the dust filters. Similar as for the DSH, the liberated dust has the greatest impact on safety, health, and economical risks due to the dust settlement on surrounding equipment and pathways (Figure 6.10). Although using the dust collection system as a primary means for dust control is not optimal, it is a good solution with the utilization of a front loader.

Figure 6.10: Dust settlement on equipment surrounding the reclaim bunker

Transfer chute

The fully enclosed system effectively prevents dust particles to be liberated. Therefore, transfer chutes are optimal means in terms of dust control. Airborne dust particles within the system are extracted by dust collection systems. As expected, a challenge is that the dust collectors can only be used for one bulk product, in this case soda. The dust filters need to be shielded from dust when other bulk materials are being handled, otherwise the product may get contaminated. A simple solution is the implementation of a valve, which is only opened during the transport of soda. However, when not operated correctly, the dust filters are not usable anymore and need to be replaced. Therefore, the reliability largely depends on the operation of the valves. In conclusion, the enclosed transfer chutes with additional dust collection systems has a good performance, but needs to be carefully operated.

6.3. Conclusions

Based on the experiences with all kinds of dust control measures, the main recommendation of Verbrugge is enclosing and dust collection. The performance of dust control measures improves with a more continuous flow of bulk product, which can be achieved by regulating the throughput. Reduced performance is often a result of inaccurate practice of the operator or design flaws of the dust control equipment. The latter is possibly caused by time, space, and/or budget limitations, which often have a great influence on the selection and design of the dust control method.

As investigated in Chapter 4, external air flow is usually the primary cause of dust generation. Therefore, it is no surprise that enclosures, which act as both a preventive and suppressive measure, have the most effective dust control performance. Preventive techniques like the telescopic chute and DSH perform good with regard to the dust generation principle they oppose. However, for optimal dust control, other causes should also be accounted for. For example, in case of the DSH without an impact prevention measure, it is best applied in combination with an enclosure and dust collection for compensation. Flex-flaps, dust skirts, and dust collection systems are good dust suppression techniques, and are best applied as secondary means in addition to a preventive measure.

Each dust control technique has its pros and cons and a limited applicability. Hence, the most effective measure depends on the specific application. Following a general step-by-step plan may facilitate the selection process.

7

Development of dust control strategy

Dust emissions can be caused by various mechanisms and numerous factors have influence on the formation and spreading of dust emissions. Moreover, the wide variety of available dust control techniques make it even more challenging to implement dust control measures in bulk handling equipment. The regulations concerning dust emissions imply appropriate dust control measures must be taken, as shown by the quote in Figure 7.1. However, besides providing a large number of possible methods (BAT), the legislation lacks an extensive approach to address the problem. In order to tackle this challenge for all types of dust sources with a systematic approach, a dust control strategy is developed. By following a standardised procedure, the most suitable dust control method is selected. In this chapter, the development of the dust control strategy and its components are described.

(a) all the appropriate preventive measures are taken against pollution;

(b) the best available techniques are applied;

Figure 7.1: Quote from European Commission (2006)

7.1. Strategy components

The systematic strategy should be applicable for all types of dust sources and dust control techniques, while taking into account their features and influencing factors. Criteria are devised to ensure a comprehensive dust control strategy. The dust control strategy should:

- be applicable for all types of bulk handling dust sources
- be applicable for all types of bulk materials
- consider the requirements and boundary conditions of the dust source
- consider the applicable regulations
- consider all types of dust control measures
- consider the integration of multiple dust control measures
- evaluate dust control methods

7.1.1. Dust source

The dust control challenge starts with a certain dust source. In order to obtain an effective dust control approach, it is essential to first establish the properties and limitations of the dust source. This concerns its type of operation, requirements and boundary conditions, relevant bulk material properties, dust emissions cause, and the urgency to reduce dust emissions.

Operation type
Dust sources can be categorised based on their type of operation: loading, unloading, transfer, conveyance, and storage. Loading operations consists of discharging bulk material into into either a storage facility or the transportation mode, whereas retrieving the stored bulk material is considered an unloading operation. Mechanisms passing on product from one piece of equipment to another are transfer operations. Conveyance of bulk materials comprises the transportation over larger distances, like by conveyor belts. Finally, storage is considered as stockpiled materials in rest at an assigned location. The type of operation often implicates the cause of dust emissions and the feasibility of dust control techniques.

Requirements and boundary conditions
Requirements and boundary conditions are often imposed for the dust control methods. Requirements may include dimension limitations, capacity, and budgetary constraints. Boundary conditions could be related to regulation compliance, interaction with other equipment, and the handling conditions. Also the type of bulk materials that will be handled by the dust source need to be indicated. Measures that are not conform these requirements and boundary conditions can be disregarded from consideration as they are unsuitable for the specific application.

Bulk material properties
Chapter 3 examined the bulk properties that may influence the bulk handling equipment. Some of these characteristics could also affect the feasibility of dust control measures. An important property of bulk materials is their dust classification, which does not only indicate their sensitivity to dust formation, but also whether it is wettable or not. This may possibly already rule out wetting techniques, for example. In addition, the dust classification may suggest the handling conditions, such as the maximum wind speed at which the bulk material is handled, as imposed by the regulations. Characteristics concerning the flowability and clump formation, may also play a role in excluding dust control measures from consideration. The performance of some techniques may partly depend on the bulk material's properties, like in case of the DSH. The risk of problems occurring using a DSH increases with poorer flowability or the tendency to form clumps. Moreover, abrasive and corrosive properties, usually influencing the material selection, should also be taken into account regarding dust control measures prone to wear or corrosion. Finally, hazardous properties of bulk products could play a role in the consideration of dust control methods. Such bulk materials may need to avoid contact with heat, moisture, or other (bulk) materials, which may not be achievable by all techniques.

Dust emissions cause
The dust generation principles have been described in Chapter 4 and can be summarized to aerodynamic forces and impact. The cause of dust generation can be established by examining the operation type and handling conditions. Aerodynamic forces can be induced by the relative motion of bulk material through air, an external air flow such as wind, or air entrainment due to dispersion of the bulk material. Dust sources implemented indoors, or otherwise enclosed, are protected against wind. Aerodynamic forces will be induced by the velocity difference between the air flow and the bulk material. Hence, the dust control measure should primarily focus on minimising the relative velocity difference. Impact in bulk handling is a result of bulk material changing direction or velocity. During storage and conveyance, the bulk product is in rest relative to interacting surfaces. Therefore, impact as a dust cause only has to be considered at loading, unloading, and transferring operations. Suitable dust control measures address at least one of the dust generation principles.

Dust control requirements
The main objective of the dust control strategy is to reduce dust emissions as much as possible. In selecting an appropriate dust control method, companies often need to make compromises in the decision-making process based on other factors, such as the costs or life expectancy. The importance of dust control should be taken into account in order to make trade-offs. Regulations already impose limitations on dust dispersion. However, in some cases it may be necessary to reduce the dust emissions even further. Based on the urgency of dust control, the minimum threshold of dust control can be determined.

The urgency of dust control can be evaluated based on the number and severity of risks posed by the dust emissions generated by the dust source. Common dust emissions threats are:

- Health risks
- Safety risks
- Economical risk
- Environmental risk
- Nuisance to residents
- Frequency

Health risks comprise of direct hazard to the health of employees and depends largely on the bulk material. Dust emissions may cause irritations, increase the risk of diseases, or may even be highly toxic. Safety risk involve hazards to the employees working with or nearby the equipment, such as impaired visibility due to dust clouds, slippery walkways as a result of settled dust, or explosive bulk materials. An economical risk is involved in the form of product loss, downtime, maintenance, and replacements. Dust settlement on surrounding equipment contribute to wear and reduce the performance and life time of components. Dust affecting the equipment may require more maintenance or replacements of parts, which also involves downtime of the equipment. The environmental risk indicates the degree of contamination when dust emissions pollute the air, soil, or water. Dispersion of dust emissions beyond the borders of the bulk terminal may also lead to nuisance to nearby residents, such as settled dust on their properties, or a bad smell. Finally, the urgency to reduce dust emissions may depend on the frequency of using the installation. Frequent utilization demands for better dust control than when the equipment is used sporadically.

If at least one of the dust emission threats is very harmful to either health, safety, or the environment, the urgency of dust control is at the highest level and no dust emissions are allowed. The dust emissions from dust sources not posing any direct hazards can be set equal to the limitations imposed by the regulations.

7.1.2. Dust control measures

All possible dust control measures, as addressed in Chapter 5 and by the BAT, should be considered. The measures are categorised as organisational, based on the operator's behavior, or technical. Although some organisational measures may be enforced by the equipment design, the relevant measures for the equipment ought to be applied by the operators. The dust control strategy focuses on the incorporation of technical measures, so that the minimum required dust control is independent of the operator.

A clear overview of the technical dust control measure's features may be convenient for establishing its feasibility. Therefore, the dust control measures can be categorised based on:

- Preventive or suppressive method
- Operation type
- Opposing dust cause

The distinction between preventive or suppressive method is due to the prioritization of prevention over suppression. Preventive measures should be implemented to address the cause of dust generation. As completely preventing dust liberation is usually not feasible, a combination of preventive and suppressive measures should be considered. The operation type categorisation suggests the applicability with the associated operation type of the dust source. Most techniques can only be deployed for certain purposes. For example, a loading technique may likely not be applied for unloading. The opposing dust cause category indicates whether the dust control measure could be effective at the specific dust source. Table 7.1 presents the technical dust control measures addressed in Chapter 5 and their characteristics.

Table 7.1: Categorisation of technical dust control measures

	Preventive / Suppressive	Operation types	Opposes impact	Opposes relative air flow	Opposes external air flow	Opposes air entrainment
Enclosing installation	P S	U L T C R		✓	✓	
Reducing drop height	P	U L T	✓	✓		✓
Increasing impact angle	P	U L T	✓			
Consolidating stream	P	U L T		✓	✓	✓
Optimised grab	P	U L			✓	
Optimised conveyor belts	P	C		✓		
Cleaning conveyor belt	P	C				
Telescopic chute	P	L T		✓	✓	✓
Cascade chute	P	L T	✓	✓	✓	✓
DSH	P	L T				✓
Wet spray system	P S	U L T C R		✓	✓	
Dust skirt	S	L T				
Flex-flaps	S	L T	✓		✓	
Dust collectors	S	U L T C R				

P = Preventive
S = Suppressive
U = Unloading operations
L = Loading operations
T = Transfer operations
C = Conveying operations
R = Storage

7.1.3. Dust control methods

Dust control at bulk handling often consists of a combination of various measures. In order to take the complete design space into consideration, exploration of the possible dust control methods is desired. Hence, after establishing the characteristics of the dust source and the applicable measures, dust control methods containing feasible combination of measures are composed. An effective dust control method should consist of distinctive, preferably both preventive and suppressive, measures. Combinations containing redundant measures, such as both an enclosure and telescopic chute, which is itself enclosed, can be disregarded. To obtain feasible combinations, the following conditions are composed:

- The method contains at least one preventive measure for each dust generation principle
- The method meets the dust control requirements
- The method does not contain similar or redundant measures
- The method distinguishes from other combinations

In addition to these general conditions, the requirements and boundary conditions of the specific dust source may supplement more conditions. For example, if the dust sources handles bulk materials from dust class S1 or S3 outdoors, it requires at least one enclosing dust control measure. Each distinctive, feasible combination represents a possible dust control method. The methods are evaluated to make a well-considered decision.

7.1.4. Evaluation

The objective of the dust control strategy is to select the ‘best’ dust control method. A feasible dust control method must at least meet the required limits regarding dust emissions, established by the dust control urgency. The dust control that meet these requirements are further assessed using a weighted multi-criteria analysis. This approach consists of prioritizing criteria, establishing their significance with corresponding weights, and evaluating the methods based on these criteria.

Pearce (2016) describes 14 aspects usually considered in equipment selection. There are three cost-related factors: first costs, ownership costs, and maintenance costs. The first costs concern the installation of the equipment, whereas the operational costs during its life time are included in the ownership costs. Maintenance costs involve repair and replacement costs of the equipment’s components. The suitability aspect evaluates the applicability of the equipment. However, infeasible dust control methods are eliminated earlier in the strategy process. Hence, the dust control methods do not need to be evaluated on their suitability again. The constructability concerns the achievability of implementation within a certain time frame. A limited schedule should be included in the requirements, hence evaluation on constructability is not necessary. Another aspect described is the experience with the equipment (or manufacturer). However, including this factor in the evaluation may prevent the exploration of new dust control methods. Instead of a criterion, it could be used as a final deciding factor in case two methods have a similar performance. The impact on other elements regards the disruption on other operations by the installation of the equipment. This may be incorporated in the boundary conditions of the dust source. Therefore, this factor does not need to be considered. Noise criteria relates to the frequency scales of noise. However, equipment needs to comply with legislation, which include regulations imposing limitations on noise. The life span of equipment is a relevant criterion to consider. It relates to both the costs and the sustainability. Sustainability also considers the material use, energy consumption, and environmental impact. Pearce (2016) divides these into both an energy benefit and environmental attribute criteria. The scalability and modularity of the equipment involves the efficiency with different applications, such as its performance at varying loads. The handling conditions of the dust source are incorporated by the boundary conditions. Therefore, the dust control strategy takes this factor into account earlier in the process. The redundancy and failure-node risk can be described as the reliability of the equipment. It concerns the equipment’s robustness and the risk of failure. Last but not least, the safety aspect should be considered. Although a certain level of safety is imposed by standards, it may be an objective to aim for more safe equipment.

In conclusion, the following criteria should be included in the evaluation of dust control methods:

- Costs Total lifetime costs (installation and operational costs)
- Reliability Risk of failure
- Maintenance Intensity of required maintenance
- Life span Expected life span
- Safety Risk of hazards
- Complexity Ease of utilization
- Sustainability Energy consumption, material usage, recyclability

7.2. Dust control strategy

The developed dust control strategy is graphically presented in Figure 7.2. The strategy can be divided into three components. The first part consists of establishing the specifications of the dust source, consisting of the operation type, requirements and boundary conditions, relevant bulk material properties, the cause of dust generation, and the requirements of dust control. Next, the feasible dust control measures are selected based on the applicability at the dust source. Measures that do not fit the operation type, oppose the cause of dust, or comply with the requirements and boundary conditions are disregarded. In the last strategy component, the remaining dust control measures are combined into feasible dust control methods. The methods meeting the dust control conditions are evaluated using a weighted multi-criteria analysis. The best rated dust control method is selected.

