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Author:	Philip Schilder

Title (in Dutch)	Ontwerp van een productielijn voor het verwerken en opslaan van cacao cake.

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Initiator (university):	Prof. Dr. ir. G. Lodewijks, Dr. ir. D.L. Schott
Initiator (company):	[redacted]
Supervisor:	Dr. ir. H.P.M. Veeke
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Subject: **Design of a production line for storage and processing of cocoa cake**

Introduction and problem definition

[redacted] transforms cocoa beans into cocoa liquor, butter and powder. [redacted] The trend of recent years is that the demand for powder and butter grows. [redacted] responds to this trend by pressing more cocoa liquor into cake and butter. The cake is grinded into powder and packed in bags before delivery to the customer.

An alternative for increasing the powder output by pressing more cocoa liquor is importing cocoa cake as semi-finished product and grinding this cake into powder at [redacted] The cake silos between the pressing stage and cake grinding stage decouple the two adjacent processes.

[redacted] The future prospect is that large amounts of cake, a total of 25000 MT, are imported and fed to the cake grinding stage. This significantly increases the powder output and makes the cake grinding stage less dependent of production cake. Moreover, different cocoa cakes are blended ensuring the right quality for the customer. [redacted] sees the import of cocoa cake as a business opportunity and is curious how it will affect the current production practices. Furthermore, the equipment handling the cocoa cake is investigated to ensure the powder output of 45,000 MT can be realized.

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Research goal

Redesign the production system for storage, blending and processing of cocoa cake, in order to meet the future demand of cocoa powder.

Research structure

- Analyze the processes at [redacted] with the Delft Systems Approach
- Determine the current and future productmix
- Design the production system based on the forecasted powder output and the functional requirements
- Perform shear cell measurements to obtain the bulk solid properties of cocoa cake
- Use proven silo design principles of Schulze to design storage equipment
- Study and use relevant literature for substantiation

Voorwoord

Dit rapport beschrijft het afstudeeronderzoek waarmee de masteropleiding Transport Engineering and Logistics van de faculteit Werktuigbouwkunde aan de Technische Universiteit van Delft wordt afgerond. Tijdens het onderzoek ben ik vanuit de universiteit begeleid door Dr.ir. Hans Veeke, Prof. Dr. ir. Gabriel Lodewijks en Dr. ir. Dingena Schott. Ik ben hen zeer dankbaar voor de begeleiding en het aansporen om door te zetten.

[redacted]

Tijdens mijn studie en met name mijn afstudeerperiode heb ik heel veel ondersteuning mogen ontvangen van mijn familie, vriendin en vrienden. Ik wil mijn ouders, Willem en Anneke, bedanken voor de onvoorwaardelijke steun. Mijn broer Willem Mathijs die mij zo goed geholpen heeft en altijd voor mij klaar staat. Rogier voor de opbouwende kritiek. Mijn vriendin Nina voor de steun en het zonnetje in huis. Allen bedankt voor de liefde en het geduld.

Summary

[redacted] is a cocoa processing factory, processing cocoa beans into cocoa liquor, cocoa butter, and cocoa powder. The trend of recent years is that the customer demand for cocoa powder and butter grows. Instead of pressing more cocoa liquor to increase the powder output, high quality cocoa cake can be imported, blended and grinded into powder. The future prospect is that large amounts of cake are imported, increasing the pressure on the functions transforming cake into powder. It is expected that the powder output increases [redacted] to 45,000 MT. [redacted] sees the import of large quantities of cocoa cake, 25,000 MT, as a solution to the increasing demand of powder and is curious how it will affect the current production practices and equipment.

The activities and current processes of [redacted] are described and analyzed. The analysis focuses on the functions inside cocoa processing and how the increased input and additional product handling affect these. Powder making does not have sufficient capacity to process the increase of cake. Examining the blending function reveals that the degree of blending in the current process cannot be controlled. The function blending is integrated in transport and grinding of cake. The malfunctioning of the cake silos makes blending not possible and causes downtime on the adjacent functions cake and powder making. Furthermore, the capacity of the cake silos is insufficient to buffer the difference in ingoing and outgoing flow of imported cake. [redacted] wants to increase the utilization of the presses and powder making lines, but the presses are currently blocked and powder making lines are starved due to respectively unavailable silo space and unavailable cake inside the silos. While exploring the processes and functions it has become clear that the expected powder output cannot be realized with the currently installed production system. From the analysis the following research question and goal is derived:

Redesign the production system for storage, blending and processing of cocoa cake, in order to meet the future demand of cocoa powder.

Before these functions are designed, goals are set for the productmix. The productmix shows the required output of each product that needs to be made by the production system. The productmix and Pareto analysis show that four basic production cakes, representing 75% of the total produced cake volume, need to be blended with imported cake. Therefore, a different production strategy and planning is used, which aims at high utilization of liquor making and cake making. Also production equipment is added to have sufficient capacity.

The product differentiation is postponed and liquor making and cake making become highly standardized in the new production system. The alternating production strategy and standardized batch sizes prevent blockages of the presses and starvation of the powder making lines, while limiting the intermediate storage of cake. Additional dedicated silos are installed before blending for the four basic cakes. The capacities of these dedicated silos are 20 MT and 40 MT. The silos decouple cake making and powder making and have sufficient capacity to store standardized powder batch sizes. An additional powder making line is added to increase the capacity of powder making ensuring the expected quantity of blended and unblended cake can be processed. The function blending is differentiated to control the degree of blending and convective blenders are chosen as they promote a random mixture. Two batch blenders, each with a volume of 4,4 m^3, have sufficient capacity to process all the cakes that need to be blended. Additional dedicated silos are installed for the basic cakes for blending.

The design of the silos is investigated by conducting experiments. The flow behavior of the cocoa cake is tested as well as the interaction between cocoa cake and silo wall material to simulate the flow of cake inside the silo. The ring shear cell tests showed that high fat cakes are more cohesive than low fat cakes. The tests showed similar results in flow behavior between cakes tested at 35 °C and 55 °C. The cake tests and the wall friction angle testes are used to design silos of 20 MT and 40 MT that promote mass flow without using discharging aids and devices. The silos are able to store cakes with the worst flow behavior. To obtain a mass flow pattern for the hot rolled SA2.5 steel silo, the critical cone angle of 6° makes the silo impractical due to the required height. Using a different wall material, lining or coating, with a wall friction angle similar to cold rolled steel, the cone angle can be increased to 26° and the height of the silo decreased to 6 m for a 20 MT cake silo. This is similar to the silos currently in operation at [redacted] In order to prevent stable arches, due to interlocking of particles, the minimum outlet diameter should be 0,36 m.

Equipment is added in the form of an additional powder making line, blenders and silos. The silo design prevents flow obstructions and promotes a mass flow pattern, without using discharge devices. By adding additional equipment and using a different planning and production strategy, the expected increase of powder output of 200 percent can be realized.

Samenvatting

[redacted] verwerkt cacao bonen tot cacao liquor, boter en poeder. Eerst worden alle bonen omgezet in cacao liquor. De liquor kan worden geperst om cacao boter en cake te maken. Door het fijn vermalen van de cacao cake ontstaat cacao poeder. De trend van de afgelopen jaren is dat de vraag naar poeder blijft stijgen. Door deze toenemende komt het poeder maak proces, maar ook cake maken en liquor maken onder druk te staan. Een alternatief voor het extra produceren van cacao liquor en cake om de input van poeder maken te vergroten, is het importeren van cacao cake. De cake kan worden ingekocht van andere cacao fabrieken binnen moederbedrijf [redacted] Zo wordt de kwaliteit van de cake gewaarborgd. Verder moet de geïmporteerde cake geblend kunnen worden met cake [redacted]. Hierdoor kunnen de eigenschappen van de cake worden veranderd en gecontroleerd. De verwachting is dat de poeder output toeneemt [redacted] naar 45,000 MT. [redacted] ziet de import van grote hoeveelheden cacao cake, 25,000 MT, als een oplossing voor de stijgende poedervraag en is benieuwd wat de impact is van de grote hoeveelheid geïmporteerde cake op het productie systeem en de processen.

De eerste stap in dit onderzoek is het beschrijven en analyseren van de processen binnen [redacted] In de analyse zijn de functies van cacao verwerken onderzocht. Voor elke functie is gecontroleerd of deze geschikt is om de toegenomen producthoeveelheden te kunnen verwerken. De analyse laat onder andere zien dat poeder maken onvoldoende capaciteit heeft om de verwachte poeder output te kunnen maken. De blend functie in het huidige proces is geïntegreerd in de functies transport van cake en cake vermalen. De mate van blenden is door middel van deze functies niet gecontroleerd. Blenden is zelfs onmogelijk door storingen die optreden in de cake silo's. Tijdens de interviews zijn meerdere aspecten, zoals temperatuur, deeltjesgrootte en vetpercentage van de cake, genoemd die de flow obstructies kunnen veroorzaken. [redacted] wil de utilisatie van cake en poeder maken verhogen, maar de persen worden geblokt en de poeder maak lijnen niet altijd voorzien van materiaal. Cake maken en cake verwerken hebben tegenstrijdige capaciteiten, die afhankelijk is van het vetpercentage van de cake. De functie cake opslag heeft naast de storingen ook een capaciteitsprobleem. De capaciteit van de cake silo's is onvoldoende om het verschil tussen input en output van geïmporteerde cake te kunnen bufferen. De conclusie van de analyse is dat het huidige productiesysteem niet in staat is om de verwachte poeder output te realiseren. Uit de analyse en conclusie is het volgende onderzoeksdoel opgesteld:

Herontwerp het productiesysteem voor de opslag, het blenden en verwerken van cacao cake, om aan de verwachte poeder vraag te voldoen.

Voordat deze functies worden ontworpen, is de huidige en toekomstige productmix onderzocht. De productmix geeft aan wat de output is van elke functie en de verwachtingen van het productieproces. De productmix en de Pareto analyse laten zien dat 75% van het totale geproduceerde volume bestaat uit vier standaard cakes, die geblend moet worden met ingekochte cake. Daarom is er een andere productie strategie ontworpen, gericht op hoge utilisatie van liquor en cake maken. De product differentiatie is uitgesteld en liquor en cake maken worden gestandaardiseerd. Ook moet er capaciteit worden toegevoegd aan de productie. Om de hoeveelheid cake te kunnen verwerken moet een poederlijn, identiek aan de andere twee poederlijn, worden toegevoegd. De functie blenden wordt gedifferentieerd om de mate van blenden te kunnen controleren. Twee batch blenders elk met een volume van 4,4 m^3 worden toegevoegd om de verwachte hoeveelheid geblend product te maken. Voor de basis cakes worden aparte silo's toegekend van 20 MT en 40 MT. De capaciteit van deze silo's komt overeen met de standaard batch grootte's van poeder maken en ontkoppelen de productieruns van cake en poeder maken. Het nieuwe productiesysteem, de standaardisering, het limiteren van de batchgrootte's en het verplicht afwisselen tussen producten, op basis van vet, laag vet, en blend ratio, zorgt ervoor dat de hoge utilisatie van de processen gerealiseerd wordt.

Het ontwerp van de silo's is verder onderzocht met behulp van experimenten. De flow van cake is onderzocht en de interactie tussen cake en de silo wand. De experimenten zijn uitgevoerd op een Ring Shear Cell tester. De uitkomsten van de experimenten laten zien dat de temperatuur van de cake niet van invloed is op de interactie tussen cake en cake. Het verkleinen van de deeltjesgrootte en het verhogen van het vetpercentage zorgen er wel voor dat de cake slechter stroomt. De uitkomsten van de experimenten zijn gebruikt om mass flow silo's te ontwerpen met een capaciteit van 20 MT en 40 MT. De silo's zijn in staat om cake met de slechtste flow karakteristieken op te slaan. Om mass flow in de silo, gemaakt van SA 2.5 warmgewalst staal, te bereiken is een cone angle nodig van 6°. Een nadeel is dat de silo hierdoor erg hoog wordt en onpraktisch. Om de hoogte van de silo te beperken

moet de wrijving en wall friction angle afnemen. Daarom zijn de cake-wall testen herhaalt met een sample van koudgewalst staal. De maximale cone angle, nodig voor mass flow, neemt hierdoor toe tot 26° en de benodigde hoogte wordt gereduceerd tot 6 m. Dit komt overeen met de hoogte van de huidige cake silo's bij [redacted] De minimale outlet opening van de silo's is 0,36 m en wordt bepaald door de maximale deeltjesgrootte van cake.

Voor het nieuwe productiesysteem is capaciteit toegevoegd in de vorm van een extra poeder-maak lijn, blenders en silo's. De silo is ontworpen voor massa flow en voorkomt flow obstructies. Door het toevoegen van extra capaciteit en een andere productiestrategie kan de poeder output met 200 procent worden verhoogd.

List of symbols

m	Meter
m^3	Cubic meter
kg	Kilogram
MT	Metric tons
h	Hour
Pa	Pascal
N/m^2	Newton per square meter
σ	Stress in N/m^2
φ	Angle
C	Celsius

List of abbreviations

HACCP	Hazard Analysis and Critical Control Points
CODP	Customer Order Decoupling Point
SKU	Stock Keeping Unit
MB	Mid-Brown
MR	Mid-Red
Proper	Process Performance
FF	Flow Function
ff	Hopper flow factor
σ_1	Major consolidation stress
σ_c	Unconfined yield stress

Table of contents

1. Introduction

[redacted] transforms cocoa beans into cocoa liquor, cocoa butter, and cocoa powder. The portfolio consists of high quality; often tailor made, products made from sustainable, certified and ethically produced beans.

[redacted] delivers a wide variety of cocoa products on short notice as soon as the customer requests these. The trend of recent years is that the customer demand for cocoa powder and butter grows. [redacted] responds to this trend by pressing more cocoa liquor into cake and butter. This increase puts pressure on the processes liquor and cake making. An alternative for increasing the powder output by pressing more cocoa liquor is importing high quality cocoa cake as semi-finished product and grinding this cake into powder at the production facility of [redacted] To ensure the quality requirements of the ordered powder are met, the cakes can be blended.

Currently, only a small fraction of the powder output is made with imported cake. Furthermore, blending cakes and or powder currently takes place sporadically. The future prospect is that large amounts of cake are imported, blended, and processed into powder. The cake silos between the pressing stage, and cake-grinding stage further decouples the two adjacent stages. The pressure on the cake and powder handling activities will increase extensively due to the import and blending of imported cake.

It is expected that the powder output will increase with 200 percent. The consequences of this increase on the production system and especially cake making, cake storage, blending and grinding is not yet investigated. [redacted] sees the import of large quantities of cocoa cake as a solution to the increasing demand of powder and is curious how it will affect the current production practices and equipment. The initial assignment was formulated as:
"Investigate the flow from cocoa cake to packed powder after the decoupling of the pressing stage and the cake grinding stage, considering optimal occupation of presses, storage of cake, blend capacity and cake grinding capacity."

In chapter 2, general information about the [redacted] is given. In the third chapter the process and activities of [redacted] are analyzed. The outcomes of this analysis and the initial problem statement described above are used in chapter 4 to formulate the research question and goal. Chapter 5 describes the current and future product mix, which gains as input for the solution. The solution of the research question is divided into two parts. The first part is discussed in chapter 6 and focuses on the logistic aspects and design of the production process. The second part is discussed in chapter 7. This chapter zooms in on the design of bulk handling equipment ensuring the resources used in the production process are suitable to process the right quantity and quality. Chapter 8 presents the conclusion of this research and both parts of the solution. In chapter nine the recommendations for further research are presented.

2. [redacted] profile

This chapter provides the reader with general information about [redacted] For those who are familiar with the [redacted] and are only interested in the analysis and or solution of the problem, this chapter can be skipped.

First the history of cocoa and the establishment of [redacted] are described. Secondly, the role of [redacted] and the parent [redacted] in the supply chain of cocoa are shown. In the third paragraph the products of [redacted] are listed, followed by the organ structure that shows how these products are made. Paragraph 5 looks at the different sections, housing the processes responsible for the transformation, inside the factory. The final paragraph shows the personal structure of [redacted]

2.1 History

Fermented beverages made from cocoa pods date back to the time of the Aztecs. The Aztecs believed that cacao beans where the gift from the god of learning and wind [1]. They believed that drinking chocolate, made from the beans, brought mortals aphrodisiac powers and wisdom. The seeds had so much value that they were used as a form of currency and tax. [1] Columbus brought the first cocoa beans to Europa. After its arrival in the beginning of the sixteenth century, sugar was added to the liquor by the Spanish and its popularity spread to Central and Northern Europa.[2]
In 1828, Dutchman van Houten develops a method to gain cocoa butter from cocoa liquor. [2] The remaining cocoa pieces, the cake, are grinded and used as cocoa powder. Van Houten also discovers a technique to make the cocoa more soluble in water. This alkalizing process raises the pH-degree ensuring a mild taste and darkens the color of the cocoa. [redacted]

[redacted] The Delft Systems Approach presents a fundamental approach for the analysis and design of industrial systems, which emphasis a concept that can be used by all disciplines involved and makes a logical systematic combination of quantitative and qualitative modeling [4]. This method will be frequently used in the remaining chapters of this thesis.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted] The cocoa trees yield pods, which hold the cocoa beans. The pods are opened and the beans are removed with the adhering pulp. The layer of pulp surrounding the beans heats up and ferments the beans. [5] After fermenting the beans dry several days in the sun before they are packed into sacks.

Unlike large industrial crops, 80 to 90 % of the cocoa comes from family-run farmers. [5] Farming takes place in tropical environments, within 20° of latitude from the equator. The total demand for chocolate grows, but a growth in the production of cocoa is not guaranteed as cocoa trees are sensitive to changing weather patterns and farmers tend to switch to alternatives like palm oil. [5]

The farmer sells the beans to a buying station or local agent. These transport the sacks to an exporting company where it is stored before shipment. The exporter ships the beans to a processing location, where the cocoa is stored until needed. From the storage, the cocoa beans are transported to the processor. The cocoa beans are roasted and transformed into cocoa liquor. The cocoa liquor is used in chocolate manufacturing or can be pressed to make cocoa cake and butter. The cake is sold on the market or is grinded into fine powder. The processing of cocoa beans serve as a key metric for market analysts, as it is the phase in which cocoa bean demand can be compared to supply to all manufacturing industries. [5]

[redacted]

[redacted]

Fig. 2.3 Cocoa supply chain and role of [redacted]

The cocoa liquor, butter and powder are primarily used for chocolate making but also in other manufacturing industries like cosmetics. To make chocolate, cocoa liquor, butter and sugar are conched and tempered. Chocolate is sold in liquid or block form to confectioner, dairies and bakers and consumed all around the world in different forms.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

2.3 Products

[redacted]

Cocoa beans are a product of nature and thus the characteristics of the beans may vary. To maintain the high quality standards, cocoa beans are carefully selected and tested before processing. This may lead to adjusting process steps to ensure products with the right specifications are made.

The products are made with different type of beans, from different origins and with certificates, following different recipes [redacted] The powder is natural, light or highly alkalized and delivered in four different ranges of fat: 10-12%, 16-18%, 20-22%, and 22-24%.

The products are delivered to the customer in bulk or in different stock keeping units (SKU's). [redacted] The powder is always packed in bags, [redacted] For small bags, multiple bags are piled up on a pellet, whereas only one Big Bag fits a pellet.

[redacted]

[redacted]

2.4 Processes

This paragraph shows the different processes of cocoa processing. The organ structure depicts the functions in the production process that are fulfilled to obtain the liquors, butters and powders. First, all the cocoa beans are transformed into cocoa liquor. The cocoa liquor is delivered as finished product or acts as intermediate for the production of cocoa cake and butter. By pressing the cocoa liquor, cocoa cake and butter are made. The butter needs to be refined and the cake grinded into power before delivery to the customer.

2.4.1 Roasting: transforming cocoa beans to cocoa liquor

[redacted] The beans are delivered to the factory in trucks. The so-called de-bagging takes place before the transport, but the arriving bulk load is not completely free of packaging material. During bean intake the beans pass through a first filter to take out some of the present plastics and ropes. The beans are then transported to the storage silos passing through numerous cleaning steps. In these steps plastic, dust, sand and metal are removed from the product flow. The waste material is collected and is recycled by other companies.

After storage, the remaining contamination is removed from the material flow. In these cleaning steps clusters of cocoa beans and rocks are removed. The cleaned beans are being weighed before breakage.

The beans are broken on one of the three production lines, to separate the shell from the core. The core material of the bean is called a nib. The broken parts, nibs and shells, are then separated in multiple sieves. Each of these sieve layers is equipped with a vacuum transport that separates the nibs and shells due to the difference in density. The shells are collected and sold as they serve as fuel or compost. The nibs are used for the production of liquor

The nibs are alkalized or burnt naturally without alkalizing. Alkalization, by adding Potash solution raises the pH of the product and changes the color. The type of bean and the roasting process also influence the liquor characteristics, like the color and aroma. During roasting the nibs go through several phases and temperatures at which heat is transferred through convection and conduction. The process ends when the desired temperatures and moisture content is reached. In Fig. 2.7, one of the batch burners is shown during maintenance on the left.

[redacted]

The batch from the burner is discharged and cooled on a bed to obtain crispy nibs. This cooling step promotes the grinding of the nibs. The burnt nibs contain a fat percentage of 55 percent that is released from the core when the nibs are grinded. Grinding releases the fat inside the core to create liquid paste, the cocoa liquor. The heat generated during the grinding process promotes this liquid phase.

To obtain the right fineness, the liquor is grinded and sieved in several steps. The mass is coarse and fine grinded in different steps to ensure the right fineness for the customer and or for pressing cocoa liquor. One of the grinders, producing fine liquor is shown in Fig. 2.7 on the right. If the butter percentage of the cocoa nibs is too low, fat can be added to the grinding mills.

The fine liquor is pumped to the liquor storage tanks, from where it is delivered to the customer in bulk or packed in boxes. From the storage tanks, the liquor is also fed to the cocoa presses that transform the liquor into butter and cake. Before pressing the liquors can be blended.

2.4.2 Pressing: making cocoa cake and cocoa butter

Cocoa cake and butter are produced when cocoa liquor is pressed in hydraulic presses. The liquor destined for the presses is first heated in a conditioning tank. This promotes filling of the chambers inside the presses and enhances the pressing cycle. A picture of a cocoa liquor press is shown in Fig. 2.8 on the left.