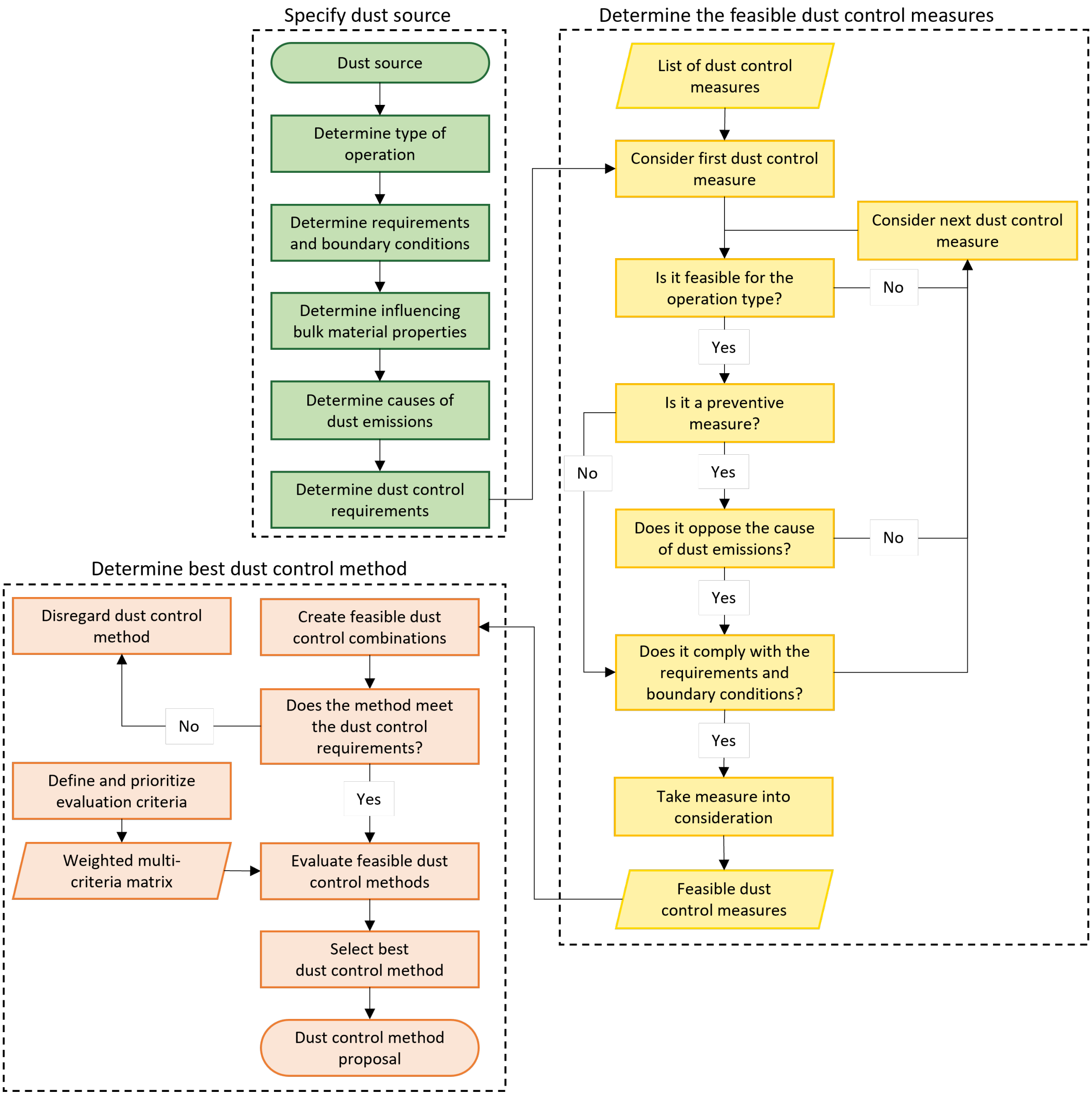


Figure 7.2: Dust control strategy

8

Implementation of dust control strategy

In this chapter, the dust control strategy developed in Chapter 7 is implemented to obtain dust control solutions at three dust sources at the bulk terminal of Verbrugge. The outcomes are evaluated and compared to the currently applied dust control methods. Based on these results, the validity of the dust control strategy can be established and dust control methods are proposed to improve dust control.

8.1. Dust sources

The bulk terminal at Verbrugge consists of numerous potential dust sources and dust control methods. Whereas Verbrugge is content with the dust control measures at some installations, others require a new approach on tackling the dust problem. As it would be too extensive to implement the dust control strategy at each dust source, a small selection is made. This selection distinguishes the following dust sources:

1. A dust source with a well performing dust control method
2. A dust source with an insufficient performing dust control method
3. A dust source and dust control method that is yet to be implemented

The first dust source is considered to establish whether the results of the dust control strategy are comparable to the currently implemented dust control method. The considered dust source is the transfer between two conveyor belts. Implementation of the dust control strategy at the second dust source aims to propose an improved dust control method. By comparing the results with the current dust control method, the reason behind the inadequate approach can be identified. The considered dust source with currently an insufficient dust control method is the transfer between a grab and the RM hopper. By selecting the last dust source, the current decision for dust control can be justified. Verbrugge is engaged with the installation of a new RM ship loader. The loading of vessels with this ship loader is considered as the third dust source.

8.2. Transfer between conveyor belts

At numerous locations at the terminal of Verbrugge bulk materials are transferred from one conveyor belt to another. This is a common operation, usually implemented by an enclosed transfer chute and a dust collection system. Dust may only be liberated into the air if the enclosures contain insufficient sealing, or spread within the conveyance installation. Since the specifications may differ among various conveyance systems, one specific transfer point is considered. For this case, the transfer point between the conveyor belt deriving from the unloading pit and the conveyor belt towards warehouse 42 and 48 is selected (Figure 8.1).

8.2.1. Dust source specifications

The specifications of the transfer point between conveyor belts are presented in Table 8.1. This specific transfer chute is only used for soda. Therefore, it only needs to take the bulk properties of one material

Figure 8.1: The considered transfer chute between two conveyor belts at Verbrugge

into account. The installation is located on the quay, in the open air and has a requirement that the transfer point is fully enclosed. The distance between the two conveyor belts is 5.4 meters in the vertical direction and 3.4 meters in the horizontal direction. Hence, the transfer point must contain an inclined chute. At the start of the first conveyor line, the bulk material passes a grid of 38 by 38 mm. However, the humid environment implies the possibility of the formation of larger clumps. Due to the enclosed chute, the influence of external air flow does not need to be considered. The inclination largely prevents dispersion of the bulk material when falling, hence air entrainment is minimal. The main causes of dust generation are relative air flow and impact.

Soda poses no very hazardous risks for either health, safety, or the environment. The major consequence of dust emissions is the possibility of nuisance in the surrounding area. Therefore, the urgency of dust control is not very high and the limit of dust emissions is set equal to the regulations. On the other hand, dust spreading inside the installation impairs the performance of equipment, reduces the life span, and contributes to increased maintenance. Therefore, the spreading of dust within the installation should be restrained.

8.2.2. Feasible dust control measures

In establishing the feasible measures, the suitability is determined by checking the operation type, requirements and boundary conditions, bulk properties, and causes of dust generation. The dust control measures that are not applicable for transfer operations are ‘Optimised grab’, ‘Optimised conveyor belts’, and ‘Cleaning conveyor belt’, so these are eliminated. Wet spray systems are not possible due to the handling of a non wettable bulk product. Furthermore, due to the construction of the installation, the techniques ‘Telescopic chute’, ‘Cascade chute’, and ‘DSH’ are not applicable. Therefore, the suppressive measure ‘Dust skirt’ is also eliminated. The remaining feasible dust control measures are

Table 8.1: Specifications of transfer point between two conveyor belts

Operation type	Transfer between two conveyor belts
Requirements and boundary conditions	· Enables transferring of soda · Flow rate of 400 t/h · Complies with the regulations regarding dust emissions · Complies with the regulations regarding noise · Complies with the regulations regarding safety · Fits within the layout of the current installations · Needs to be enclosed · Has a vertical displacement of 5.4 meters · Has a horizontal displacement of 3.4 meters · The bulk products has passed a grid of 38x38 mm · Bulk product is handled in a humid environment
Influencing bulk material properties	Considering properties of soda: Dust classes S1 · Dust sensitive · Not wettable · Handled at maximum wind force 4 Good flowability Tendency to form clumps Mildly corrosive
Causes of dust generation	Relative air flow due to high velocity of the bulk material Impact due to large height difference
Dust control urgency	Health: May be irritating to eyes Safety: Settled dust may cause slippery pathways; Some visual impairment Economical: Product loss not too costly; Increased wear of equipment Environmental: Large quantities may affect pH levels, not too harmful Nuisance: Settled dust may cause annoyance Frequency: Regularly

presented in Table 8.2.

As described in Chapter 7, the organisational measures are assumed to be implemented. However, since the influence of the organisational measures often depends on the operators, their contribution to dust control is not taken into account in this chapter.

8.2.3. Feasible combinations

The measure ‘Enclosing installation’ is a requirement, and due to the diagonal nature of the transfer chute, ‘Increasing the impact angle’ is automatically incorporated. Hence, the causes of dust generation is already addressed, so it is not strictly necessary to incorporate another preventive measure. The enclosed chute is simultaneously a suppressive dust control measure. Therefore, a combination containing just these two measures, a typical transfer chute at an inclination, is already an appropriate dust control method. The preventive measure ‘Consolidating stream’ aims to reduce the dust generation due to relative air flow. The bulk product experiences no free fall, but slides down the inclined chute, so the expansion of the stream is expected to be minimal. Moreover, since the influence of relative air flow is already tackled by the other two measures, including an additional consolidation measure is considered redundant. Impact is only addressed by one measure, hence incorporating the measure ‘Reducing drop height’ is still relevant. This may be achieved by a valve, which divides the passage into two segments with both smaller drop heights. As additional suppressive dust control

Table 8.2: Feasible dust control measures for the transfer between two conveyor belts

	Preventive / Suppressive	Opposes impact	Opposes relative air flow	Opposes external air flow	Opposes air entrainment
Enclosing installation	P S		✓	✓	
Reducing drop height	P	✓	✓		✓
Increasing impact angle	P	✓			
Consolidating stream	P		✓	✓	✓
Flex-flaps	S	✓		✓	
Dust collectors	S				

techniques, ‘Flex-flaps’ and ‘Dust collectors’ both are suitable for implementation with the intention to avoid the dispersion of dust within the installation. Since they have a similar objective and little dust is expected above the flex-flaps, including both measures in the combination is redundant. The feasible combinations established are:

(A) Transfer chute
(B) Transfer chute with flex-flaps
(C) Transfer chute with a dust collector
(D) Transfer chute with a valve
(E) Transfer chute with a valve and flex-flaps
(F) Transfer chute with a valve and a dust collector

Schematic illustrations of these combinations are shown in Figure 8.2.

8.2.4. Evaluation

First, the dust control methods are assessed against the dust control requirements. The remaining feasible dust control methods are evaluated based on the criteria as described in Chapter 7. The performances of dust control and other criteria are qualitatively determined, based on the findings in Chapters 5 and 6.

Each of the proposed methods consist of an enclosed chute, which prevents dust dispersion into the air. Hence, each method complies with the dust control regulations. Conditionally, the method must also prevent dust dispersion within the installation. Even though the main cause of dust is opposed by the enclosed and inclined chute, and for methods D, E, and F with a valve, there is expectedly still some dust generated in the chute, which may rise and spread within the installation. This can be prevented by including the flex-flap or dust collection system. Dust control methods A and D will not suffice the dust emission requirement inside the installation and are disregarded.

The priorities of these criteria are determined by the following departments at Verbrugge: Finance, Projects, Compliance, Operations, and Technical. The prioritising process of the departments are presented in Appendix B, Tables B.1, B.2, B.3, B.4, and B.5. The results of each department are added up to establish the average priorities for Verbrugge. The weights are determined by normalizing the criteria scores. The established averaged company priorities and the corresponding normalized weights are presented in Table 8.3.