[redacted]

After the chambers inside the hydraulic presses are filled with liquor, the hydraulic pumps exert a force on the chambers. The volume decreases and butter escapes through the pierced plates of the chambers. The duration of the pressing cycle determines the amount of butter that is pressed from the liquor.

The liquid butter is stored in butter tanks and filtered. Filtration separates the clean butter from the solid butter fractures. Clean butter is directly delivered to the customer or further processed by deodorizing. During this heating and cooling process the structure of the butter changes, removing unwanted flavors and aromas from the butter. Cleaning of the presses ensures the high quality product standards are met. Replacing seals of the pressing chambers prevents leakages and uncontrolled pressing cycles.

By the end of a pressing cycle the chambers are opened and the remaining cake is dropped onto a conveyor belt transporting the cake to a grinder. Cooling the cakes promotes the transport and the filling of the silos. The grinded hot cakes are cooled and pneumatic transport is used to transport the cake particles to the cake silos. The pneumatic transport prevents product contamination and deterioration of the product, guaranteeing food safety and quality. In the cake silos all the cake is stored needed for production, including cake coming from import and powder that needs reworking. The cake silos mainly couple the pressing and grinding stage. These silos are shown in Fig. 2.8 on the right.

2.4.3 Grinding: making cocoa powder

Powder is produced when cake from the storage is grinded at the powder making lines. Each powder line consists of a classifier that grinds the cake particles into fine powder. The flow of air in combination with the particle weight makes sure only powder with a certain fineness proceeds to the next step. The shear forces in the classifier-grinding wheel also lead to beta-crystallization of the cocoa powder. For chocolate making, beta crystallization is desired.

Due to the fat percentage inside the powder and cake, the particles stick to the inside wall of the classifier. After producing certain amounts of cake, the layer of pasted up material becomes to thick and the machines needs to be cleaned. Increasing the fat percentage of the grinded cake increases the stickiness of the cake. The classifier wheel during cleaning is shown left in Fig. 2.9. The metal detectors before the classifier wheel prevents metal pieces can enter the grinding wheel creating sparks. Furthermore, reducing the oxygen level inside the grinding wheel by adding nitrogen prevents fires.

[redacted]

After the classifier wheel the powder is still warm and needs controlled cooling. The cooling takes place during transport and in the cooling silos, which promote the formation of stable crystals, color and the packaging process. [redacted] for small bags is a fully automated machine, whereas the Big Bag system needs manual assistance from an operator. The operators position the big bags underneath the filling nozzle and close the bag when the bag is completely filled. Each powder making line is equipped with quality control sections where samples of powder can be taken or automatically gained from the flow.

After filling of the powder bags and labeling, all bags are placed on pallets. The palletized bags are sealed, coded, scanned and stored in the warehouse. From the warehouse the pellets are loaded into trucks and transported to another storage location before it is send to the customer.

2.5 Factory plan and sections

The factory floor plan in Fig. 2.10 shows the different sections inside the factory that transform cocoa beans into cocoa liquor, cake and powder. [redacted]

By roasting, the nibs become sterile and after roasting other hygiene requirements are in place. [redacted]

[redacted]

[redacted]

[redacted]

Fig. 2.10 Factory floor plan

2.6 Organizational chart

In Fig. 2.11 the hierarchy of the organization is shown. The employees are divided into departments following a line-staff structure [8]. The organization chart shows the number of full-time equivalents and the delegation of responsibilities. Each individual or group is part of a functional autonomy that contributes to the overall process. [9] The hierarchy follows the control functions at each echelon of the production system and also follows the time span of decision-making. [8]

Requirements from the environment are transformed into standards by the management and transformed into actions at the production level. [redacted]

[redacted]

3. Problem Analysis

The previous chapter provided general information about the organization, the processes, and the products of [redacted] This chapter provides a more in depth analysis of the processes transforming cocoa beans into liquor, cake and butter and shows how these are affected by the increase in production.

In the first paragraph the trend of recent years and the expected change is discussed. The second paragraph shows the main function cocoa processing and these changes in volume. The Delft Systems approach [4] is used to zoom in onto the main function to provide the desired level of detail. The subsequent paragraphs reveal the different functions inside cocoa processing. The subsequent paragraphs, reviewing each function separately, show how the increase in expected powder output will affect the function and check if this increase can be met. The production data of 2015 are analyzed and used to gain insight in the capacities of the currently installed equipment. This year is representative for the shift towards an increased powder production. Since no changes have been made regarding the resources and production practices, the production numbers of 2015 provide a clear view of the capacities and the performance of the production system.

From the analysis presented in this chapter, the final research question and goal will be determined.

3.1 Cocoa processing

The main function is processing cocoa beans and cake into cocoa liquor, butter and powder. [redacted]
The total quantities and daily average of input and output for the year 2015 is shown in Fig. 3.1. The requirements consist of bean throughput and requirements of customers. The performance consists of the yield of the production process and production numbers. The quality of the cocoa products is determined by the quality of the beans, the recipes and the control over the production process.

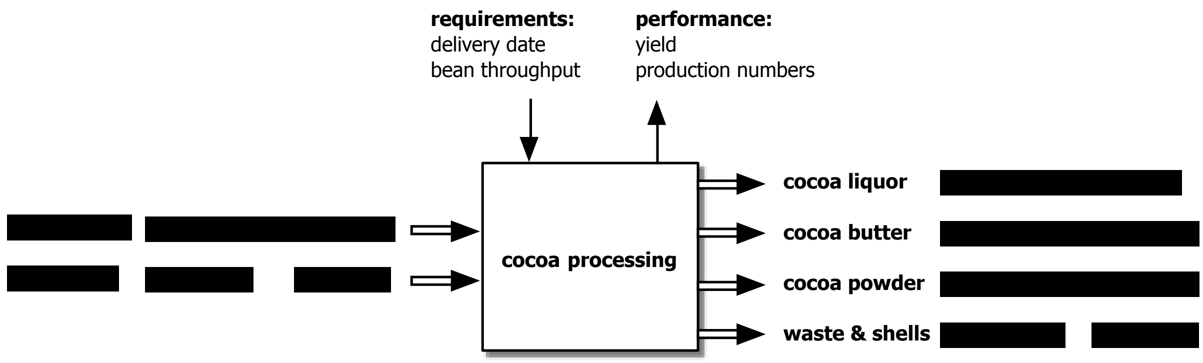


Fig. 3.1. Model main function cacao processing 2015

3.2 Cocoa processing and volume change

The ingoing and outgoing product quantities will change radically in the near future as [redacted] plans to import large quantitates of cocoa cake. The change in the future product output is presented in Fig. 3.2. A new requirement can be added that states the cocoa processing function must be able to realize the expected output of 45,000 MT.

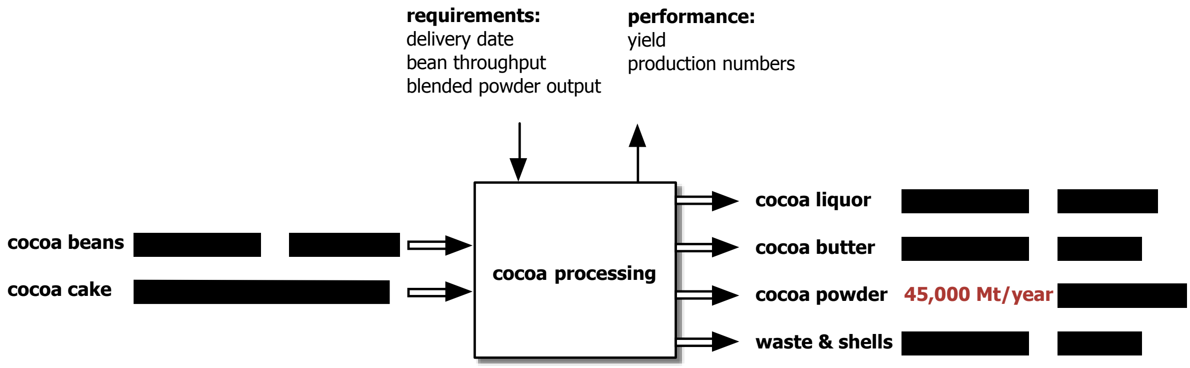


Fig. 3.2. Model main function cacao processing future

The increase in powder output is achieved by increasing the input of cocoa cake and cocoa beans. The increased input in cocoa beans is used to produce more cocoa cake, which can be blended with imported cocoa cake. Blending is done in order to control the specifications of the cake satisfying customer demand.

The ingoing and outgoing flows of the future cocoa processing function are predicted. The 45,000 MT of powder output consists of 25,000 MT of imported cake and an estimated 20,000 MT of production cake. [redacted]

The next step is to gain insight in the underlying production process by opening the black box cocoa processing. The next chapter will describe the functions inside the black box and the influence of the increased flow.

3.4 Current process analysis

In the [redacted] profile three important tasks are discussed for the production process: roasting, pressing and grinding. The next step is opening the black box cocoa processing to see which functions are present to transform cocoa beans and cake into cocoa liquor, butter and powder. If we zoom in one aggregation layer the functions inside cocoa processing are revealed. This is shown in Fig. 3.3.

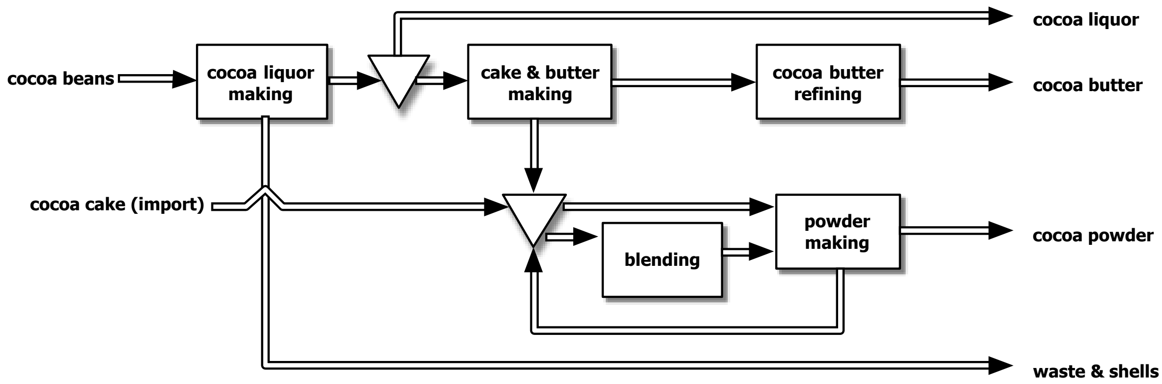


Fig. 3.3. Cocoa processing zoomed in one aggregation layer

All cocoa beans are first transformed into cocoa liquor by the function cocoa liquor making. All the cocoa liquor is then stored in cocoa liquor tanks. From there a part of the cocoa liquor is delivered to the customer and a part is processed further into butter and cake by the function cake and butter making. The trend of recent years is that the demand for powder and butter grows and [redacted] responds to this trend by pressing more cocoa liquor into cake and butter. The percentage of cocoa liquor processed into cocoa powder and butter and the future expectance is presented in Fig. 3.4.

[redacted]

Fig. 3.4. Percentage of produced liquor pressed into cake and butter

The butter is refined before delivery. The imported 25,000 MT of cake, and produced 20,000 MT cocoa cake is stored before it is grinded into powder. The cocoa cake can be blended before powder making. On average 1-2 percent of the total powder is rework.

In the next paragraphs, each of the processing functions is reviewed to see what the impact is of the increased production. The first function, which will be discussed is cocoa liquor making.