The dust control methods are evaluated on each criteria and assigned a rating between 1 and 5. These ratings are based on the qualitative assessment of each dust control measure individually, displayed in Appendix B, Table B.6. The ratings are multiplied with the weights, and the scores of each

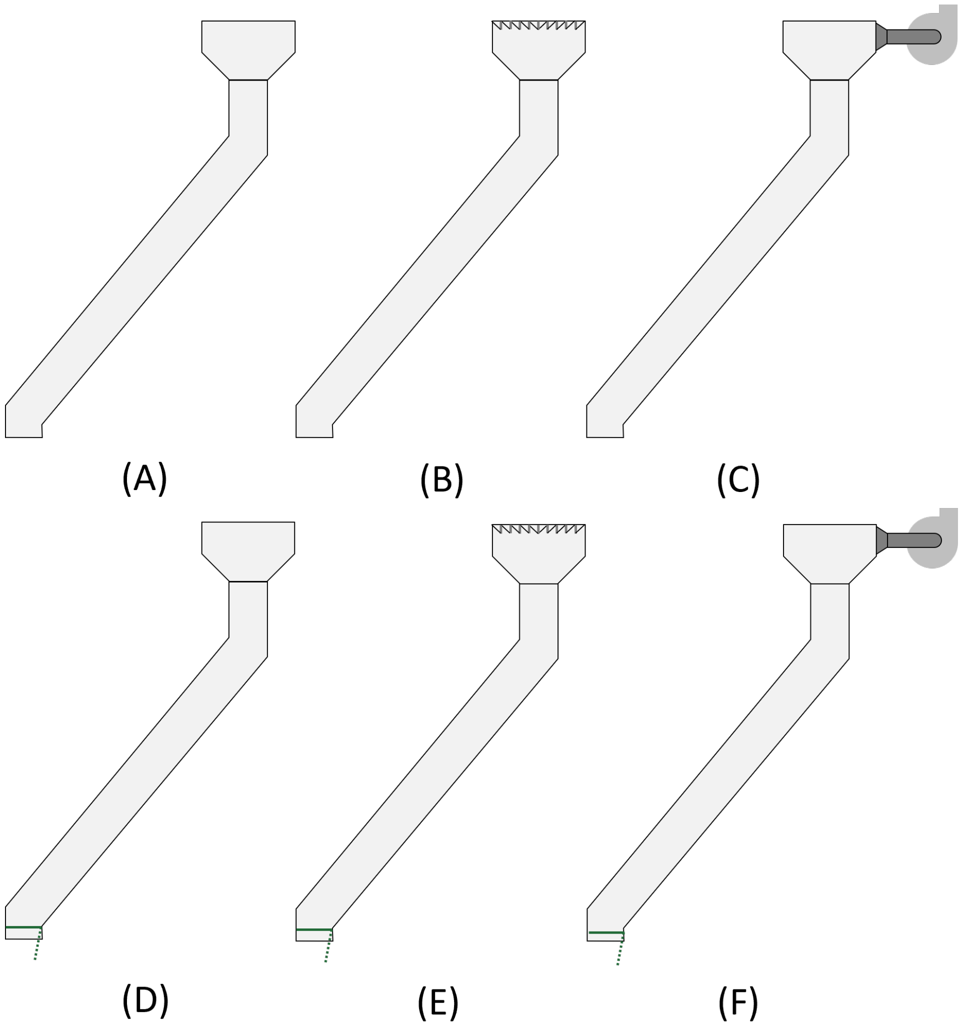


Figure 8.2: Feasible dust control methods for the transfer between two conveyor belts

Table 8.3: Prioritized criteria by each department at Verbrugge

	Finance	Projects	Compliance	Operations	Technical	Total	Weight
Costs	4	1	0	0	2	7	0.067
Reliability	3	3	4	4	5	19	0.183
Maintenance	5	2	2	2	4	15	0.144
Life span	1	2	1	3	5	12	0.115
Safety	6	6	6	6	3	27	0.260
Complexity	1	3	4	5	0	13	0.125
Sustainability	1	4	3	1	2	11	0.106

criteria are added up. This total score represents the overall performance of the dust control methods based on the prioritized criteria by Verbrugge. The dust control method with highest total score is considered the best option, considering the preferences of Verbrugge. However, even though one solution has the overall best performance, this dust control method should not automatically be selected as the final method. It may occur that the best rated method scores the lowest on a highly desired criteria or dust control, which is possibly in disagreement with the company. Hence, the individual ratings should also be taken into consideration in the decision-making.

The weighted multi-criteria analysis shows that the chute provided with flex-flaps at the inlet has the best overall performance. The generation of dust is reduced by the enclosed and inclined chute, while the flex-flaps avoid dust spreading into the installation. Although the performance of dust control is not the best in comparison to the other methods, it is expected to meet the requirements. One consideration with this dust control method is the implementation of flex-flaps at the chute. This combination was not found in literature, so it likely is not a widely applied dust control measure, or has possibly never even been investigated. Therefore, the feasibility of flex-flaps at top of the chute should first be examined before implementation.

Table 8.4: Weighted multi-criteria analysis of dust control methods for the transfer chute between two conveyor belts

		Chute with flex-flaps		Chute with dust collector		Chute with flex-flaps and valve		Chute with dust collector and valve	
Criteria	**Weight**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
Safety	0.260	4	1.04	2	0.52	4	1.04	2	0.52
Reliability	0.183	3	0.55	2	0.37	3	0.55	2	0.37
Maintenance	0.144	3	0.43	1	0.14	3	0.43	1	0.14
Complexity	0.125	4	0.50	4	0.50	4	0.50	4	0.50
Life span	0.115	4	0.46	4	0.46	4	0.46	4	0.46
Sustainability	0.106	4	0.42	3	0.32	4	0.42	3	0.32
Costs	0.067	4	0.27	3	0.20	2	0.13	1	0.07
			3.67		**2.51**		**3.54**		**2.38**

8.2.5. Results

The current dust control method consist of an enclosed transfer chute with a dust collector. This method is rated significantly lower on the overall performance in comparison to the flex-flap system, mainly due to the higher demand for maintenance, and compromised safety and reliability. As opposed to flex-flaps at a chute, numerous transfer points at Verbrugge are provided with dust collectors and have offered good dust control. On the other hand, dust collectors can only be utilized for one bulk product and is accompanied with the challenge of avoiding contamination with other bulk materials. Although this particular transfer chute is currently only used for soda, for other transfer points this may be an important concern. Therefore, it may be valuable to investigate the implementation of flex-flaps at chutes.

Both the proposed methods containing only either flex-flaps or a dust collector are assumed to provide sufficient dust control regarding the requirements. However, an additional valve near the outlet of the chute expectedly enhances dust control even more, especially beneath the valve. In comparison to the method without valves, only the costs are increased. Hence, regarding the objective of improving dust control, it is recommended to also consider the implementation of a valve. Moreover, if the implementation of flex-flaps at a chute is deemed feasible and the performance of dust control is comparable to that of a dust collector, it presents a valuable alternative.

8.3. Transfer between grab and hopper

At Verbrugge, ships are unloaded using a grab. The bulk material is either directly transshipped to trucks, or temporarily stockpiled in a storage facility. For the latter option, the bulk material is transported by conveyor belt systems. The RM hopper is used to transfer the bulk product between the grab and the conveyor belt. Alternatively, the RM hopper may also transfer the material through a chute to trucks. The most dust emissions originate during the release of bulk material by the grab. The current dust control method consists of wind screens and flex-flaps at the inlet of the bunker, and a dust collection system inside the bunker. Although the flex-flaps and dust collection system effectively prevent dust to escape the bunker, a lot of dust still liberates during unloading the grab. When handling dust

Figure 8.3: Transfer between the grab and RM hopper at Verbrugge

sensitive materials, like soda, the current RM hopper does not comply with the regulations regarding dust emissions. Verbrugge is researching alternative methods for a replacement. Since the problem lies primarily at the exchange of bulk product between grab and hopper, this will be the main focus in the search for a dust control method (Figure 8.3).

8.3.1. Dust source specifications

The specifications of the RM hopper are presented in Table 8.5. The operations take place in the open air, meaning wind plays a role in dust generation. Based on the observations of the current installation, and considering a maximum fall height of one meter, external air flow is the largest contributor to dust generation. Due to the small drop height of max. 1 meter, impact and air entrainment may play a small role in the formation of dust. Relative air flow is negligible compared to the contribution of external air flow. The dimensions of the inlet, grid holes, and portal height of the RM hopper are determined by the requirements. The grid prevents large clumps to pass through and cause blockage in subsequent systems. The hopper must be able to transfer all bulk products handled at Verbrugge. Hence, all relevant bulk properties need to be taken into consideration. Most bulk materials at Verbrugge are categorised as dust classes S1 or S3, thus may not be wetted. Whereas the flowability of some products are quite good, other may be more troubling. In addition, the humid environment contributes to the tendency of clump formation, which affects the flowability. As described in Chapter 3, experience indicate the adhesive property of phosphate. Also the corrosivity, characterised by most fertilizers, should be taken into account. The bulk materials handled at Verbrugge do not pose an immediate hazardous threat for health, safety, or the environment. Provided that the dust control regulations are met, the largest motivators to further reduce dust emissions are economical or resident nuisance. Dust inside the installation contributes to the wear of equipment and must be cleaned when switching between bulk products. Moreover, nuisance in the neighborhood may possibly occur due to a stench or dust settlement on people’s properties. Hence, the bulk handling by the RM hopper has a low dust control urgency. The limit of dust emissions is equal to the regulations.

Table 8.5: Specifications of RM hopper

Operation type	Transfer by RM hopper
Requirements and boundary conditions	· Enables transferring of (all) bulk materials handled at the bulk terminal · Flow rate of 1000 t/h · Fed by grab · Can transfer to a conveyor belt · Can transfer to a loading chute of trucks · Complies with the regulations regarding dust emissions · Complies with the regulations regarding noise · Complies with the regulations regarding safety · Fits within the layout of the current installations · Bulk products are handled in the open air · Fall height minimised, but at least limited to 1 meter · RM hopper has a minimal portal height of 9 meters · Bunker is made of RVS 304 and equipped with wear plates · The inlet of the bunker is 8 m x 8 m · Bunker is equipped with grid of 150 x 150 mm · Desired life expectancy of 15 years
Influencing bulk material properties	Considering properties of all bulk materials handled at Verbrugge: Dust classes S1 & S3 · Dust sensitive · Not wettable · Handled at maximum wind force 4 (S1) or 6 (S3) Flowability ranges from good to passable Adhesivity Tendency to form clumps in humid environment Corrosivity
Causes of dust generation	External air flow due to handling in open air Impact due to free fall of the bulk material Air entrainment due to free fall of the bulk material
Dust control urgency	Health: May be irritating to eyes, skin and lungs Safety: Settled dust may cause slippery pathways; Some visual impairment Economical: Product loss not too costly; Downtime due to cleaning in between product switches; Increased wear of equipment Environmental: Water contamination should be avoided Nuisance: Fertilizer dust may cause stench; Settled dust may cause annoyance Frequency: Regularly

8.3.2. Feasible dust control measures

First, the agreement of the type of operation is checked. Although the RM hopper transfers bulk materials between a grab and conveyor belts, the dust control measures ‘Optimised grab’, ‘Optimised conveyor belts’, and ‘Cleaning conveyor belt’ are not relevant for the transfer operation by the RM hopper itself. Furthermore, dust control techniques as the ‘Telescopic chute’, ‘Cascade chute’, and

'DSH' are not capable to receive bulk materials by a large grab. Therefore, these measures can be eliminated from consideration. Also consolidating the stream by the grab is not possible. Moreover, the dust classifications of the bulk materials do not allow wet spray systems to be deployed. From an operational point of view, reducing the drop height is already incorporated, as the grab is lowered as much as possible before opening. The remaining feasible dust control measures are presented in Table 8.6.

Table 8.6: Feasible dust control measures for the RM hopper

	Preventive / Suppressive	Opposes impact	Opposes relative air flow	Opposes external air flow	Opposes air entrainment
Enclosing installation	P S		✓	✓	
Increasing impact angle	P	✓			
Flex-flaps	S	✓		✓	
Dust collectors	S				

8.3.3. Feasible combinations

The primary cause of dust emissions during the exchange of bulk material between grab and RM hopper is the wind. The only feasible measure that addresses the external air flow is enclosing the installation. Therefore, the combinations must at least incorporate this measure. Fully enclosing the RM hopper is not feasible, as the grab needs to be able to discharge the bulk material into the hopper. Hence, including the enclosure measure implies partial enclosures, such as wind screens. Although impact plays a smaller role in the formation of dust emissions in comparison to wind, it is not necessarily redundant to incorporate an impact measure. The only feasible measure to reduce impact is by increasing the impact angle. Air entrainment also plays small role, but there is no feasible measure to oppose this dust generation principle. As suppressive measures, flex-flaps and dust collectors may be incorporated to suppress airborne dust particles from the bunker. To account for the air displacement in the bunker when using flex-flaps, an additional dust collection system is recommended. The current dust control method contains wind screens as partial enclosure, flex-flaps, and dust collectors. Since this combination does not provide sufficient dust control, it can be assumed any combination consisting less measures will also not perform satisfactorily, and will not be taken into consideration. The following combinations are established:

(A) Partial enclosure with flex-flaps and a dust collector

(B) Partial enclosure with increased impact angle and a dust collector

(C) Partial enclosure with increased impact angle, flex-flaps and a dust collector

Schematic models of these combinations are presented in Figure 8.4.

8.3.4. Evaluation

The dust emission restriction is equal to the legislative limit. The current dust control method (A) exceeds the limit for dust emissions. Methods B and C, including inclined impact plates, have enhanced dust control with regard to impact. However, since impact plays a much smaller role than wind in the generation of dust, these methods are not expected to suffice the dust emission limits. This means none of the presented methods comply with the regulations.

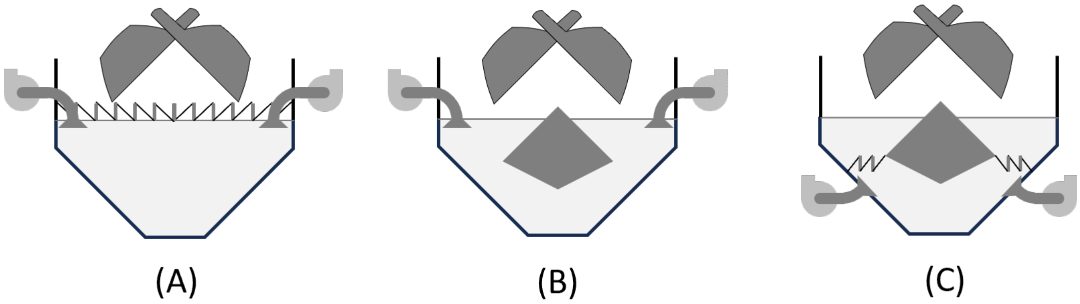


Figure 8.4: Feasible dust control methods for the RM hopper

8.3.5. Results

The currently applied dust control method (wind screens, flex-flaps, and dust collector) does not provide sufficient dust control. Two other feasible dust control methods, proposed by implementing the dust control strategy, are also expected to not comply with the regulations. Instead of investigating the feasibility of implementing dust control measures, in this case it may be more effective to enhance the measures that are already used. Since wind is the major dust generation cause, the design of the wind screens should be revised. It is recommended to use computational modelling, such as Computational Fluid Dynamics (CFD), to model the air flows and enhance the design of wind screens, such that the wind exerts less influence on the bulk material and reduces the trajectories of airborne dust particles.

In this case, using the dust control strategy to select an appropriate dust control method did not result in a satisfying result. However, this approach clarifies that the solution lies not within the selection of dust control measures, but the design of the measures.

8.4. Vessel loading with a ship loader

Due to a new client with high demand for exporting soda by vessels, Verbrugge has made the strategic decision to include a ship loader to the bulk terminal (Figure 8.5). The ship loader, utilizing the rails at the quay, will mostly be used for soda, but can also be deployed for other bulk materials handled at Verbrugge. As dust sensitive bulk materials need to be transported over a significant height difference next to water surface, an effective dust control approach is essential.

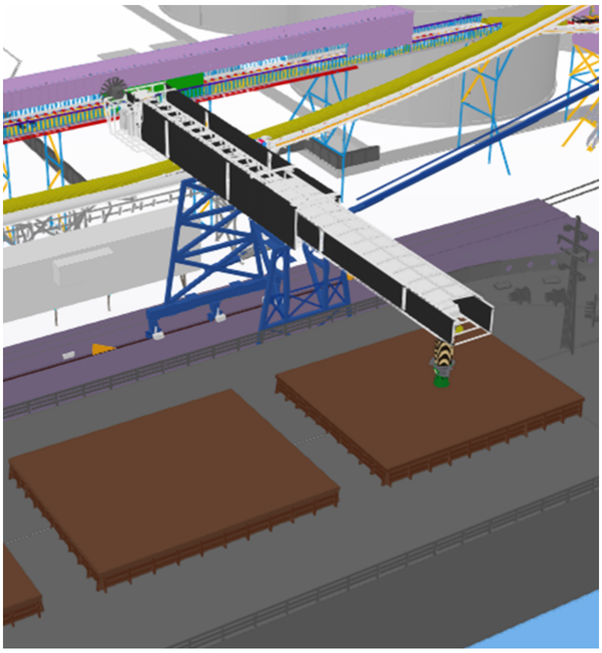


Figure 8.5: 3D model of the ship loader to be installed at Verbrugge

8.4.1. Dust source specifications

The specifications of the ship loader are presented in Table 8.7. A noteworthy requirement is that a chute must be used for loading, which limits the design of the possible dust control methods. Moreover, the ship loader will operate at the quay, in the open air and should be able to be utilized for loading all bulk products handled at Verbrugge. Even though soda as the main product is decisive in the design, the characteristics of all other materials also need to be taken into account, such as the varying flowability, adhesivity, and clump formation. Loading in the open air entails that external air flow is likely present. However, if the loading chute has a telescoping feature and can provide an enclosure over the full distance, the external air flow does not need to be taken into account. The large height difference the bulk material travels ensures a relative air flow during loading, followed by an impact force as the bulk material lands in the vessel's hold. As explained in Section 8.3, the bulk materials are quite harmless, and dust emissions will mainly have some influence on the equipment, required maintenance, and nuisance. Therefore, the dust control urgency is low, but dust dispersion into the ship loader should be avoided. The limitations for dust emissions into the air are equal to the imposed regulations.

8.4.2. Feasible dust control measures

The characteristics of the dust source are used to establish which dust control measures may be considered. First of all, dust measures that are not applicable for loading operations can be eliminated. This concerns 'Optimised conveyor belts' and 'Cleaning conveyor belts'. The requirement of using a chute for loading excludes the measure of 'Optimised grab'. Furthermore, due to the dust classifications of the bulk materials, 'Wet spray systems' are not allowed to be deployed. As described in Chapter 6, the performance of a DSH may deteriorate when handling bulk materials with a poorer flowability or the presence of clumps. Hence, it is discouraged to utilize a DSH with the bulk products handled at Verbrugge. The remaining dust control measures that are feasible for this application are presented in Table 8.8.

8.4.3. Feasible combinations

The preventive dust control measures that remain can be used to address the dust generation principles. An additional condition is the dust control method uses a chute for loading. For telescopic chutes, measures against external air flow do not have to be taken into account. The ship loaders needs to be able to load various vessel sizes, up to the size of a Panamax vessel. Adding the different water levels during loading, it is assumed a telescopic chute is preferred over a chute with a fixed length. Therefore, the chute is considered to fully enclose the bulk material during loading and preventing external air flow. Moreover, the utilization of a telescopic chute entails the consolidation of the bulk stream. The dust control measures 'Telescopic chute', 'Consolidating stream' and 'Enclosing installation' are already incorporated and do not need to be considered anymore. Besides the external air flow measure, the combination should contain at least one dust measures against impact, one against relative air flow, and one against air entrainment. However, since the measures opposing air entrainment also oppose the relative air flow, it is not necessary to include two separate measures. Hence, the method should contain impact and relative air flow opposing measures. The combinations of the preventive dust measures regarding impact and relative air flow are presented in Table 8.9.

The dust control measure 'Reducing drop height' acts against both impact and relative air flow. Although the total drop height remains equal, it may be divided into a series of smaller drop heights. This could be achieved by rubber flaps that open under the weight of the bulk products, similar to the flex-flap system, controlled valves that allows temporarily accumulation of the material before opening, or a cascading type system. The latter approach is not distinctive from the 'Cascade chute' measure, and therefore disregarded. Moreover, when the ship loader feeds a continuous bulk material flow to the chute, the rubber flaps would be forced to remain in an open position. The option that remains is a telescoping chute with controllable valves.

Given that the 'Cascade chute' naturally reducing the drop height and increasing the impact angle, addressing each dust generation principle, it can be used as a standalone preventive dust control measure. Since 'Increasing impact angle' and 'Reducing drop height' are achieved by utilizing a cascade chute, the measures do not have to be considered separately.

The feasible combinations have been deduced to two distinctive dust prevention methods: a telescopic chute with controllable valves and a cascade chute.

Table 8.7: Specifications of the ship loader

Operation type	Loading vessels
Requirements and boundary conditions	· Enables loading of (all) bulk materials handled at the bulk terminal · Soda as the main product (65%) is decisive in the design · Flow rate of 1000 t/h · Loading through chute · Complies with the regulations regarding dust emissions · Complies with the regulations regarding noise · Complies with the regulations regarding safety · Enables loading of Panamax vessels · Fits within the layout of the current installations · Enables cleaning of the loading equipment · Bulk products are handled in the open air · Installation is cleaned with water · Ship loader installation is fully enclosed · Installation time frame of 5 quarters
Influencing bulk material properties	Considering properties of all bulk materials handled at Verbrugge: Dust classes S1 & S3 · Dust sensitive · Not wettable · Handled at maximum wind force 4 (S1) or 6 (S3) Flowability ranges from good to passable Adhesivity Tendency to form clumps in humid environment Corrosivity
Causes of dust generation	External air flow due to handling in open air Relative air flow due to significant velocity of the bulk material Impact due to the free fall of the bulk material Air entrainment due to the free fall of the bulk material
Dust control urgency	Health: May be irritating to eyes, skin and lungs Safety: Settled dust may cause slippery pathways; Some visual impairment Economical: Product loss not too costly; Downtime due to cleaning in between product switches; Increased wear of equipment Environmental: Water contamination should be avoided Nuisance: Fertilizer dust may cause stench; Settled dust may cause annoyance Frequency: Regularly

To enhance the dust control of the two combinations, they can be supplemented with dust suppression measures. The feasible measures are a dust skirt, flex-flaps, and a dust collection system. The purpose of a dust skirt is to prevent dust to be released after discharged by a chute. Including flex-flaps and a dust collection system at the inlet of the chute both prevent dust inside the chute to rise up into the ship loader installation. Since they both have a similar function, including both measures would be redundant. However, it is possible to use both a dust skirt and either flex-flaps or a dust collection system. The following combinations are established:

(A) Telescopic chute with valves and a dust skirt

Table 8.8: Feasible dust control measures for the ship loader

	Preventive / Suppressive	Opposes impact	Opposes relative air flow	Opposes external air flow	Opposes air entrainment
Enclosing installation	P S		✓	✓	
Reducing drop height	P	✓	✓		✓
Increasing impact angle	P	✓			
Consolidating stream	P		✓	✓	✓
Telescopic chute	P		✓	✓	✓
Cascade chute	P	✓	✓	✓	✓
Dust skirt	S				
Flex-flaps	S	✓		✓	
Dust collectors	S				

Table 8.9: Combination matrix for preventive measure against impact and relative air flow

		Relative air flow measures	
		Reducing drop height	**Cascade chute**
Impact measures	**Reducing drop height**	Telescopic chute with valves	Redundant
	Increasing impact angle	Redundant	Redundant
	Cascade chute	Redundant	Cascade chute

(B) Telescopic chute with valves and flex-flaps
(C) Telescopic chute with valves and a dust collector
(D) Telescopic chute with valves, a dust skirt, and flex-flaps
(E) Telescopic chute with valves, a dust skirt, and a dust collector
(F) Cascade chute with a dust skirt
(G) Cascade chute with flex-flaps
(H) Cascade chute with a dust collector
(I) Cascade chute with a dust skirt and flex-flaps
(J) Cascade chute with a dust skirt and a dust collector

Schematic models of these combinations are presented in Figure 8.6.

The valves deployed at telescopic chute are expected to considerably prevent dust generation below the valve, but provide less dust control above the valves. To fulfill the demands for dust control and avoid dust spreading into the installation, the inlet of the chute should also be implemented with a dust dust suppression measure. Therefore, dust control method A is disregarded. Since the cascade chute

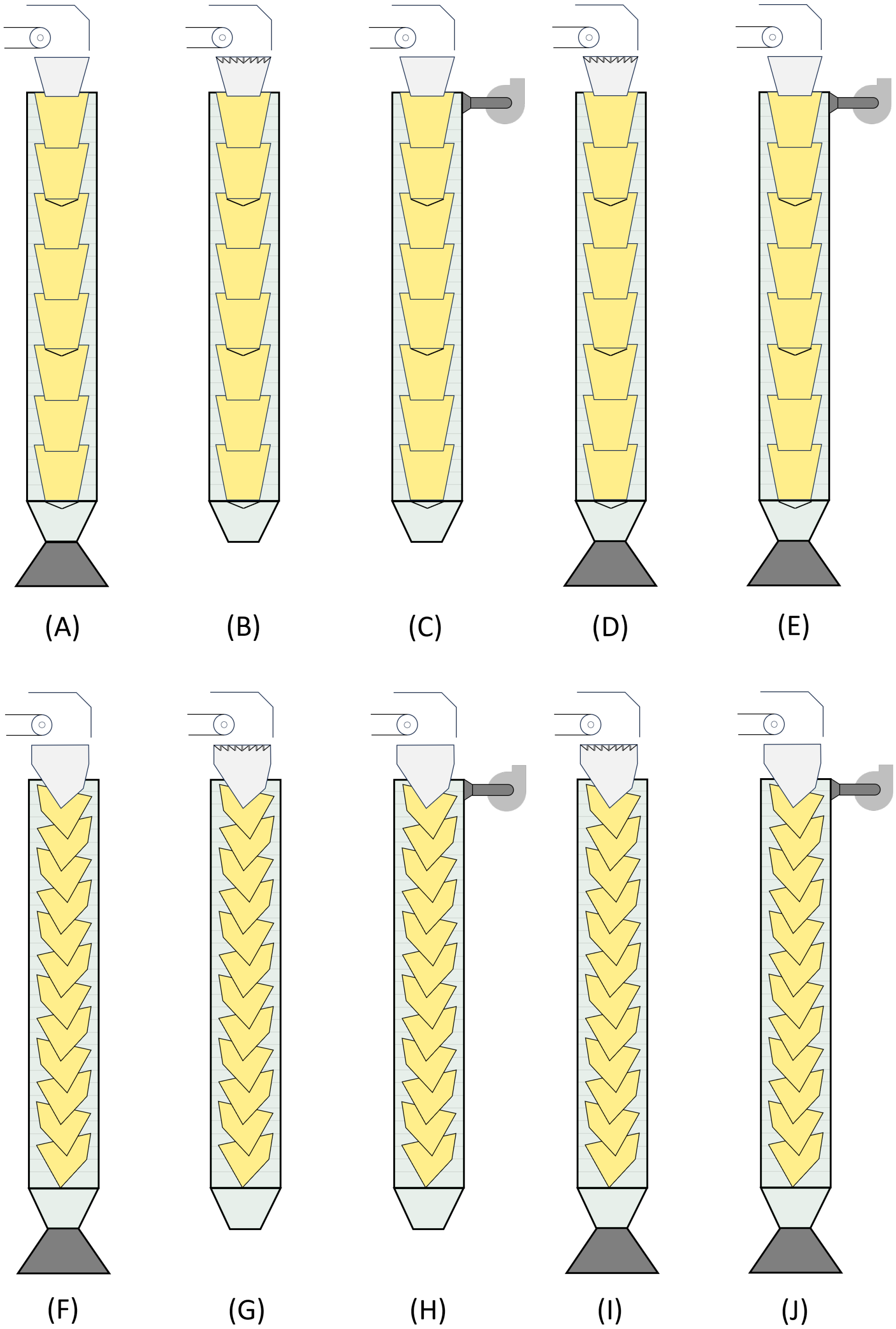


Figure 8.6: Feasible dust control methods for the ship loader

uses all four principles to prevent dust generation, it is expected that an additional dust suppression at the inlet of the chute is not necessarily required to meet the dust control demands.

8.4.4. Evaluation

The dust control methods are evaluated based on the same weighted multi-criteria analysis as explained in Section 8.2.4. The ratings and total scores are presented in Table 8.10. The dust control method rated the highest for the overall performance contains a cascade chute and a dust skirt.