3.4.1 Cocoa liquor making

First the product flows around liquor making and storage are shown. Fig. 3.5 gives insight in the yearly and daily production quantities. The calculations underneath the function model in Fig. 3.5 clarify the ingoing and outgoing quantities.

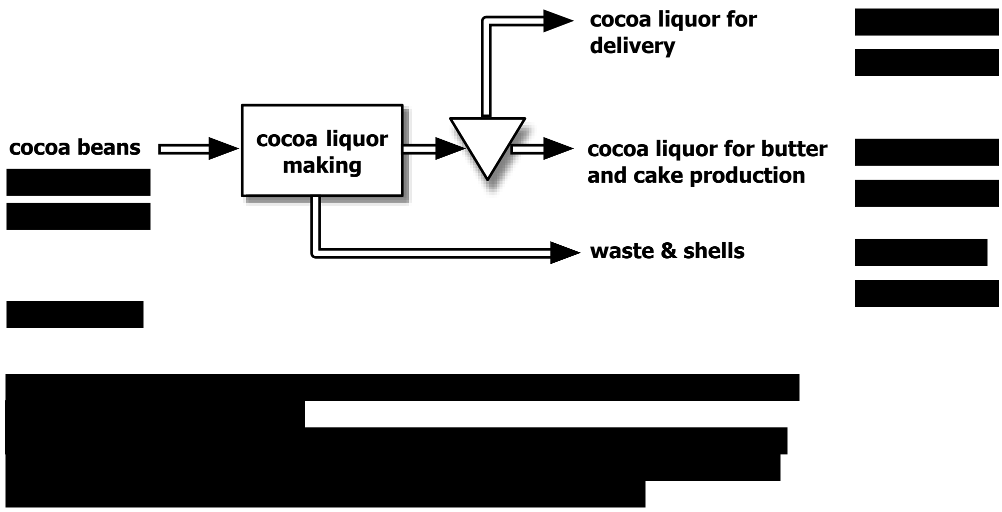


Fig. 3.5. Cocoa liquor making and liquor storage

The main question is to determine if extra capacity is available to process the increase in cocoa beans. Therefore, the functions inside liquor making are investigated. Zooming in onto cocoa liquor making reveals the following functions, which are shown in Fig. 3.6.

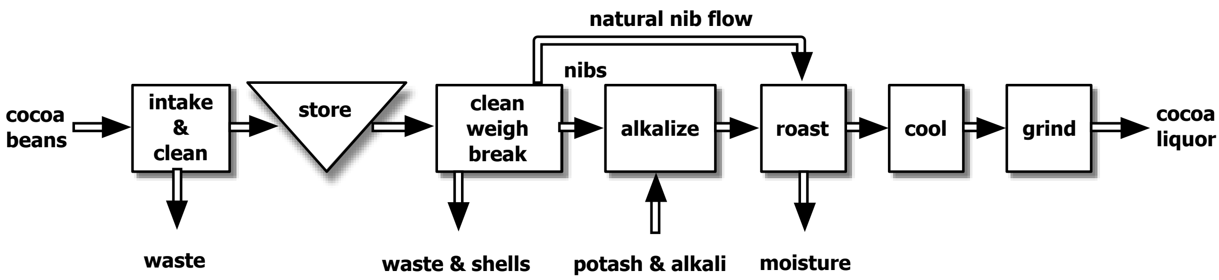


Fig. 3.6 Cocoa liquor making zoomed in one aggregation layer

The beans are temporary stored at a company nearby and transported to the factory when needed. When a truck of beans is ordered, it can be delivered to the factory within 2 hours. The beans are loaded and transported to the factory in trucks that can carry a maximum load of 30 tons. The operators check the incoming bulk load before intake and create a batch. There is room for two trucks in bean intake, but only one truck can be served at a time. The average time of bean intake is measured and takes on average 3 hours for a fully loaded truck. During the import, contamination is removed from the flow of beans.

The beans are stored before further processing. [redacted] The storage capacity of one silo is equal to the maximum load a bulk truck can carry.

After storage, the beans can be processed on one of the three liquor-making production lines. The remaining contamination is removed in the cleaning steps after storage. The weight of the beans is measured after cleaning to determine the yield of the beans, which is the weight of the beans after cleaning divided by the weight before cleaning. The clean cocoa beans are then buffered awaiting bean breakage. [redacted].

[redacted] he broken parts, nibs and shells, are then separated. The operators take samples of the flow of nibs and shells and test these in the laboratory. The analysis is used to determine the amount of shells in the flow of nibs and the amount of nibs in the flow of shells. Nibs in shells are direct loss of valuable product, whereas shells in the flow of nibs affect the quality of the liquor. The nibs are used for the production of liquor and are stored inside the batch buffers.

The batch buffers feed the alkalizing units, where the nibs are mixed with water, potash and alkali according to the product recipe. This solution raises the pH-degree, darkens the color of the cocoa and improves solubility in water. Alkalizing can also be skipped, to roast the nibs naturally.
The roasting process is performed by one of the three batch burners and is the key production step determining the capacity of the whole liquor making process. The roasting duration depends on the degree of alkalization. The capacities of the three burners for natural, light and highly alkalized nibs are listed in table 3.1.

[redacted]

	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]

The capacity of line one and two is less than the capacity of line three as the burners are smaller on line one and two. Therefore, the maximum output of liquor depends on the line on which the liquor is produced and the volumes of high and low alkalized liquor. To see if the function cocoa liquor making is future proof, the expected liquor demand is translated into production days to see if it can be produced. This calculation is shown in Fig. 3.7

[redacted]

[redacted]

[redacted]

Fig. 3.7 Calculation of cocoa liquor production days

With the expected ratio of high alkalized: low alkalized/natural liquor, this amount can be met with the current three production lines. The calculation shows that there is no need to adjust the capacity of liquor making for the future situation.

After the roasting cycle the batch is cooled in a bed to ensure crispy nibs that promotes the nib grinding. When the nibs are grinded the butter is released from the core, resulting in liquid mass. This cocoa liquor is coarse and fine grinded in different steps to ensure the right fineness for the customer and or for pressing cocoa liquor. All produced liquor is stored in the liquor tank park, which consists of 8 tanks of 75 metric tons each. From there the liquor is delivered to liquid bulk trucks, the packing stage or pumped to the two pressing tanks, of 30 metric tons each, feeding cake and butter making. The cocoa liquor can be blended before pressing. The most common liquor blend mid-red (MR) is made of light-alkalized Mid-brown (MB) liquor and high-alkalized Red liquor. Blending liquors ensures the cakes and butters produced by the presses have the right color and pH-degree.

3.4.2 Cake and butter making

The goal of this paragraph is to determine the capacity of cake and butter making and to check if the increased production can be realized. The function cake and butter making and the functions inside cake and butter making, revealed by zooming in one aggregation layer, are depicted in Fig. 3.8. The input and output of 2015 and the future quantities are also shown in this figure.

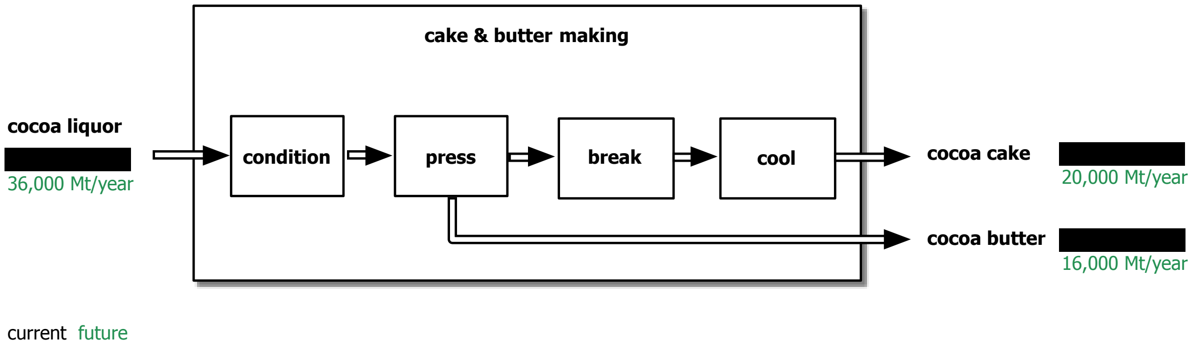


Fig. 3.8 Function cake and butter making and functions revealed by zooming in one aggregation layer

From the 30 MT pressing tanks, the liquor is transported to the conditioning tanks. These tanks heat the cocoa liquor to promote good filling of the presses and to enhance the pressing cycle. The duration of conditioning is on average fives minutes for each pressing cycle. There are a total of six conditioning tanks, in line with the six presses.

By pressing cocoa liquor, cocoa butter and cake are formed. Multiple cakes with different butter (fat) percentages can be made from one type of cocoa liquor. The duration of the pressing cycle determines the amount of butter that remains inside the cake, the fat percentage, and the production of cake and butter making in MT/hour. Furthermore, the capacity of the presses determines the capacity of the function cake and butter making. The capacities of each press for different cakes are shown in table 3.2

TABLE 3.2 CAPACITIES CAKE AND BUTTER MAKING PER PRESS PER CAKE

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

The three major aspects of cocoa cake are pH-degree, color and fat percentage. The two aspects pH-degree and color are determined during the previous liquor making stage. The aspect fat percentage of the cake is established by the pressing cycle. After a pressing cycle the press opens and the remaining cake drops on a conveyor belt underneath the presses. The conveyor belt transports the cake to the hammer mills to break the cakes. The cake is broken into particles ranging from fine powder to particles up to 6 cm. Cake before and after breakage is shown in Fig. 3.9

Fig. 3.9 Pressed cake on conveyor [10] and broken cake particles after hammer mills

After three runs of a new batch and periodically a sample is taken of broken cake particles, to evaluate the quality of the cake particles. If the fat percentage does not meet the standard the duration of pressing is adjusted.

There are a total of four cool screws connecting the presses with the cake silos. Presses 1 and 2 are connected to the cool screws of respectively 4 and 3. The cake is pneumatically transported to the cake silos. The breakers, cooling screws, and pneumatic transport in the current configuration have sufficient capacity to process the pressed cake.

The operators can choose in which silo the cake is stored. Furthermore, they can assign presses to the liquor that needs to be pressed. However, in the current situation presses 1 to 4 are used as a set, focusing for the greater part on the production of low-fat cocoa cake batches. The focus of presses five and six is mainly on the production of fat cakes. The reason for the preferred assignment of presses according to fat percentage of the cake is ease of use and control. Furthermore, the cooling of cakes in cool screws 3 and 4 is endangered due to the increased flow of cake coming from presses 1 and 2 while producing fat cakes.

Changeover time between to another batch of liquor pressing is on average 0,75 hour. During this time interval the cooling screws are emptied to cool new cake, a new batch is created, and cocoa liquor is made ready for pressing. On average, each press is down for 0,75 hour each day, due to cleaning.

[redacted]

[redacted]

Fig. 3.10 Daily powder production distribution

[redacted] From the daily production numbers it is clear that this quantity can be realized, also when the cake is primarily low-fat cake with longer pressing cycles.

From the downtime analysis of 2015 one can conclude that the capacity of the butter filters is not always sufficient to process the flow of butter. The butter filter process has been improved in 2016 and does not affect cake and has sufficient capacity to meet the increased flow of butter. However, cake and butter making is blocked due to unavailable silo space. Information from the downtime analysis shows that in 2015, all presses combined were blocked for 2711 hours. That is on average almost 19 lost production days for each press. This type of downtime reduces the capacity of cake and butter making and is further examined in this research to see what the reasons are for the blockages and how these are avoided.

3.4.4 Cake storage and blending

The cake storage facility is the connection between the cake making stage and the powder making stage. All cocoa cake is part of an order and is stored as intermediate product in the silos before it is transformed into powder.

Cake storage consists of six silos. The first four identical silos have a capacity of 20 metric tons each, whereas silos 5 and 6 have a smaller capacity of respectively 18 metric tons and 8 metric tons. Silo 1, 2, 3 and 4 receive cake coming from cake and butter making, while silo 5 and 6 are used to process rework and imported cocoa cake. The storage function and calculations for the input and output are shown in Fig. 3.11. A gross estimate for the future quantities for blended and unblended cake is made. The exact forecast is determined later on, in chapter 5, by zooming in on the produced and imported cakes and the possibilities for blending.

[redacted]

Fig. 3.11 Storage cake and powder

The main reason why silos are needed is to decouple the incoming process from the outgoing process. The ingoing process consists of cake coming from the presses, import and rework. The outgoing cake goes directly to the powder making stage or is blended first. Decoupling is needed because the capacities of cake making and powder making are different. In the previous paragraph the downtime is mentioned due to unavailable cake storage space. On of the major causes of this downtime are the contradictory capacities of the adjacent functions of cake storage. Another cause is the malfunctioning of the silos and the flow obstructions that occur during operation.

Like in the previous chapters, the function cake storage is examined to see if it is able to meet the future demand. In this paragraph the cake storage is examined regarding two aspects. The first aspect is the capacity of cake storage. The second aspect is the problem with flow from the silo. Cake storage does not only store cake coming from the presses but also needs to function in order to feed cake to the powder making lines. This silo problem affects the performance of current production and will most likely cause problems in the future.

Storage capacity

In the current process it occurs that the presses are blocked due to unavailable silo space; while in other cases the powder making lines are starved due to insufficient cake in the silos. The [redacted] 20 MT cake storage silos are large enough in the current situation to store the differences in capacity of cake making and powder making provided that the production runs are limited and the production on the two adjacent stages is coordinated.

The most significant change on the input side is the increased import of cocoa cake. The cake is delivered in containers of 20 MT or packed in Bulk Bags of 800 kg and must be stored in the silos. The current silos 5 and 6 are used for rework and dumping. The average amount of import cake each day is 71 MT and the capacity of the silos combined is 26 MT. Furthermore, it is expected that the number of imported cakes exceeds two types. Silos 5 and 6 have insufficient capacity to decouple the ingoing and outgoing process.

Malfunctioning of the cake silos

A common error in the production process is obstruction of flow from the cake silos. Flow obstructions directly affect the performance of the adjacent powder making stage and incomplete emptying of the silos causes downtime on the presses. The operators consider the lack of flow as a familiar error, as it occurs almost every day. Especially the last remaining tons of cake in the silos do not flow out. The used remedy for these discharging problems is striking a hammer on the convergent part of the silo wall in order to promote flow. The hammer marks can be seen on the silo in Fig. 3.12, indicating problems with flow [11]. Another method currently performed to force the cake out of the silos is wrecking a large pipe in the outlet opening to break possible arches of cake. These actions lead to dangerous situations and affect the quality of the product.

Fig. 3.12. Hammer marks on the converging part of the silo

It is not known what the main cause is or causes are for the obstruction of flow from the silo. During the interviews with operators and managers several possible causes are mentioned. The main qualitative statements are listed:

- Temperature dependence. Pneumatic blowers are situated underneath the cake storage area and transfer their heat through the open staircase to the silo room. The silos and the cake in the silos are heated to high temperatures of around 50° Celsius. This worsens the flow behavior.
- Furthermore, the cake from presses 5 and 6 is grinded into finer particles, while the hammer mills behind presses 1 to 4 break the cake into coarser material. The finer particles are more likely to result in stagnation of the flow.
- The fat cakes, containing more butter, are more likely to cause problems during discharge.
- The design of the silo is the reason for obstruction of flow. There is a possibility that material does not pass any obstructions on the inside.

These statements need further examination to see which ones are valid and which can be discarded. The first and second argument states that the temperature and particle size affects the flow properties of the cocoa cake. The flow properties of a bulk solid material can be affected by chemical composition, moisture, temperature, particle size distribution, and particle shape [11]. In general, a bulk solid flows more poorly if the particle size is smaller [11]. The temperature and particle size dependency should be further examined as it affects flow properties of bulks solid materials. According to the third statement, the flow properties of the cocoa cake decreases when the fat percentage of the cake increases. Just like the temperature dependency and the influence of the particle size, measurements can outline the dependency of the fat percentage on flow behavior. The last statement considers the design of the silo. The dimensions of the silos are known and by testing the cocoa cake, and the interaction of the cake with the inside of the silo, the design of the silo can be reviewed. The dimensions and design of the silos 1-4 is shown in Fig. 3.13.

An important design principle of the storage of cake and powder is First In First Out (FIFO). The product entering the silo first must also come out of the silo first during discharge. This ensures the quality of the product is maintained and no material gets stuck or deteriorates inside the silo. The silos are equipped with a bin activator and an inverted cone that initiates flow and discharges material. Therefore, it can be considered both a discharge aid and discharge device. [11] The inverted cone reduces segregation and promotes mass flow to meet the FIFO principle. Furthermore, the silos are equipped with mechanical and pneumatic discharge aids, respectively vibrating motors and air nozzles, to promote flow.

In order to examine the statements further, the cocoa cake and interaction between cake-silo wall needs to be measured.

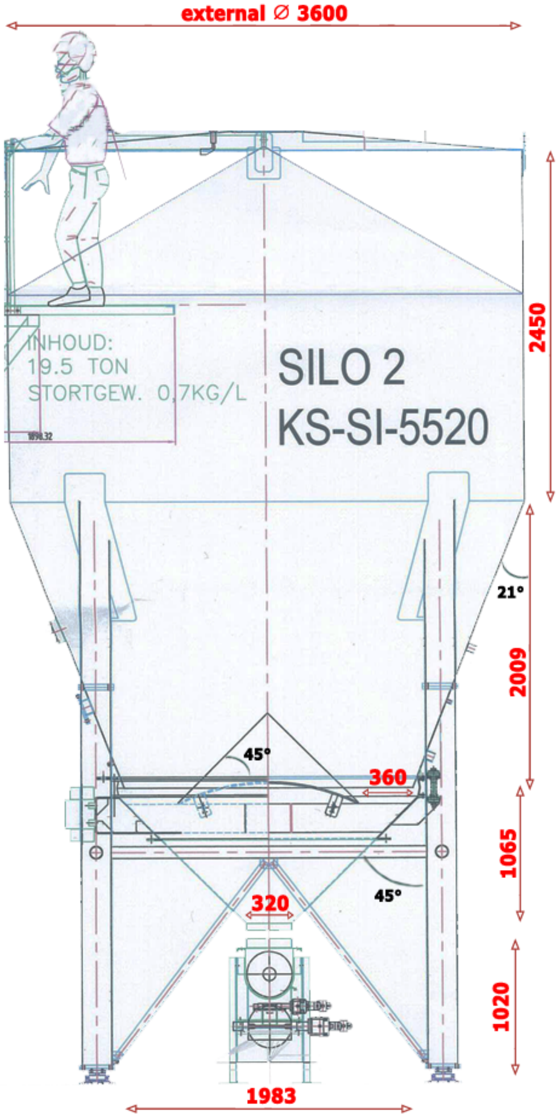


Fig. 3.13. Dimensions of silos 1 to 4

3.4.5 Blending function

Blending takes place in the current production process at liquor making. The liquors are blended before pressing to obtain blends, like mid-red (MR), a blend of mid-brown (MB) and Red liquor. Instead of blending liquors, [redacted] wants to blend cakes. Currently, the cake output from the storage goes directly to the powder making stage and is rarely blended. In the future [redacted] wants to blend large amounts of the imported cake with production cake. The amount of cakes destined for blending increases to 25,000 MT, of which 15,000 MT consists of production cakes and 10,000 MT is imported cakes. The affect of this increase on the cake blending function will be discussed in this paragraph.

Blending cake is a proven technique and is used by other cocoa grinding companies to change and control the specifications of cocoa cake [12]. The current blending process and function are shown in Fig. 3.14. Furthermore, the expected input and output of blending is shown.

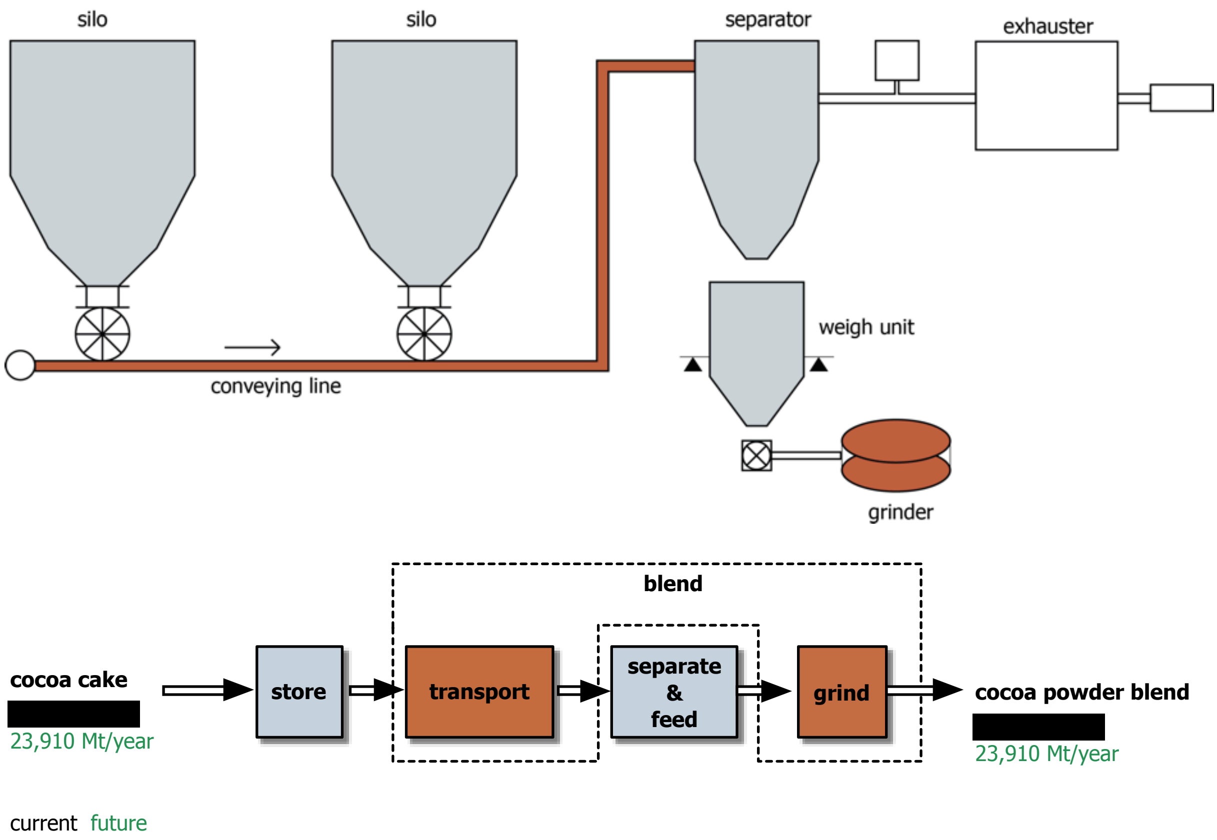


Fig. 3.14 Blending equipment (top) and function (bottom)

Blending in the current process is exerted by transportation and classifying. The function *blending* is integrated in the functions *transport* and *grind* as shown in Fig. 3.14. The blending process starts by feeding cake from multiple silos to one pneumatic transport. During transport the fed product streams are mixed. The mixed product is blown into the hopper and separated from the airflow. After weighing, the mixed product flow is fed to the grinder in which the air streams and grinding wheel mix the mixed product flow once more. In this blending process the quality of the mixture or blend is not controlled. It is a side effect of two functions, which are not designed and controlled to influence the degree of mixing.