Table 8.10: Weighted multi-criteria analysis of dust control methods for the shiploader

		Telescopic chute with valves and flex-flaps		Telescopic chute with valves and dust collector		Telescopic chute with valves, dust skirt, and flex-flaps	
Criteria	**Weight**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
Safety	0.260	3	0.78	2	0.52	3	0.78
Reliability	0.183	3	0.55	2	0.37	3	0.55
Maintenance	0.144	3	0.43	1	0.14	3	0.43
Complexity	0.125	4	0.50	3	0.38	4	0.50
Life span	0.115	4	0.46	4	0.46	3	0.35
Sustainability	0.106	3	0.32	3	0.32	3	0.32
Costs	0.067	3	0.20	3	0.20	3	0.20
			3.24		**2.38**		**3.13**

		Telescopic chute with valves, dust skirt, and dust collector		Cascade chute with dust skirt		Cascade chute with flex-flaps	
Criteria	**Weight**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
Safety	0.260	2	0.52	3	0.78	3	0.78
Reliability	0.183	2	0.37	4	0.73	3	0.55
Maintenance	0.144	1	0.14	3	0.43	3	0.43
Complexity	0.125	4	0.50	4	0.50	4	0.50
Life span	0.115	3	0.35	4	0.46	4	0.46
Sustainability	0.106	3	0.32	3	0.32	3	0.32
Costs	0.067	2	0.13	3	0.20	4	0.27
			2.33		**3.42**		**3.31**

		Cascade chute with dust collector		Cascade chute with dust skirt and flex-flaps		Cascade chute with dust skirt and dust collector	
Criteria	**Weight**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
Safety	0.260	2	1.52	3	0.78	2	0.52
Reliability	0.183	2	0.37	3	0.55	2	0.37
Maintenance	0.144	1	0.14	3	0.43	1	0.14
Complexity	0.125	3	0.38	4	0.50	4	0.50
Life span	0.115	4	0.46	4	0.46	4	0.46
Sustainability	0.106	2	0.21	3	0.32	2	0.21
Costs	0.067	3	0.20	2	0.13	2	0.13
			2.28		**3.17**		**2.34**

8.4.5. Results

The currently selected dust control measure for the ship loader is also a cascade chute with dust skirt. Additionally, the chute is provided with a preparation to implement a dust collection system, if it later turns out to be necessary. However, the expectation is that the cascade chute and dust skirt will provide sufficient dust control. Although the Verbrugge has no experience with a cascade chute, the technique have proven itself to be very effective in dust control at other facilities. Moreover, implementing valves at the cones of a telescopic chute may be difficult. Hence, even without direct experience, the decision for a cascade chute is very reasonable.

The dust control strategy results in the same dust control method as selected by Verbrugge. Although, the dust control strategy may seem redundant for this dust source, much time, research and many meetings preceded the decision-making process without this approach. Utilizing the dust control strategy led to the same outcome, while involving only a couple of hours.

8.5. Conclusions

In this chapter, the dust control strategy is implemented at three dust sources. The most effective dust control methods are proposed and the results imply the validity of the strategy.

8.5.1. Dust control proposals

The proposed dust control method for the diagonal transfer point between two conveyors consists of an enclosed chute, provided with flex-flaps at the inlet of the chute. Although the suitability and dust control performance of flex-flaps in a chute first need examination, it offers a safer, more reliable, less expensive, and maintenance friendlier solution in comparison to the currently applied measure, a dust collector. If a more enhanced dust control is desired, a valve near the outlet of the chute is proposed.

Dust control at the transfer of dust material between a grab and RM hopper appears to be very challenging. The dust control strategy was unable to propose a feasible combination of dust control measures that meets the requirements for dust control. Hence, instead of exploring alternative dust control measures, it is recommended to investigate optimisation of the wind screens. The wind screens should be designed such that the external air flow entering and leaving the hopper is minimised. Moreover, since external air flow is the main cause of dust generation, it is suggested to strictly comply with the organisational measure and regulation to not operate above the maximum wind speeds.

A cascade chute with a dust skirt attached to the outlet of the chute is proposed for the ship loader. The outcome of the dust control strategy is equal to the decision made by Verbrugge. The cascade chute prevents the generation of dust by utilizing all four dust prevention principles, and the dust skirts offers a suppressive approach to avoid dust dispersion after discharge. An additional suppression measure at the inlet of the chute, either flex-flaps or a dust collector, may be implemented if it turns out dust disperses into the ship loader.

8.5.2. Validity of dust control strategy

The dust control strategy has been implemented at three distinctive dust sources. The outcome of the strategy for the transfer between two conveyor belts does not correspond to the current dust control method, even though Verbrugge is content with this system. Despite the need for research into the proposed method, it provides a beneficial solution, with better performances regarding several criteria.

Applying the dust control strategy to the transfer between a grab and RM hopper did not result in a sufficient dust control method, but demonstrates that the exploration of alternative dust control measures is not effective, and it is more valuable to optimise the applied measures, especially the partial enclosures.

The dust control method for the ship loader resulting from the dust control strategy is equal to the method selected by Verbrugge. Although the performance on this method still needs to be verified, it shows that this approach enables a good proposal, considering both the dust control requirements and other criteria, with less time and effort than the conventional decision-making process.

Considering the results of the three dust sources, the dust control strategy is deemed a useful tool in a decision-making process. The strategy may not always result in a directly applicable dust control method, it also provides useful insights in the challenges and opportunities for enhanced dust control. Moreover, by using a weighted multi-criteria analysis, subjective arguments in the decision-making are eliminated. The selection of a dust control method is well substantiated, easing the identification of the cause if the selected solution does not meet the expectations.

9 Discussion

In this chapter, a recap of the most important findings of this research is presented, highlighting the most significant results and insights gained from this study. Additionally, the limitations are addressed to provide a clear context for interpreting the findings of this research.

9.1. Key findings

The legislation regarding dust emissions proposes numerous dust control measures, but lacks a structural approach in selecting an effective dust control method. This finding led to the development of a dust control strategy, aiming to provide a substantiating decision-making tool to identify the most suitable dust control method. By including a weighted multi-criteria analysis, the strategy takes other criteria, in addition to the dust control performance, into account.

The implementation of the dust control strategy to the transfer point between two conveyor belts has led to the proposal of a flex-flap system, instead of a dust collector. Although this dust control method does not further reduce the dust emissions, it suggests the replacement improves on other criteria, such as reliability and maintenance, while maintaining the performance of dust control. Moreover, the flex-flap system can be applied for all bulk products, whereas the dust collector system may only be used for one material.

The dust control strategy did not yield an improved dust control method for the RM hopper. Although this demonstrates the dust control strategy may not always result in a suitable dust control method, the strategy gives valuable insight in why dust control at this dust source is difficult, and what is suggested to actually reduce the dust emissions.

The implementation of the dust control strategy for the ship loader resulted in the proposal of a cascade chute with a dust skirt. This outcome is equal to the method independently selected by Verbrugge. Although the performance of this dust control method still needs to be confirmed, this result shows that the decision-making process can save a significant amount of time and effort. Moreover, the selection is well-substantiated, providing useful insights if the method does not perform as well as expected.

Overall, the developed strategy is an effective approach in evaluating feasible dust control methods and offering valuable insights regarding potential improvements and considerations. It can be implemented for all kinds of bulk handling installations and bulk products.

9.2. Limitations

This research presents a useful approach to propose dust control methods to reduce the dust emissions at bulk handling facilities. Yet, the limitations of this study need to be addressed to demonstrate the validity of the conclusions.

First of all, the experiments to explore the influence of the dust generation principles were conducted under limited conditions. The drop tests were executed with a single bulk product (soda) and with an inconsistent discharging approach. Including limited workspace and equipment, the accuracy of the measurements is debatable. However, the results were in accordance with the expectations and only used as an indication.

Secondly, as presented by the BAT, dust control measures can be organisational or technical. Although the organisational measures have been addressed in Chapter 5, they are not included in the implementation of the dust control strategy, because their influence on the dust control often depends on the operator's behavior, which may not be consistent. Hence, the results of the strategy consist solely of the technical measures. However, since implementing organisational measures will only further reduce dust emissions, the compliance with the dust control requirements of the proposed methods is not jeopardized.

Another notable limitation of this study is the use of qualitatively descriptions of both dust generation and dust control. Accurately measuring dust emissions is challenging and requires specialized equipment. Dust emissions largely depend on the (varying) conditions, such as the wind speed, making it difficult to obtain reliable, and comparable quantitative measurements. Therefore, the qualitative approach deemed more practical and feasible for this research.

Using the bulk terminal at Verbrugge as a foundation for this study allowed for the implementation of the dust control strategy at realistic, well-defined dust sources, resulting in reliable dust control methods. Consequently, the dust control strategy has not been verified for dust sources at other bulk facilities, handling other (perhaps hazardous) bulk products, with possibly stricter dust control requirements. Hence, the applicability of the dust control strategy is limitedly tested.

Moreover, the bulk properties taken into account at Verbrugge's dust sources are now based on three selected bulk products. Although these materials are expected to represent the most significant bulk properties, a more comprehensive exploration of the occurring bulk properties being processed by the dust source would be required for more reliable decision-making. As a result, the proposed dust control methods in this study are not guaranteed to be suitable for each bulk product at Verbrugge.

Lastly, the comprehensiveness of the dust control strategy is disputed. The strategy is used to select which dust control measures are to be implemented, but not how. Although for some measures it is straightforward, others require a more detailed design proposal to establish their performance and feasibility. The results of implementing the strategy for the transfer between the grab and hopper are a great example. A dust control method with wind screens may be effective, but depends on the actual design of the wind screens.

10

Conclusions

The handling of dry bulk materials, including dust sensitive products, involves the challenge of limiting the dust emissions. As outlined in Chapter 1, the dispersion of dust emissions is accommodated with hazardous risks for health, safety, and the environment. Furthermore, it contributes to economical losses and possibly causes nuisance in the neighborhood. Despite numerous available dust control measures, dust emissions generated during bulk handling are regularly not sufficiently reduced and exceed limitations imposed by regulations. Handling multiple dry bulk products, like at Verbrugge, makes it even more difficult to address this problem. This has led to the main question addressed by this research:

How can the dust control methods of bulk handling equipment processing various dry bulk products be improved in order to further reduce dust emissions?

A dust control strategy is developed to provide a structural approach for selecting the most suitable dust control method. Regulations plays a significant role in reducing dust emissions at bulk handling facilities. Legislation imposes limitations for dust emissions and proposes several dust control measures, yet lacks a clear approach on how to determine the most suitable dust control method. The developed dust control strategy extends the legislation with a general procedure, applicable for all types of bulk handling operations and bulk products. In order to achieve this, it incorporates the specifications of the dust source, investigates the feasibility of dust control measures, and creates and evaluates combinations. The methods meeting the dust control requirements are evaluated through a weighted multi-criteria analysis, where the methods are assessed on prioritized criteria.

The strategy is implemented for three dust sources at Verbrugge to propose the most suitable dust control methods to further reduce dust emissions. For transfer chutes between two conveyor belts is suggested to incorporate a flex-flap system at the top of the chute, instead of the dust collector system currently used. This proposal maintains a comparable dust control performance and a substantial better overall performance. Further, the strategy shows that changing or adding dust control measures at the RM hopper is not effective. The implementation of the dust control strategy has given the insight that it would be more valuable to optimize the design of the wind screens to improve the dust control at the transfer between the grab and hopper. Implementing the dust control strategy at the soon-to-be-installed ship loader results in the proposal of a cascade chute with a dust skirt. The cascade chute is expected to sufficiently prevent dust emissions by addressing all causes of dust generation, while the dust skirt suppresses the escape of dust particles after discharge. The implementation of the dust control strategy demonstrates that the approach may not only be used to determine the most suitable dust control methods, but also to obtain valuable insights into establishing potential issues that may arise and providing possible solutions. Moreover, by using the strategy to substantively select the dust control method, the time and effort invested in the decision-making process may significantly be reduced.

The development of the dust control strategy is based on the gathered knowledge concerning bulk material properties, dust generation principles, and dust control measures. The bulk equipment at Verbrugge need the ability to handle the numerous bulk products. This means the design and operations of bulk handling equipment needs to take the bulk properties of the relevant bulk products into account.

The materials used in the equipment are influenced by the corrosivity, abrasivity, and wall friction. The bulk density and flowability of the bulk products are involved in the dimensions and shaping of the bulk handling installations. Furthermore, in case the bulk materials contain hazardous properties, precautionary measures may need to be incorporated into the equipment.

The primary causes of dust emissions are aerodynamic and impact forces acting on the bulk material. Aerodynamic forces may be caused by an external air flow, such as wind, relative air flow due to the relative motion between bulk product and air, and air entrainment. Impact occurs as the bulk material endures a physical interaction and changes velocity and/or direction. From experimental drop tests it is concluded that an external air flow is the primary contributor in dust formation. The other dust generation principles play a smaller role, but are in accordance with the expectations. After the generation of dust emissions, the trajectory of airborne dust particles majorly depends on the particle dimensions and weight.

Based on the dust generation mechanisms, the dust control principles are proposed. The primary principles to prevent dust generation are enclosing the installation, reducing the drop height, increasing the impact angle, consolidation of the bulk stream, and increasing the cohesion. Common preventive dust control techniques implementing these dust control principles are telescopic chutes, cascade chutes, Dust Suppression Hoppers, and wet spray systems. Dust emissions that cannot be prevented may be addressed by limiting the trajectories of particles, which may be achieved by enclosing the installation, utilizing the air flow, or increasing the dimensions and/or weight of dust particles. Regularly used suppressive dust control techniques implementing these considerations are (partial) enclosures, dust skirts, flex-flaps, wet spray systems, and dust collection systems.

Experience at Verbrugge has learnt that for effective dust control, the techniques require a proper design and a good compatibility with the characteristics of the bulk products. Enclosures appear to be the most effective dust control measure, as it is both a preventive and suppressive method. Telescoping chutes perform best when fully enclosed, but is also an adequate technique when implemented with a dust skirt. A DSH is recommended to only use in an enclosed environment, as the impact after discharge still creates significant dust emissions. Flex-flaps are a simple approach to suppress dust particles below, but needs an additional measure to prevent the dust generation above. Dust collection systems require a lot of maintenance, but achieve good reductions in dust emissions and may best be applied in (fully) enclosed spaces.

10.1. Recommendations

The findings of this research have led to several recommendations for further research, serving both academic and practical purposes.
The following academic recommendations are proposed:

- In this study, an indication of the contribution of the dust generation principles is examined with limited resources. To obtain a better understanding of the influence of the different mechanisms, more extensive experiments should be conducted. This could involve additional drop tests with various bulk products with specialized equipment to collect more accurate data. Such research may illustrate the relevance of dust causes and the importance of dust control measures.

- The dust control performances of organisational measures were not investigated in this research, because they often depend on inconsistent factors. To demonstrate the influence of human interventions, the effects of organisational measures can be established through controlled experiments. Additionally, the enforcement of organisational measures through technical design choices should be explored to avoid the dependency on operators.

- It is also recommended to quantify the contributions of dust generation mechanisms and performances of dust control measures. More accurate measurements could be used to better predict dust generation and improve the assessment of dust control performances, leading to better dust control proposals. Possible dust measuring technologies are laser diffraction or real-time monitoring systems.