The input for this mixing process is not guaranteed as cake gets stuck inside the silo during discharge. This results in unblended cake and an unreliable function. Furthermore, the cake feed is limited due to the constraint that only flows larger than 200 kg/hour can be dosed into the pneumatic transport. Below this amount the valve and corresponding dosing system are not controlled. The final flaw of the current blending function is that (blended) powders are examined after the powder making stage, so interventions like adjusting the feed rates to the transport to adjust the blend ratio are initiated too late.

Generally it is best to separate the mixing and particle size reduction process, as the combined process is more difficult to control. An example of this combination is found in the current blending practice. The classifier-grinding machine is designed to control the particle size reduction aspect reduction and not to mix the combined product flow. There is no relationship between the parameters of the machine and the effect on the degree of mixing.

Another possibility is grinding all the cakes first and blending powders instead of cake. The function blending is then situated after the grinding stage. Blending powder is beneficial, as a homogeneous mixture is easier to accomplish by blending powders. The mixture of coarse material and fine particles after blending cakes leads to segregation. Powder blending may also be beneficial as it results in standardized cake-grinding lines for large quantities of produced and imported cake.
The main reason that [redacted] does not want to blend after cake grinding is that additional silos are needed to store the powder. [redacted] wants to investigate blending cakes and not powders and therefore powder blending is not further elaborated in this research.

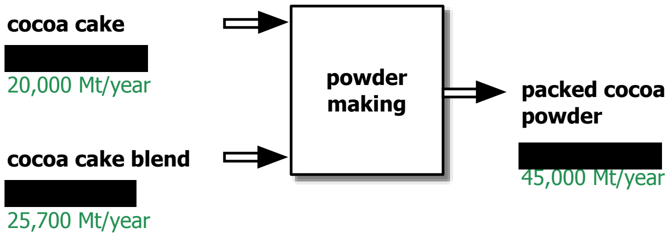
The three major aspects of cocoa cake that are manipulated in the blending process are fat, color and pH-degree. Blending based on fat percentage is straightforward. The weights of the cakes in the blend and their fat percentages determine the resulting fat percentage. The blend ratio for the aspects color and pH-degree are more difficult to obtain and need to be determined in the laboratory. The pH of cocoa cake is the negative logarithm of the hydrogen ion concentration of a suspension in water [12]. The color is described by its LAB values and influenced by type of bean, alkalizing conditions, burning cycle and fat percentage. Moreover, there is a difference in external and intrinsic color. The external color of the powder is influenced by fat on the solid particles and the crystallization of the butter, whereas the intrinsic color is the color of the final product in which the powder is solved[12]. To determine the outcomes of blending two cakes with different pH-degrees and color, a solution must be prepared and measured. Cake and powder can also be alkalized to influence the pH and color, but this is not included in the scope of this research.

Since only the fat-percentage of the imported cake is a given, blending based on fat percentage is further examined. All the 25,000 metric tons of imported cake has a low-fat percentage. The imported low-fat cake can be blended with home made fat or low-fat cake. A blend of two low fat cakes will result in a low fat cake, whereas blending low-fat and fat cakes results in 16-18% or 20-22% cake. To make a 24% cake no additional low-fat cake is blended, since 24% is the maximum fat percentage that is pressed.

3.4.6 Powder making

The cocoa cake coming from cake storage and blending is further grinded into cocoa powder at the powder making stage. This paragraph reviews the processes and capacities of powder making. The goal of this paragraph is to see if the increase in powder output can be realized with the current production equipment.

The output of powder increases to a yearly production of 45,000 MT. The average daily production quantity for this future situation is 129 MT of powder/day. The function powder making is shown in Fig. 3.15 at the top with the yearly production quantities.



[redacted]

[redacted]

The capacity of the function is examined by zooming in one aggregation layer and by looking again at the different functions inside the black box. The powder making stage consists of two lines with the functions shown in Fig. 3.16. Both lines are identical except for the number of cooling steps and the buffer space. The cake from a silo can only be fed to one powder making line at a time by the pneumatic transport. After grinding the cake is cooled in the cooling silos. From the buffers after the cooling steps the powder is fed to the packaging machines. A batch of powder making can consists of multiple customer orders packed into different bags with different labels. The powder is packed in big bags of 800 kg or in small bags with a volume of 25 kilograms or 50 pounds (22,69 kg).

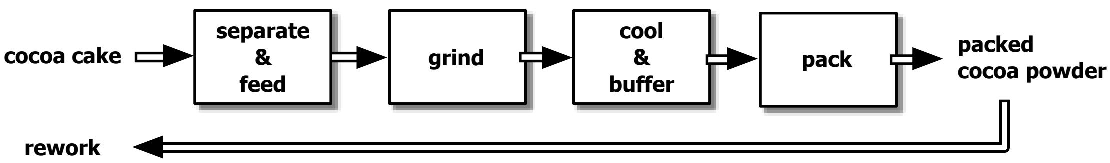


Fig. 3.16 Powder making zoomed in one aggregation layer

The cake is pneumatically transported to the powder making facility and is fed to a hopper in which it is separated from the flow of air. After the hopper the cake enters a weigh bin that is used to control the flow of cake to the grinder. The cake is fed to the classifier-grinder, which grinds the cake into fine powder. The powder classifiers of each line have the same capacity, which depends on the fat percentage of the powder that is produced. The higher the fat percentage of the cake, the lower the capacity of the classifier. The capacities of the classifier wheel in operation are:

- 2 MT/hr (fat cake)
- 4 MT/hr (low-fat cake)

At the cake and butter making stage the capacity increases while processing fat cake. For powder making this is the other way around. The capacity of the function powder making in current practice is less than 2 or 4 MT/hr and this has several causes. The first is that powder making is influenced by the capacity of cake making and the availability of cake inside the silos. The powder making lines are often starved, due to unavailable cake. According to the downtime analysis, the two powder making lines combined are starved for 732 hours in 2015. Also flow obstructions occur, preventing cake transport to the powder making lines. The second is that operators lower the feed rate of cake to the powder making lines to prevent congestions and problems with the pneumatic transport. The third reason why the capacity is less in practice is the downtime on the packaging stage that lowers the capacity of the entire powder making line. [redacted] The cycle times of packaging 50 pound- and 25 kilogram bags are measured during operation and these range between 22 seconds to 45 seconds. This means that during uptime, capacities up to 4 MT/hour can be realized. More than 5 Big Bags of 800 kg can be packed per hour, thus Big bag packaging also has sufficient capacity. The bottleneck of the powder making line is the classifier-grinding wheel.

The classifier wheel needs cleaning after producing 20 MT of fat cocoa cake or 40 MT of low-fat cake. The duration of cleaning depends on the amount of operators available for cleaning and is on average 3 hours. Change over time between two different powder batches takes on average 2-3 hours. During this time, before producing a new batch, all the powder remaining in the cooling silos and buffers must be packed. The first 10 bags of a new batch are used to clean the powder making lines. These cleaning bags may contain rests of product from the previous batch and are labeled as rework.

The capacity and throughput of the function powder making is determined by the fat percentage and the batch size. The batch size distribution for fat and low fat cake production in 2015 is presented in Fig. 3.17.

[redacted]

Fig. 3.17 Batch size distribution 2015 low fat and fat cakes

As shown in Fig. 3.17 most batches have a size of 20 to 25 MT. This amount is equal to the amount of fat cake that can be produced before cleaning, but is not equal to the 40 MT of low-fat cake production before cleaning. The small batch sizes are infeasible for powder making, due to the 3 hour downtime at changeovers, whereas the large batch sizes are infeasible as the silo capacity is limited and unable to store the difference in capacity of cake and powder making. When the batch sizes are too small or too large, respectively the number of silos and the capacity of the silos are insufficient to prevent blockages and starvation.

The current maximum capacity of the powder making lines depends on the fat percentage of the cake and the batch size affecting changeovers. To examine if the current two powder making lines have sufficient capacity to process the future amounts of cake, the amounts of low fat cake, high fat cake and the batch sizes need to determined. These amounts can be estimated by looking at the possibilities of blending and by making assumptions based on the product mix and batches of 2015. The ratio of low-fat and fat cake for the 45,000 Mt powder out is estimated in chapter 5. Assuming maximum blending gives a total of 36,440 Mt low-fat and 8,559 Mt fat cake.

The calculation for the required capacity, assuming ideal batch sizes according to the cleaning intervals, is shown in Fig. 3.18. In ideal batches the cleaning times and change over times can be aggregated. This calculation shows that the two powder making lines do not have sufficient capacity to process the forecasted amounts of cake.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Fig. 3.18 Calculation required capacity powder making

3.4.7 Order processing

In this paragraph the current procedure of order processing is reviewed to provide information for the future situation. The significant increase in powder output will influence order processing, for example by increasing the sales activities. However, reviewing the capacity of sales and other departments involved in order processing will not be discussed in this paragraph.

The sales department agrees on contracts with customers. These contracts consist of several orders, which need to be delivered to the customer during specific periods. The customers contact the customer service team [redacted] when they need their order and [redacted] also contacts the customers to discuss if an order can be made. The customer request is processed and handed on the planning department by [redacted] if there is a consonance with the client.

At the planning department the contracts and orders are added to the long term planning. This long term planning lists which orders need to be delivered within the upcoming months. There is a long term planning spreadsheet for the delivery of cocoa liquor, butter and powder. Pressing liquor makes cake and butter, both used to fulfill customer orders. In the product spreadsheets all the contracts are listed and updated.

The planner also produces the short-term schedule, manually, with a time horizon of one week. This factory planning is discussed every Wednesday with the direction, head of production, sales, and customer service. In this meeting the previous week schedule and actual production are evaluated and used to adjust the planning and production process. Also the upcoming schedule is reviewed and renewed if possible difficulties are foreseen. If the schedule is approved, it is copied to the balance sheets and transferred to the factory. The balance sheets give an overview of the total scheduled and produced products.

The planner works backward from the ordered product to derive the schedule for semi-finished products and intake of raw materials. The timing of each process is based on the intuition of the planner and therefore the experience of the planner is important in this decision making process. The resulting weekly schedule is a list containing the daily production quantities for each production step to obtain the desired liquor, cake and butter, and powder products. The starting time of a batch is not stated, neither is the duration of the batch. The schedule, the production leaders and the availability of semi-finished products determine the order in which products are produced in practice. Variability in the process and the flexibility of the schedule results in differences in scheduled and actual production each day at each stage. The performance is measured by reviewing the daily production quantity, the productivity, of each step without regarding the type of product or batch size.

The planning department combines orders from different customers for the same product into production runs for the factory. The whole process is batch oriented and the operators in the control room convert these production runs into batches for the production steps. The planning does not take into account process oriented batch sizes while establishing these combined order runs. Nonetheless, the batch size is important for the performance of cake and powder making as they have contradictory capacities determined by the fat percentage of the cake. For large batch sizes the storage of cake between cake making and powder making is not sufficient to buffer the difference in capacity of the two adjacent functions.

The cycle times of the products are not measured or used to evaluate the production schedules. For a few batches the throughput time is reconstructed based on production data to provide information on the duration of the production steps. This is shown in table 3.19. It is important to mention that this data is unreliable, because the ending times of the batches do not represent the real ending times due to manual administrative processing in the batch control system.

Table 3.19 Throughput time measurements

[redacted]

The cycle times of the measured batches show variation, which cannot be directly linked to a difference in batch size or fat percentage. An example from table 3.19: a batch of 17700 kg 10-12% powder has a total cycle time of 4,5 days, while a batch of 21807 kg 10-12% powder has a total cycle time of 2,8 days. The different process steps can overlap each other depending on the state of the system. If there is sufficient amount of cocoa liquor, the presses can start pressing before the liquor-making batch is finished. This also applies to the cake making and adjacent powder making stage. During cocoa liquor making the lines were pre determined by the planners, in the cake and powder making stage the operators choose which resources and lines process the products.

Blending cakes in the future situation is responsible for a large part of the production portfolio. To make the powders other production tasks are needed than currently in place. The blending recipe will state which cakes are blended and the share of each cake. So additional information and control is needed for the future situation of order processing.

4. Research question

The product handling and powder output increases due to the increased production, increased import of cake, and increase in blended cake. In chapter three the different functions of the process are examined to see if the new product demand can be realized. While exploring each function it has become clear that not all functions have sufficient capacity and or malfunction.

Cocoa liquor making has sufficient capacity to meet the future demand. This also applies to cake and butter making. The two powder making lines do not have sufficient capacity to process the increased flow of cake. The blending function is currently integrated in the functions transport and grind, but these processes do not control the result of blending. This affects the quality of the blend and the manageability of the entire production process. Therefore, the function blending needs to be redesigned.

The current installed silos do not have sufficient capacity to buffer the difference between ingoing and outgoing flows of imported cake. In the current production process the presses are blocked due to unavailable silo space and the powder making lines are starved due to the unavailability of cake. Furthermore, flow obstructions inside the cake silos occur. This results in downtime affecting the performance of the adjacent functions and makes blending impossible. Several causes for the flow problems are mentioned in the interviews. The design of the silos and the aspects fat percentage, particle size and temperature of the cake must be examined.

These findings from chapter three result in the following research goal:

Redesign the production system for storage, blending and processing of cocoa cake, in order to meet the future demand of cocoa powder.

The system boundary for the new design, the scope of this research assignment, is outlined in red in Fig. 4.

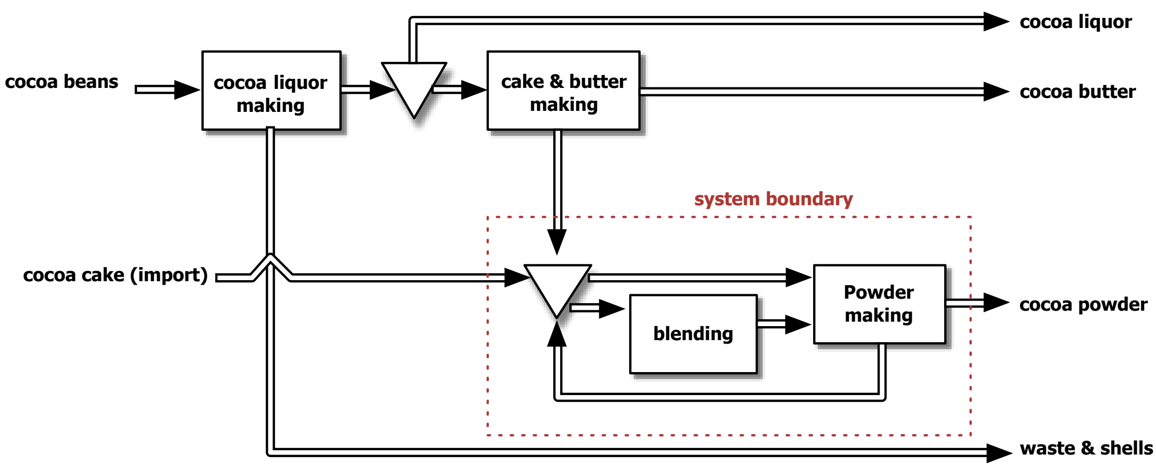


Fig. 4 Functions of design and system boundary

In the next chapter the product mix of the blended and non-blended cakes is determined, which gains as input for the solution of the research question. The following chapters present the solution for the design of the new production system. The logistic process design, including product flow and control of the system, is discussed in the logistic chapter 6. In chapter 7, the bulk solid properties of cocoa cake and the interaction between cake and wall material are tested to design cake silos. Also the design of blending equipment is addressed in this chapter.

The cake storage function is investigated in this research regarding two aspects. The first is the capacity aspect examining the number of silos and the volume of each silo, needed in the new production system. The second aspect is the design of the silos, examining the aspects of cake and silo wall material to determine how the silos should be dimensioned.

5. Productmix

This chapter looks at the cocoa cake product mix for the current and future situation. The information presented in this paragraph is used for the design of each function in the logistic chapter 6. To determine the expected increase in product handling for each step, the future product mix is determined based on the possibilities of blending, the product mix of 2015, and the expected production and import of cake.

[redacted]

[redacted]

[redacted]

Natural cake is non-alkalized cake, primarily with a low (12%) fat percentage. [redacted] tandard-alk cake is the collection of alkalized mid-brown (MB), red and mid-red (MR) cake. Mid-red is currently made of a liquor blend of mid-brown (MB) and red liquor. In the future, cakes instead of liquors are blended. Thus, MR cake is a blend of mid-brown and red cake.

5.2 Future productmix

[redacted] plans to make 20,000 MT cake per year. 15,000 MT of the total cake production is standard-alk cake, [redacted] [redacted] [redacted] The imported cake increases significantly from 500 MT to 25,000 MT. Natural cake is exclusively imported and increases to 15,000 MT. Besides natural cake, 10,000 MT of standard-alk cake is imported for blending. The future distributions of production and import cake are shown in Fig. 5.2.

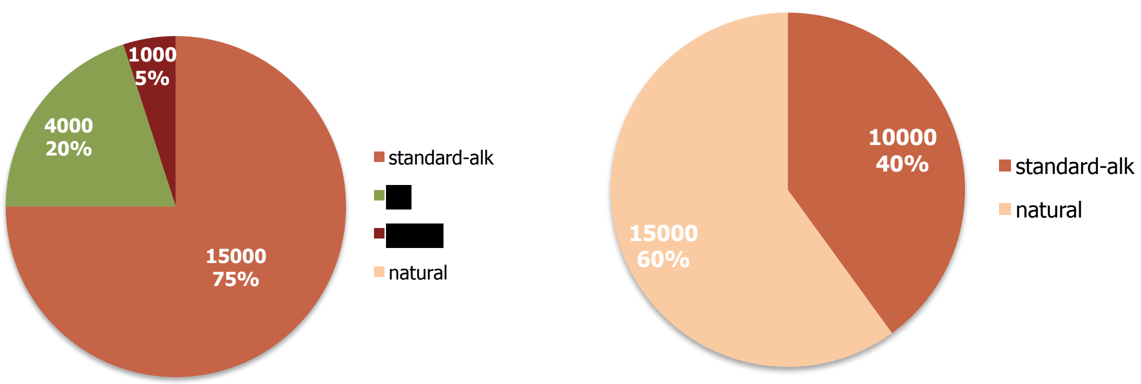
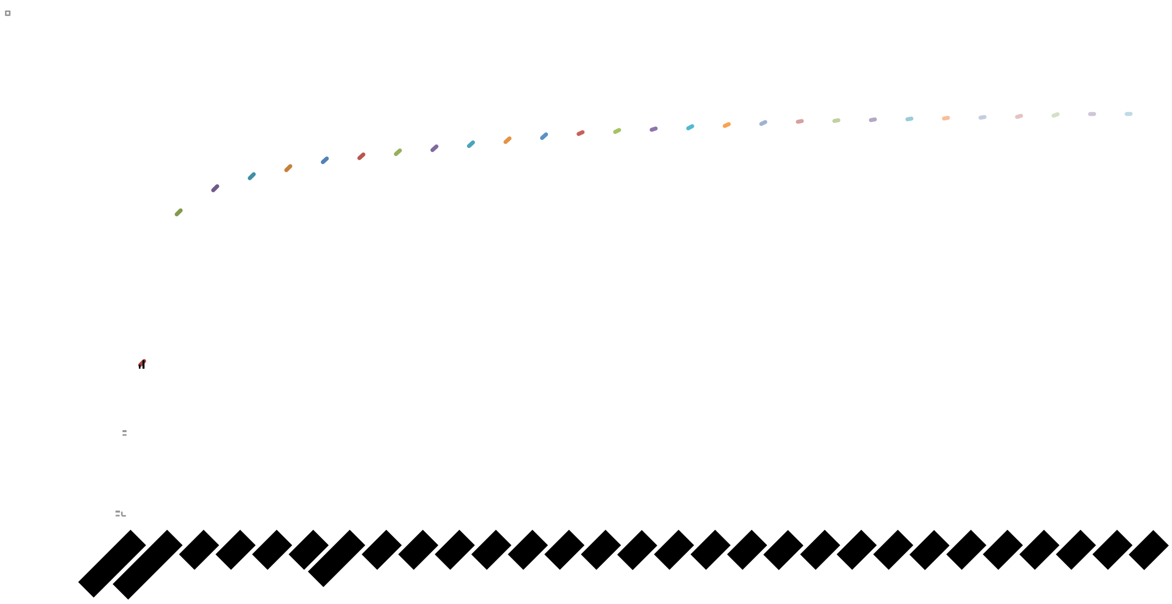


Fig. 5.2 Production cake (left) and imported cake (right) for future situation

[redacted] [redacted]

[redacted]



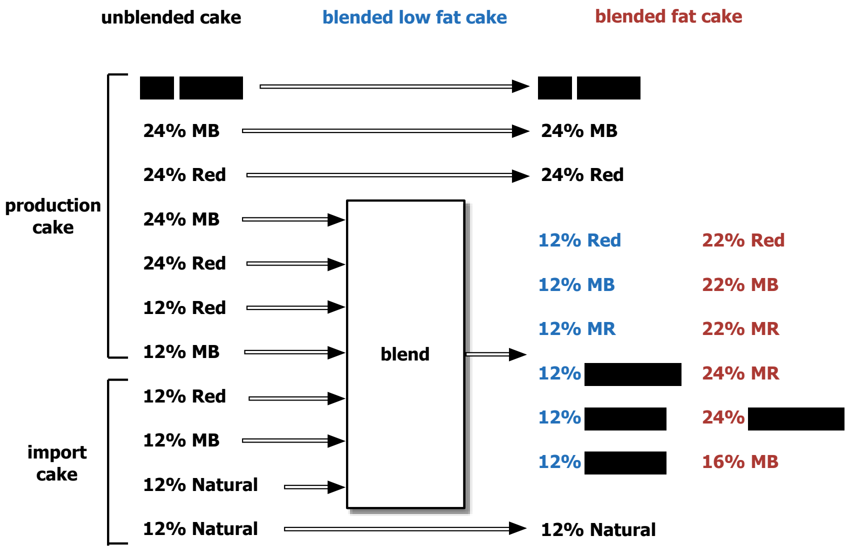
[redacted]