- The results of this study have shown the applicability of the dust control strategy at Verbrugge. Further research should consider applying the strategy in different scenarios and with other bulk materials to extend the verification of the strategy. Implementations on a larger scale can be used to refine the strategy.

- Implementation of the dust control strategy at the RM hopper has led to the suggestion to also include a ‘design’ step in the procedure, instead of solely selecting the measures. This design component could include various ways of incorporating or optimising the design of a dust control measure. Researching this strategy improvement may further enhance the proposals for dust control methods.

The following practical recommendations are suggested:

- The dust control methods proposed for Verbrugge are based on the selection of three bulk products. Although the selected materials presumably possess the most significant bulk properties, the feasibility of the methods should be examined for *all* bulk products being handled by the equipment, preventing any unanticipated issues.
- Several dust control methods proposed by the dust control strategy consisted of a flex-flap system at a chute. Research into the feasibility of this approach was not found. Considering the better performances at various criteria, the applicability of this method is potentially worth investigating. The feasibility of the flex-flap system at a chute could be studied through computational modelling or by testing it on scale.
- The results of the dust control strategy at the RM hopper showed that the deployment of wind screens is the only feasible measure to address the dust emissions generated by wind. Since the current design does not sufficiently reduce dust emissions, it is recommended to use computational modelling, such as Computational Fluid Dynamics (CFD), to model the air flows and enhance the design of wind screens, such that the wind exerts less influence on the bulk material and reduces the trajectories of airborne dust particles.

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A

Research paper

Improved Dust Control at a Bulk Terminal

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Abstract

Dust emissions developed during the handling of dry bulk products pose increased risks for health, safety and the environment. Effective dust control is a challenging problem and becoming even more difficult when various bulk products are handled. The aim of this research is to improve the design of bulk handling equipment processing various dry bulk products to further reduce the dust emissions. A dust control strategy is developed based on the knowledge gathered through both theoretical and practical research concerning the formation and control of dust emissions. The strategy provides a structural approach to identify the most suitable dust control methods through a weighted multi-criteria analysis. The strategy is applied to three dust sources at the Verbrugge bulk terminal, suggesting the replacement of dust collectors with flex-flaps at transfer chutes and optimization of hopper wind screens to mitigate wind effects. Additionally, it recommends equipping ship loaders with a cascade chute and dust skirt. This study shows the developed dust control strategy enables substantively proposing the most suitable dust control methods, offers valuable insights into potential issues, provides possible solutions or improvements, and significantly reduces the time and effort invested in the decision-making process.

1 Introduction

Air pollution is linked to many diseases and considered the largest environmental hazard to human health, according to the World Health Organization (2021). Each year, millions of deaths are estimated to be attributable to air pollution. Among the pollutants is dust generated during the handling of dry bulk products. Besides the health effects, these dust emissions also pose environmental, safety, and economical risks. Moreover, the dispersion and settlement of dust may cause nuisance to surrounding residents. As a result of the highly undesirable consequences to both the facility, their employees, and surrounding residents, regulations are imposed to drive bulk handling facilities to maintain dust emissions within limitations.

During bulk handling, the following conditions regarding dust emissions must be met:

- Visible dust dispersion beyond 2 meters from the source is prevented
- Dust dispersion may not occur above water surface

The transportation company Verbrugge has a bulk terminal in Terneuzen, the Netherlands, and is specialized in the storage and transshipment of multiple dry bulk materials. The primary product handled is soda, a powdery and highly dust sensitive bulk material. Other bulk products handled at Verbrugge are mainly fertilizing materials, such as phosphate and urea, of which several are also prone to dust liberation. Although legislation proposes numerous measures to address dust emissions, the limitations regarding dust emissions are at some installations regularly exceeded. At Verbrugge, tackling this problem is even more challenging as the bulk equipment needs the ability to handle various dry bulk products, taking the different bulk properties into account.

This research aims to improve dust control at a bulk terminal where various dry bulk products are handled. Reducing dust emissions is not only a requirement imposed by the regulations, but also economically more beneficial and essential for a healthier and safer environment. Despite the numerous available dust control measures, bulk handling facilities may need more guidance towards implementing of more effective dust control methods. The following research question is addressed: How can the design of bulk handling equipment processing various dry bulk products be improved in order to further reduce dust emissions?

First, a literature study is conducted to establish the influence of bulk properties on the operations and design of equipment, and the principles of dust generation, dispersion, and control. The theory is examined through some more practical approaches in an attempt to obtain an indication of the influence of the different dust generation causes and the performances of dust control techniques. Based on the gathered knowledge, a dust control strategy is developed to provide a structural approach in the decision-making of dust control methods. This strategy is used to propose the most suitable dust control methods at three dust sources at Verbrugge.

2 Literature study

A literature study into influencing bulk properties, the generation of dust emissions, and dust control is conducted to obtain a better understanding on how to effectively control dust.

2.1 Bulk properties

The installations at the bulk terminal of Verbrugge need to be able to handle the different bulk products. The bulk properties that influence the bulk handling equipment are investigated.

Flowability

The flowability is an important characteristic of bulk products. It relates to the ease of moving the material and often given an indication of the difficulties that may arise during operations. However, the flowability is not an intrinsic bulk property and depends on the following other bulk properties and conditions:

1. *Particle size distribution.* Smaller particles have a relative larger surface area, so more contact points, resulting in a decreased flowability. A wider particle size distribution offers smaller particles to infiltrate gaps between larger particles, increasing the contact points and cohesion strength, decreasing the flowability (Ganesan et al., 2008).
2. *Angle of internal friction.* The friction among particles of a bulk material is represented by the effective angle of internal friction. A larger internal friction angle means a larger force is required to move the particles along each other, which corresponds to a reduced flowability (Schulze, 2008).
3. *Cohesion and adhesion.* The cohesivity and adhesivity are the tendency of particles to stick to each other (cohesion) or to another material (adhesion) (Schulze, 2008). The cohesion also depends on the particle sizes, moisture content, and compressive state. Materials with increased cohesion and adhesion require larger forces to separate particles from each other or surfaces, which decreases the flowability.
4. *Compressive state.* By compressing a bulk material, the cohesion among particles increases, which decreases the flowability (Schulze, 2008).
5. *Hygroscopy.* Hygroscopic bulk materials absorb moisture and most tend to form clumps. The presence of clumps in the bulk product may obstruct the flowability (Borax, 2017).

Bulk density

The bulk density is defined as the mass of the material particles per unit of volume occupied by the material and also depends on the compressive state (Abdullah and Geldart, 1999). The demanded capacity of bulk handling equipment is usually the leading factor of dimensions and power.

Wall friction

The angle of wall friction represents the friction between the bulk material and a surface (Schulze, 2008). A bulk material with a larger angle of wall friction needs steeper slope angles to achieve mass flow.

Abrasion

The wear of equipment depends on the abrasiveness of a bulk product. The abrasion is determined by the difference in hardness between the bulk material and equipment material (Barbosa-Cánovas et al., 2005). A hard material has more resistance to plastic deformation caused by another material. The abrasiveness influences the material used in the bulk handling equipment.

Corrosivity

Corrosive materials cause damage to other materials, affecting the constructive strength of the equipment (EcoOnline, n.d.). The corrosivity of a bulk product also influences the material selection for the installations.

Hazardous properties

Some bulk materials possess hazardous properties, such as ignitability, reactivity, or toxicity (US EPA, 2015). Handling bulk products with hazardous properties usually means certain conditions are imposed on the design and operations of the equipment, such as ventilation or the disallowing of potential ignition sources.

Relevant bulk properties at Verbrugge

Verbrugge primarily handles soda and fertilizing bulk materials. The majority of the bulk products is categorised as dust class S1 or S3, and thus require significant dust control measures and disallow the use of moisturizing techniques. The flowability of the products ranges between good and moderate flowing. Another bulk property to consider is the adhesivity of some bulk materials, like phosphate, increasing the product's tendency to stick at the equipment surfaces, leave residues, or obstruct the flow. The equipment material is influenced by the corrosivity possessed by most (fertilizing) bulk products. Lastly, although the bulk materials handled at Verbrugge are relatively harmless, human contact and contamination should be avoided as it may cause irritation or form safety hazards, respectively.

2.2 Dust generation

Reducing dust emissions can be achieved through two approaches: preventing the liberation of dust particles and extracting airborne dust particles. Dust control should primarily consist of dust prevention. Hence, it is essential to understand how dust emissions are generated.

Dust generation principles

The main causes of dust liberation are impact and aerodynamic forces acting on the dust particles (Figure 1). If such a separation force exceeds the binding forces, dust particles are liberated from the bulk material. An impact on bulk material results in a change in velocity or direction. The physical interaction causes conversion of the kinetic energy of the bulk material, leading to dust liberation.

There are several mechanisms through which aerodynamic forces may be induced on the bulk material:

- A relative air flow due to a difference in velocity between the bulk material and the ambient air
- An external air flow, such as wind
- Air entrainment. Bulk material disperses as it falls and is mixed with air. This entrapped air captures dust particles, which are liberated upon release of the entrained air.

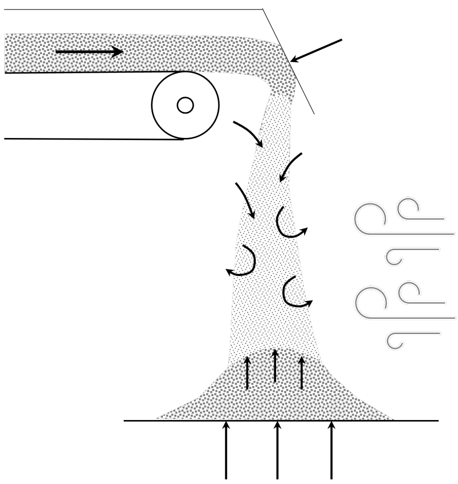

Figure 1: Dust generation mechanisms

Dust dispersion

The trajectories of airborne dust particles are mainly determined by gravitational, buoyant, and drag forces (Figure 2). The net downward force caused by gravity and buoyancy driving dust particles to settle down is proportional to the cube of the particle's radii. The drag force, dependent on the relative air velocity, is proportional to the radii squared. Therefore, drag forces play a larger role in the trajectories of smaller particles, enabling them to travel further with larger wind speeds.

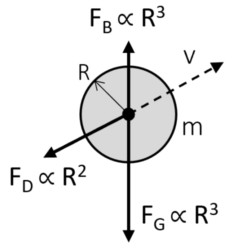

Figure 2: Forces on airborne dust particles

2.3 Dust control

Dust emissions are reduced by preventing the dust generation mechanisms and limiting the trajectories of airborne dust particles. Dust control by design considerations and techniques can be categorised as preventive and suppressive dust control.

Dust control principles

The causes of dust emissions are attributed to aerodynamic and impact forces. The impact force depends on the change in velocity or direction of the bulk flow. The aerodynamic force as a consequence of relative or external air flow relates to the velocity difference between the bulk material and air flow. The degree of air entrainment corresponds to the volume of air being entrapped in the bulk stream. The volume the air potentially entrapped is equal to the volume of voids among the dispersed bulk material. The dust generation principles can be addressed by:

- enclosing the installation
- minimising the drop height
- minimising the dispersion of the bulk stream
- minimising the change in direction of the bulk product

The influence of an external air flow can be completely avoided by enclosing the installation. The drop height influences both the velocity and extend of dispersion of a bulk material during free-fall. Hence, a smaller drop height reduces the relative air flow, air entrainment, and impact force. By increasing the angle of impact, the bulk velocity is partially redirected, and a smaller impact force is exerted on the bulk product. Consolidating the bulk flow reduces the dispersion of the bulk material. The causes of dust emissions can mostly be prevented by incorporating these design consideration, as presented in Figure 3.

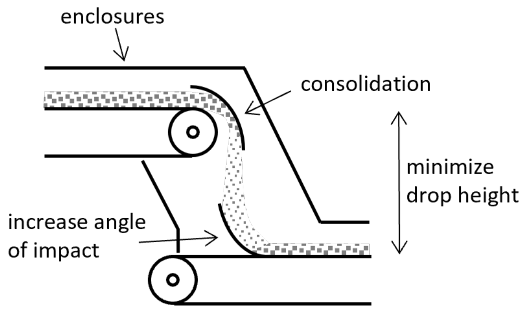

Figure 3: Primary design considerations to minimise the generation of dust emissions

Dust suppression measures are based on reducing the trajectories of the airborne dust particles. The trajectory of an airborne dust particle depends on the mass and the forces induced by the air flow. By increasing the weight of the particle or using a controlled air flow, the dispersion dust emissions is reduced. Three design considerations that may be implemented to suppress dust particles are:

- enclosing the installation
- utilizing the air flow
- increasing the size or weight of dust particles

Organisational measures

Dust control may not only consist of design-related measures, but may also include organisational approaches. These are measures to be implemented by the operators. Considering the contribution of external air flow to dust generation, an important measure is to stop operations above a wind speed of 8 m/s (S1 and S2), 14 m/s (S3), and 20 m/s (S4 and S5). Furthermore, for operators of a grab or mechanical shovel it is important to reduce drop heights and maintain a correct position during discharge for a sufficient time. Conveyor belts should be operated at a suitable speed and loaded material should be kept below the edges.

Dust control techniques

Dust control techniques use at least one of the design considerations to prevent or suppress dust emissions. Commonly applied prevention techniques at bulk handling facilities are telescopic chutes, cascade chutes, Dust Suppression Hoppers (DSH), and wet spray systems. Wet spray systems can also be deployed as a suppressive measure. Other suppression techniques regularly used are dust skirts, flex-flaps, and dust collection systems.

A telescopic chute is composed of a series of truncated cones that can slide into each other, which allows the chute to extend or retract to obtain the optimal position for loading (Cecala et al., 2019). The conical shape of the cones prevent dispersion of the bulk material during free-fall and reduces air entrainment. The outer shroud of the chute protects the bulk material against external influences, such as wind and rain.

An alternative loading chute is the cascade chute, in which the cones are placed at an angle and arranged in an alternating manner (Cleveland Cascades Ltd, 2016). The bulk material travels down the chute by sliding along the inclined cones, progressing from one cone to the next (Figure 4). The cascade breaks down the total drop height of the chute into numerous smaller segments, reducing the bulk velocity and the impact forces.

A DSH contains a conical hopper suspended by springs and a fixed central plug, which closes off the outlet of the hopper at rest. When the bulk material accumulates inside the DSH, the weight increases and the springs of the hopper extend. The opening at the outlet is increases and the bulk material flow forms a compact stream as it is pressured out of the DSH. The consolidated flow reduces air entrainment and prevents the liberation of dust particles.

Wet spray systems distributes droplets onto the bulk material (Swinderman et al., 2009). The cohesion among particles in the bulk stream increases, reducing the liberation of dust particles (preventive). If particles are already airborne, the droplets binds to the particles, increasing the weight and accelerating settlement (suppressive). Both approaches are presented in Figure 5.

A dust skirt may be attached to the outlet of a telescopic chute. The skirt lays on top of the heap of bulk product during loading, preventing dust particles to escape when discharged and enabling the dust particle to settle down before the loading chute is lifted.

When bulk material is loaded into an open-top unit, such as a hopper, developed dust may rise up and escape. The flex-flap technique avoids the dust particles to escape by forming a one-way passage for the bulk material (Figure 6). The system consists of flexible ‘flaps’ sealing off the top, but bend under the weight of bulk material to allow the material to flow through (Docksolid, 2015).

A dust collection system draws air away from the dust source and filters the dust particles. Often the extracted dust particles are redirected to the bulk stream (Swinderman et al., 2009). Dust collectors are effective methods in (partial) enclosed spaces, but require a lot of maintenance and can be used for only one bulk product to prevent contamination.

3 Methodology

Experiments are conducted to establish the contribution of the dust generation principles to dust emissions. A dust control strategy is developed based on both theoretical and practical insights.

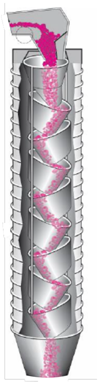

Figure 4: Cascade chute. Source: Cecala et al. (2019)

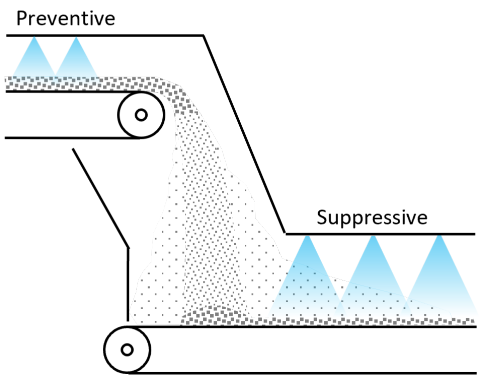

Figure 5: Wet spray systems

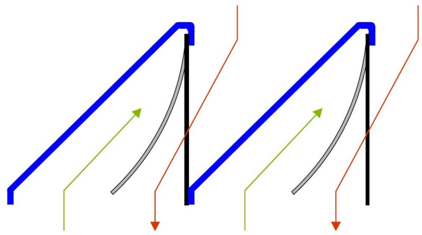

Figure 6: Flex-flap system. Source: Docksolid (2015)

3.1 Drop tests

The contribution of dust generation principles are investigating by conducting drop tests. During a drop test, a bucket of bulk material is turned over, causing the bulk product to fall down. Each repetition, one variable's value is changed while keeping the other conditions constant. Three drop tests are composed:

- *Wind speed.* The bulk material is dropped through an air flow generated by a fan. By varying the speed of the air flow, the influence of wind speed is determined.
- *Impact angle.* The bulk material is dropped onto an inclined surface. By varying the inclination angle, the influence of the impact force is determined.
- *Drop height.* The bulk material is dropped from varying drop heights. The influence of the relative air flow, air entrainment, and impact are examined.

After execution of each drop test, the distance of the settled dust particles is measured. The graph in Figure 7 shows the results.

The wind speed during the first drop test is varied between 0 m/s to 5 m/s. At 5 m/s, the dust settled beyond the working space and could not be measured. Neglecting this measurement, the graph clearly shows a strong increasing trend at higher wind speeds.

At the second drop test, the inclination angle is varied between $\theta = 0°$ and $\theta = 40°$. The graph presents the dust dispersion right after impact. As expected, a greater impact angle consistently reduces the distance of dust dispersion.

The drop heights during the last drop test is varied between 1 m and 2 m. The distance of settled dust increases with a larger drop height.

Although the measuring units of the variable among the drop tests are not comparable, a small change in wind speed significantly influences the distance of dust emission more than the other two variables. It is speculated external air flow is the largest contributor to the generation of dust emissions. The influences of impact, relative air flow, and air entrainment correspond to the theory, but have less effect than the external air flow.

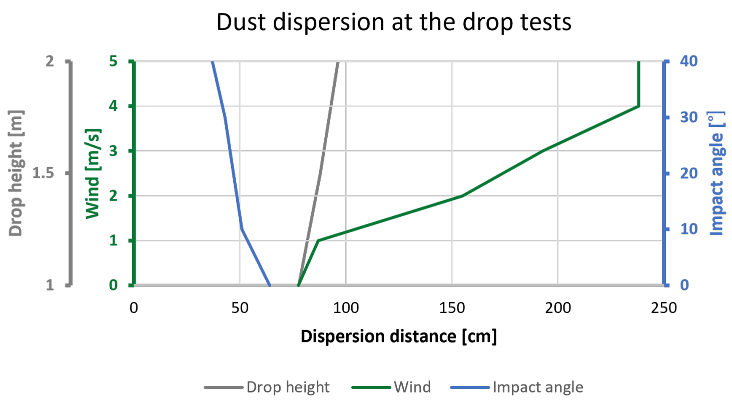

Figure 7: The dust dispersion at the drop tests

3.2 Development dust control strategy

Due to a lack of a structural approach selecting the most suitable dust control method, a dust control strategy is developed. The strategy must be applicable for all types of dust sources and bulk materials, while considering the requirements and boundary conditions and the regulations. Dust control methods are created with feasible dust control measures and evaluated to select the most suitable method. The dust control strategy aims to provide a decision-making tool for substantively selecting dust control methods.

Dust source
First, the specifications of the dust source need to be established. A dust source can be categorised based on the operation type: loading, unloading, transfer, conveyance, and storage. The design of a dust source is usually accompanied with requirements and boundary conditions, such as spatial constraints, capacity, and regulations. Furthermore, the properties of the bulk materials handled by the dust source need to be taken into account. In order to effectively control dust, the cause of dust generation needs to be established. Lastly, the limitations for dust emissions are determined based on the dust control urgency. The minimal limitations for dust emissions are equal to the constraints imposed by the regulations. The more hazardous the dust emissions are for health, safety, and environment, and a greater degree of economical risk, nuisance to residents, and utilization frequency all increase the urgency of dust control and require stricter limitations.

Dust control measures
The feasibility of dust control measures is based on the specifications of the dust source. A dust control measure is only feasible when it fits the operation type, complies with the requirements, boundary conditions, and relevant bulk properties, and opposes the cause of dust generation. The feasible dust control measures are categorised based on whether it is a preventive or suppressive measure and which dust generation cause(s) it opposes. These categories are used to combine and integrate the feasible measures to construct the dust control methods.

Dust control methods
An effective dust control method should contain at least one dust prevention measure for each cause of dust generation. To further improve dust control, the methods may include additional dust suppression methods. The dust control methods may not contain redundant or similar measures and should be distinctive from other methods. Lastly, the feasible dust control methods are assessed on their dust control performance, and whether they meet the dust control requirements.

Evaluation
The appropriate dust control methods are evaluated using a weighted multi-criteria analysis (WMCA). In this approach, relevant criteria are prioritized and given a corresponding weight. The dust control method are assessed based on their performances of these criteria and given a score. The scores are multiplied with the corresponding weights and added up. The dust control method with the highest score is proposed as the most appropriate solution. The dust control strategy is presented in Figure 8.

4 Results

The dust control strategy is implemented to improve the dust control at three dust sources at Verbrugge. The considered dust sources are:

1. The transfer between two conveyor belts
2. The transfer between a grab and a rail-mounted (RM) hopper
3. Vessel loading with a ship loader

The first dust source, the transfer point between two conveyor belts, currently consists of an enclosed chute and a dust collector, which Verbrugge is content with (Figure 9). The current method for the transfer between a grab and RM hopper, comprising of wind screens, flex-flaps, and a dust collection system, does not provide sufficient dust control to comply with the regulations (Figure 10). Verbrugge is currently occupied with installing a ship loader (Figure 11) and has made the decision to implement a cascade chute with a dust skirt. In this research focuses on the implementation of technical measures and recommends the application of organisational measures.

4.1 Weighted multi-criteria analysis

The feasible dust control methods are assessed on the following criteria: Costs, Reliability, Maintenance, Life span, Safety, Complexity, and Sustainability. Five departments within Verbrugge were asked to prioritize the criteria. Table 1 presents the results and corresponding, normalised weights. The dust control methods are evaluated on each criteria and assigned a rating between 1 and 5. The ratings are multiplied with the weights, and the scores of each criteria are added up. This total score represents the overall performance of the dust control methods based on the prioritized criteria by Verbrugge. The dust control method with highest total score is considered the best option, considering the preferences of Verbrugge.

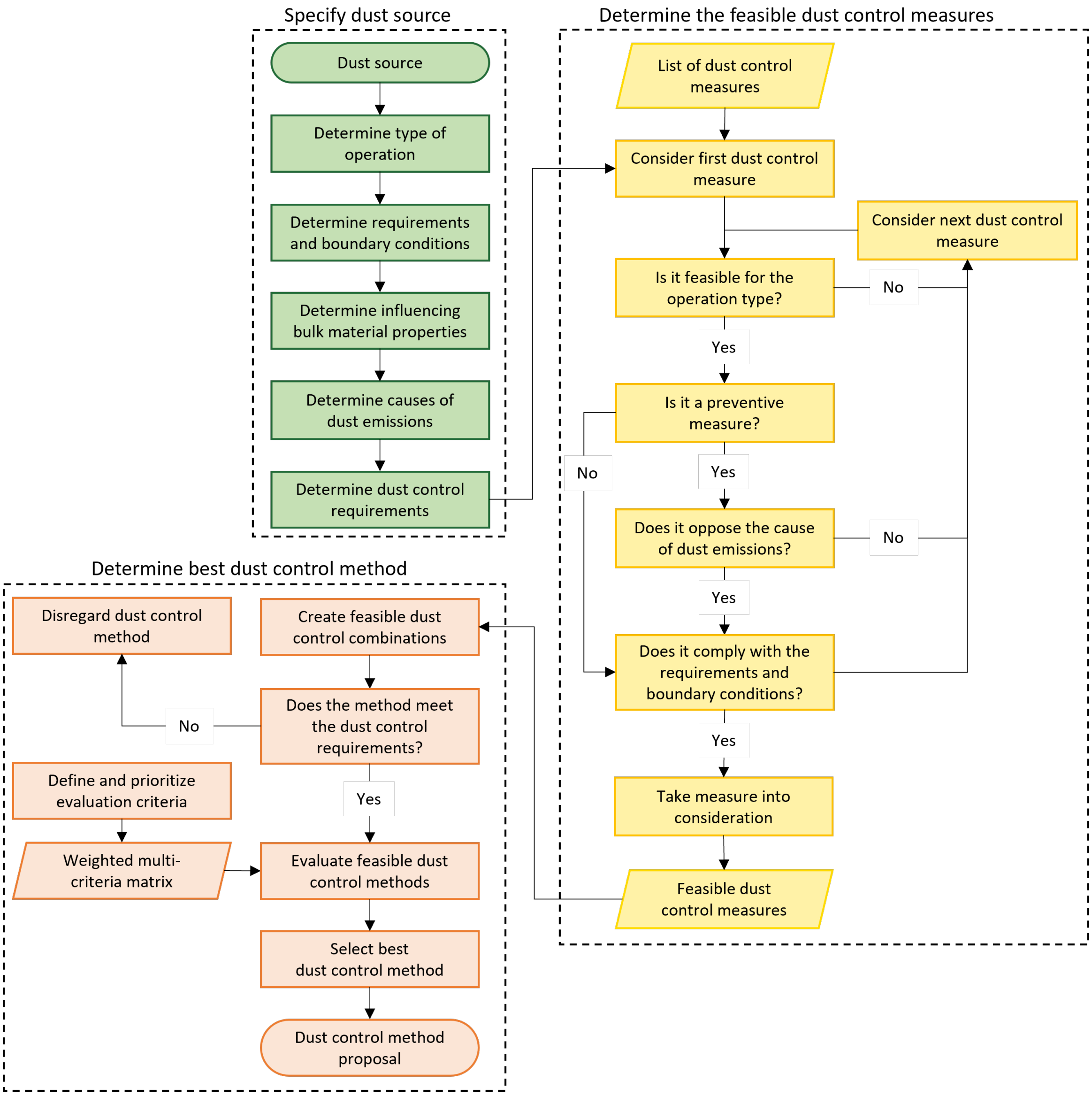

Figure 8: The developed dust control strategy

Table 1: Prioritized criteria by each department at Verbrugge

	Finance	Projects	Compliance	Operations	Technical	Total	Weight
Costs	4	1	0	0	2	7	0.067
Reliability	3	3	4	4	5	19	0.183
Maintenance	5	2	2	2	4	15	0.144
Life span	1	2	1	3	5	12	0.115
Safety	6	6	6	6	3	27	0.260
Complexity	1	3	4	5	0	13	0.125
Sustainability	1	4	3	1	2	11	0.106

4.2 Transfer chute

Dust source specifications
One particular transfer point between two conveyor belts is selected to specifically define the dust source specifications. The installation is only used for handling soda, needs to be fully enclosed, needs to comply with the regulations regarding dust emissions, noise, and safety, and has a vertical and horizontal displacement of 5.4 m and 3.4 m, respectively. Soda is highly sensitive to dust generation, not wettable, and has the tendency to form clumps due to the humid environment. Due to the large height difference, the cause of dust generation are impact and relative air flow. Since an enclosed chute is required, there is no contribution of an external air flow. The diagonal displacement suggests the chute is inclined, which

prevents the dispersion of the bulk stream, and thus air entrainment. Soda poses no very hazardous risks for either health, safety, or the environment. The major consequence of dust emissions is the possibility of nuisance in the surrounding area and dust spreading inside the installation, which impairs the performance of equipment, reduces the life span, and contributes to increased maintenance. Therefore, the urgency of dust control is low and the limit of dust emissions is set equal to the regulations, but the spreading of dust within the installation should be restrained.

Feasible measures

The dust control measures that are not applicable for transfer operations are optimised grab, optimised conveyor belts, and cleaning conveyor belt, so these are eliminated. Wet spray systems are not possible due to the handling of a non wettable bulk product. Furthermore, due to the construction of the installation, the techniques telescopic chute, cascade chute, and DSH are not applicable. Additionally, the suppressive measure Dust skirt is also eliminated. The remaining feasible dust control measures are enclosures, increasing impact angle, consolidating stream, reducing drop height, flex-flaps, and dust collectors.

Dust control methods

The first three feasible measures are already incorporated due to the nature of the chute. Since these measure also oppose both dust generation causes, an additional measure is no requirement. However, to enhance dust control, the impact may be further reduced by reducing the drop height. This may be achieved by a valve, which divides the passage into two segments with both smaller drop heights. As additional suppressive dust control techniques, 'Flex-flaps' and 'Dust collectors' both are suitable for implementation with the intention to avoid the dispersion of dust within the installation. Since they have a similar objective and little dust is expected above the flex-flaps, including both measures in the combination is redundant. The feasible combinations established are:

(A) Transfer chute

(B) Transfer chute with flex-flaps

(C) Transfer chute with a dust collector

(D) Transfer chute with a valve

(E) Transfer chute with a valve and flex-flaps

(F) Transfer chute with a valve and a dust collector

First, the dust control methods are assessed against the dust control requirements. Each method consist of an enclosed chute, which prevents dust dispersion into the air, and thus complies with the regulations. Additionally, the method must prevent dust dispersion within the installation. Even though the main cause of dust is opposed by the enclosed and inclined chute, and for methods D, E, and F with a valve, there is expectedly still some dust generated in the chute, which may rise and spread within the installation. This can be prevented by including the flex-flap or dust collection system. Dust control methods A and D will not suffice the dust emission requirement inside the installation and are disregarded.

Evaluation

The dust control methods are evaluated on the criteria, as describes in Section 4.1. The highest score is achieved by the chute provided with flex-flaps at the inlet. The generation of dust is reduced by the enclosed and inclined chute, while the flex-flaps avoid dust spreading into the installation. Although the performance of dust control is not the best in comparison to the other methods, it is expected to meet the requirements. One consideration with this dust control method is the implementation of flex-flaps at the chute. This combination was not found in literature, so it likely is not a widely applied dust control measure, or has possibly never even been investigated. Therefore, the feasibility of flex-flaps at top of the chute should first be examined before implementation.

Figure 9: Transfer chute between two conveyor belts

Figure 10: RM hopper. Source: Verbrugge (2024)

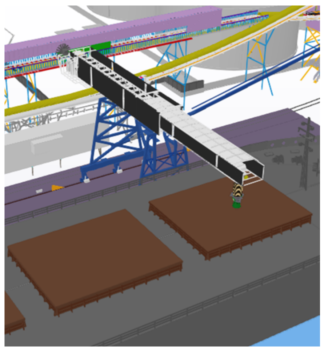

Figure 11: Preliminary design of the ship loader

4.3 RM hopper

The same procedure is followed at the implementation of the dust control strategy at the RM hopper. For the full implementation is referred to Versluijs (2024).

The primary cause of dust emissions at the RM hopper is the wind. Partial enclosure (wind screens) is the only feasible dust control measures opposing the external air flow. As suppressive measures, flex-flaps and dust collectors may be incorporated to suppress airborne dust particles from the bunker. Impact plays a small role in the development of dust emissions, but may be addressed by an increased impact angle. The following dust control methods are established:

(A) Wind screens with flex-flaps and a dust collector

(B) Wind screens with increased impact angle and a dust collector

(C) Wind screens with increased impact angle, flex-flaps and a dust collector

Evaluation
The dust emission restriction is equal to the legislative limit. The current dust control method (A) exceeds the limit for dust emissions. Methods B and C, including inclined impact plates, have enhanced dust control with regard to impact. However, since impact plays a much smaller role than wind in the generation of dust, these methods are not expected to suffice the dust emission limits. This means none of the presented methods comply with the regulations. Instead of investigating the feasibility of implementing dust control measures, in this case it may be more effective to enhance the measures that are already used. Since wind is the major dust generation cause, the design of the wind screens should be revised.

4.4 Ship loader

The implementation of the dust control strategy at the ship loader is also similar to the transfer chute. For the full implementation is referred to Versluijs (2024).

One condition for the ship loader it the utilization of a loading chute, which entails the deployment of either a telescopic chute or cascade chute. Both measures simultaneously address the external and relative air flow, and consolidate the bulk stream. Additionally, the cascade chute reduces the drop height and increases the impact angle. A telescopic chute may be implemented with valves to reduces the drop heights and thus address impact as dust generation cause. The dust skirt, flex-flaps, and dust collectors may be incorporated as dust suppression measures. The following dust control methods are established:

(A) Telescopic chute with valves and a dust skirt

(B) Telescopic chute with valves and flex-flaps

(C) Telescopic chute with valves and a dust collector

(D) Telescopic chute with valves, a dust skirt, and flex-flaps

(E) Telescopic chute with valves, a dust skirt, and a dust collector

(F) Cascade chute with a dust skirt

(G) Cascade chute with flex-flaps

(H) Cascade chute with a dust collector

(I) Cascade chute with a dust skirt and flex-flaps

(J) Cascade chute with a dust skirt and a dust collector

Evaluation
The dust control methods are evaluated on the criteria, as describes in Section 4.1. The highest score is achieved by the cascade chute with a dust skirt. Although the Verbrugge has no experience with a cascade chute, the technique have proven itself to be very effective in dust control at other facilities. Moreover, implementing valves at the cones of a telescopic chute may be difficult. Hence, even without direct experience, the decision for a cascade chute is very reasonable.

5 Discussion

This research presents a useful approach to propose dust control methods to reduce the dust emissions at bulk handling facilities. The limitations of this study are addressed to demonstrate the validity of the conclusions.

The drop tests were executed with a single bulk product (soda) and with limited workspace and equipment. Consequently, the conclusions drawn from these tests may not fully represent the behavior of a broader range of bulk materials or different handling conditions. Furthermore, the organisational measures are not included in the dust control strategy, as their influence on the dust control often depends on the operator's behavior. However, since implementing organisational measures will only further reduce dust emissions, the compliance with the dust control requirements of the proposed methods is not jeopardized. This study uses qualitatively descriptions of both dust generation and dust control. Accurately measuring dust emissions is challenging and requires specialized equipment. The qualitative approach deemed more practical and feasible for this research.

6 Conclusions

The lack of a structural approach in selecting dust control methods has led to the development of a dust control strategy, providing a substantiating decision-making tool for identifying the most suitable dust control method and offering valuable insights into potential issues and solutions. The strategy has led to the proposal of flex-flaps at a transfer chute, offering a better overall performance while maintaining sufficient dust control. However, it is recommended to first examine the feasibility of this uncommon method. An improved dust control method for the RM hopper could not be established. Yet, the outcome demonstrated the importance of optimising the design of the wind screens. The implementation of the strategy for the ship loader led to the proposal of a cascade chute with a dust skirt. This result shows that the time and effort invested in the decision-making process can significantly be reduced.

To enhance the implementation and results of the dust control strategy, it is recommended for further research to include a 'design' step in the procedure, instead of solely selecting the measures. Additionally, it is recommended to quantify the contributions of dust generation mechanisms and performances of dust control measures. More accurate measurements could be used to enhance the prediction model of dust generation and improve the assessment of dust control performances, leading to better dust control proposals. Also the effects of organisational measure can be investigated. Possible dust measuring technologies are laser diffraction or real-time monitoring systems.

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B

Input weighted multi-criteria analysis

Table B.1: Criteria prioritization by the finance department

	Costs	Reliability	Maintenance	Life span	Safety	Complexity	Sustainability	Total
Costs		+	-	+	-	+	+	4
Reliability	-		-	+	-	+	+	3
Maintenance	+	+		+	-	+	+	5
Life span	-	-	-		-	-	+	1
Safety	+	+	+	+		+	+	6
Complexity	-	-	-	+	-		-	1
Sustainability	-	-	-	-	-	+		1

Table B.2: Criteria prioritization by the projects department

	Costs	Reliability	Maintenance	Life span	Safety	Complexity	Sustainability	Total
Costs		-	-	+	-	-	-	1
Reliability	+		-	+	-	-	+	3
Maintenance	+	+		-	-	-	-	2
Life span	-	-	+		-	+	-	2
Safety	+	+	+	+		+	+	6
Complexity	+	+	+	-	-		-	3
Sustainability	+	-	+	+	-	+		4

Table B.3: Criteria prioritization by the compliance department

	Costs	Reliability	Maintenance	Life span	Safety	Complexity	Sustainability	Total
Costs		-	-	-	-	-	-	0
Reliability	+		+	+	-	-	+	4
Maintenance	+	-		+	-	-	-	2
Life span	+	-	-		-	-	-	1
Safety	+	+	+	+		+	+	6
Complexity	+	+	+	+	-		-	4
Sustainability	+	-	+	+	-	-		3

Table B.4: Criteria prioritization by the operations department

	Costs	Reliability	Maintenance	Life span	Safety	Complexity	Sustainability	Total
Costs		-	-	-	-	-	-	0
Reliability	+		+	+	-	-	+	4
Maintenance	+	-		-	-	-	+	2
Life span	+	-	+		-	-	+	3
Safety	+	+	+	+		+	+	6
Complexity	+	+	+	+	-		+	5
Sustainability	+	-	-	-	-	-		1

Table B.5: Criteria prioritization by the technical department

	Costs	Reliability	Maintenance	Life span	Safety	Complexity	Sustainability	Total
Costs		-	+	-	-	+	-	2
Reliability	+		-	+	+	+	+	5
Maintenance	-	+		-	+	+	+	4
Life span	+	-	+		+	+	+	5
Safety	+	-	-	-		+	+	3
Complexity	-	-	-	-	-		-	0
Sustainability	+	-	-	-	-	+		2

Table B.6: Reasoning of evaluation

	Costs	Reliability	Safety	Maintenance
Transfer chute	€€	Low risk of blockage	Overflowing bulk product mostly remains within enclosure. Low safety risk	Occasional inspection, easy to clean
Flex-flaps	€ - €€	Risk of blockage, accumulation and improper throughput	Improper throughput may lead to increased dust emissions, but is quickly noticed. Low safety risk	Frequent inspection, occasionally replacing flaps, less easy to clean
Dust collector	€-€€€	Risk of caking, failure of heater, and contamination with other bulk products	Cross-contamination of incompatible bulk products may cause hazardous reactions. Improper dust control may lead to health, environmental, and safety risks, dependent on the bulk product being handled. High safety risk	Regular inspection, replacements, and (difficult) cleaning
Valve	€	Risk of blockage, accumulation, and malfunction	Dust or overflowing bulk product mostly remains within enclosure. Low safety risk	Periodical inspection, occasional repairs, easy to clean
Wind screens	€€	High risk of damage by grab	Damage may compromise the structural integrity of the wind screens. Medium safety risk	Sporadic inspections, easy to clean
Inclined impact plate	€€	Low risk of accumulation	Accumulated bulk product may (slightly) increase dust emissions. Low safety risk.	Occasional inspection, easy to clean
Telescopic chute	€€€€€	Risk of accumulation, blockage, and malfunction of retraction	Blockage or malfunction may increase dust emissions. Medium safety risk.	Regular inspections, repairs, and/or replacements of buckets, difficult to clean
Cascade chute	€€€€€	Risk of accumulation, blockage, and malfunction of retraction	Blockage or malfunction may increase dust emissions. Medium safety risk.	Regular inspections, repairs, and/or replacements of buckets, difficult to clean
Dust skirt	€€	Risk of inadequate operation (correct height to loaded bulk material)	Incorrect use may lead to increased dust emissions. Medium safety risk	Occasional inspection and repairs. Less difficult to clean

Table B.6: Reasoning of evaluation *(Continued)*

	Life expectancy	Complexity	Sustainability	Dust control
Transfer chute	Little wear, long life span	No moving parts, easy utilization	No energy consumption, moderate material usage, recyclable	Preventive and suppressive measure, reduces external and relative air flow, and impact. Some dust control inside enclosure, excellent dust control outside
Flex-flaps	Considerable wear, flaps may need replacing. Adequate life span	No moving parts, adequate utilization	No energy consumption, moderate material usage, less durable	Suppressive method. Contains dust particles below system. Little effect above system
Dust collector	Considerable wear, filters may need replacing. Adequate life span	Includes fans, possibly cleaning mechanisms. Moderate utilization	Significant energy consumption, moderate material usage, less durable	Suppressive method. Considerable dust control inside enclosure.
Valve	Some wear, adequate life span	Moving parts to operate valve, moderate utilization	Moderate energy consumption, limited material usage, recyclable	Preventive method, reduces impact and relative air flow. Moderate dust control.
Wind screens	Little wear, long life span	No moving parts, easy utilization	No energy consumption, considerable material usage, recyclable	Preventive and suppressive method. Reduces external air flow and dust dispersion. Moderate dust control
Inclined impact plate	Some wear, long life span	No moving parts, easy utilization	No energy consumption, considerable material usage, recyclable	Preventive method, reduces impact. Some dust control
Telescopic chute	Some wear, cones may need replacing. Adequate life span	Retractable chute, moderate utilization	Moderate energy consumption, considerable material usage, less durable	Preventive and suppressive method. Reduces external and relative air flow, contains dust inside chute. Moderate dust control
Cascade chute	Considerable wear, cones may need replacing. Adequate life span	Retractable chute, moderate utilization	Moderate energy consumption, considerable material usage, less durable	Preventive and suppressive method. Reduces impact, external and relative air flow, contains dust inside chute. Considerable dust control
Dust skirt	Considerable wear, adequate life span	No moving parts, moderate utilization	No energy consumption, moderate material usage, less durable	Suppressive method, prevents dust flaring up. Considerable dust control