[redacted] [redacted]

[redacted]

2

b



	[redacted]	2017	production	import	average % blended
10-12% MB		6905	3226	3679	53%
10-12% RED		7382	3449	3933	53%
10-12% MR		2839	1326	1513	53%
[redacted]		841	421	421	50%
		643	514	129	20%
		86	64	21	25%
Total low fat alk		**18697**	**9000**	**9696**	**52%**
16% MB		519	216	303	58%
22% MB		2105	1754	351	17%
22% Red		666	555	111	17%
22% MR		658	548	110	17%
24% MB (no blend)		1148	1148	0	0%
24% Red (no blend)		1212	1212	0	0%
24% MR		490	490	0	0%
[redacted]		76	76	0	0%
Total high fat alk		**6874**	**6000**	**874**	**13%**
Total alk		**25571**	**15000**	**10570**	**41%**
[redacted]		5000	5000		
natural		14430		14430	
Total powder output		**45000**	**20000**	**25000**	**46%**

Fig. 5.4 Cake types and quantities

Fig. 5.4 shows that a maximum of 874 MT of low-fat imported cake can be blended with produced 24% cake. Thus, 9126 MT of the total imported standard alk cake must be blended with standard alk low fat cake from production. This means that the main focus of blending lies on blending low-fat cakes. A small fraction, 570 MT, of the imported natural cake is also blended with production low-fat cake to obtain [redacted] Blending 9000 MT of produced cake with 9696 MT of imported cake results in an annual average blend percentage of 52%.

To determine the total amount of fat and low fat cakes for the cake grinding stage all the cake flows are summarized:

- [redacted]
- After blending the total amount of fat cake is 4514 MT and 18697 MT of low-fat cake.
- Total natural unblended cake is 14430 MT of low-fat cake.
- Total fat cake = 6874 + 1280 + 470 = 8624 MT
- Total low fat cake = 18697 + 14430 + 2720 + 530 = 36377 MT
- Total powder output = 45000 MT

6. Design of future production process

In the previous chapter, goals are set for the future product mix. For the future production process large volumes of cake are imported and blended to fulfill customer orders.

In this chapter the production process is redesigned to produce, blend and process the cakes into powder. Depending on the requirements and the function, the necessary changes in capacity and control steps are developed. Although the strategy, planning and scheduling of the cocoa process is not the main focus of this research, principles concerning these aspects are made. These principles, discussed in the first and second paragraph, are important for the initiation of the production process and for the design of the functions. The third and fourth paragraphs respectively show the powder making function and blending function and what is needed to process the increased cake input. The proceeding paragraph shows the solution for cake storage in the redesigned production system. In the last paragraph the control of the production system is discussed.

6.1 Strategy and CODP

A common development in the food industry that applies to [redacted] is the tendency to restrict set-ups, batch sizes and produce economically using stable and repetitive cycles [14]. On the other hand the production process needs to be flexible reacting on customer demand. To decrease the negative effect of product variety on the operational performance, a common strategy in the food industry is to postpone the product differentiation activities as much as possible [15]. A feature of this strategy is stocking intermediate products and using them to produce end products according to customer demand [16]. An example of this postponement and storage of intermediate products is pressing standard cocoa cakes and blending these cakes to fulfill powder orders. The main blending function moves downstream from blending liquors to blending cakes. As mentioned earlier, blending cakes is a proven technique and is used by other cocoa grinding companies to change and control the specifications of cocoa cake [12]. The previous chapter showed that four standard production cakes, Red 12%, Red 24%, MB12% and MB 24%, are used for blending. With a small number of cakes a large number of blended powders can be made.

The forecast driven activities are split from the customer-order driven activities by the Customer Order Decoupling Point (CDOP) [14]. The CODP currently lies at the storage of beans. Imported cake enters the production system between cake making and powder making. In the future, the standard production cakes are made each planning period in batches on a forecast basis and linked to customer order(s) at the cake silos. The CODP shifts from cocoa beans to the cake silos for standard production cakes used for blending. This is possible since the volume of these cakes is high and the variability is low. However, for the [redacted] and [redacted] (MTO) products, the CODP will remain at the storage of beans since the volume of these cakes is low compared to the blended cakes and the variability in type of cake is high. This results in a hybrid make to order (MTO) and [14] blend to order (BTO) structure, with two CODP's, shown in Fig. 6.1.

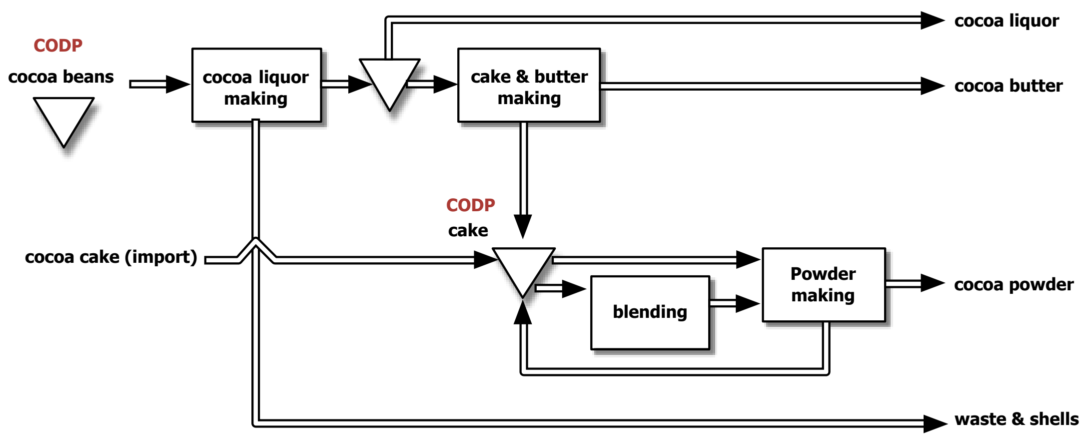


Fig. 6.1 Hybrid customer order decoupling structure

6.2 Order processing

This paragraph will discuss the effect of the hybrid strategy on order processing.

After receiving the customer order, the attributes of the orders are assigned. These attributes include product type, quantity, blend ratio (recipe) in case of blending, order name and date, and SKU. The order information is used to establish the planning. The long term planning, with a time horizon of two to three months, lists the contracts and orders with their delivery date. Orders are selected and or combined to create batches each week from the candidate production order pool. The week planning is the factory production schedule with a time horizon of one week. The production schedule is translated to a production list, stating the sequence in which the orders are produced. The functions of planning and scheduling are shown in Fig. 6.2.

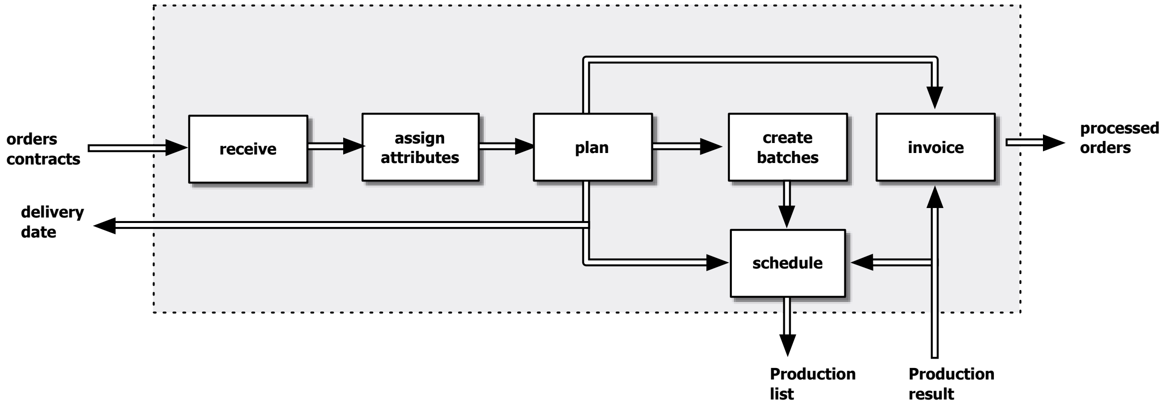


Fig. 6.2 Order processing function

Following a hybrid customer-order-decoupling-point strategy, planning has to deal with separate types of products, which will be produced using the same equipment. The [redacted] and [redacted] are produced on a make to order (MTO) basis, while the standard cakes are blended to order (BTO). Each week, capacity is reserved for MTO products. Every week, a limited amount of production time is reserved for MTO products. MTO cakes are separated from each other and produced at standard intervals in between the blend to order runs.

For the [redacted] MTO products the production steps bean intake, liquor making, cake making and powder making are directly linked to the customer orders. These steps are planned backwards from the ordered product to derive the schedule for semi-finished products and intake of raw materials. For the BTO (blend to order) products the production steps bean intake, liquor making, cake making are forecast driven. The goal is to achieve stable cycles on cake making, ensuring full utilization of the presses while minimizing change over times. For BTO standard alk products, the presses produce cake in standardized production runs that can be used in one or multiple powder batches. The downtime on powder making is minimized if the batch sizes of powder making are 20 and 40 MT, respectively for fat and low-fat batches. This aggregates the necessary cleaning downtime and change over time to another product. Using standard cycles and batch sizes eases the scheduling procedure, as the duration of processing a 20 MT fat batch and a 40 MT low fat batch on a powder making line is the same.

Each powder-making batch consists of one or multiple customer orders. During powder making, the SKU and label is changed to pack powder of the same batch for another customer. Change over time to a different SKU for a different customer in powder making is negligible. The largest customer powder order in 2015 was 24 MT. However, if a customer order is larger than the standard 20 MT or 40 MT, the order is split into multiple powder batches. A drawback of spreading an order over multiple powder batches is that the expiring date printed on the powder bags within the order may differ. Due to the high frequency and demand of these powders the interval between two similar powder batches is acceptably small.

The production runs of the presses are standardized and the intervals between these runs are known. The batches on the powder making lines are scheduled to ensure the cake is emptied from the silos and the presses are not blocked. The presses replenish the silos that have been emptied by the powder batches. Alternation in the production of cake ensures batches on the powder making line alternate. Alternating production on cake making and powder making evens out the imbalance caused by different capacities due to fat percentage and blend ratio. By limiting the cycle length and batch size, while alternating fat, low fat and blended products, the necessary intermediate storage of cake to keep both processes running is limited.

In the next paragraphs the powder making and blending function are discussed. When these functions are filled in the input and output of cake making are known. This information is then used to establish cake buffering.

6.3 Powder making

From the process analysis of chapter three it is clear that the current two powder making lines do not have sufficient capacity to produce the expected cake output. To increase the capacity of the powder making function, either the existing lines must be improved or additional capacity should be installed. It is assumed that the packaging machines are up at full capacity and do not lower the capacity of powder making. The current capacity of the powder making lines is limited by the capacity of the classifier cake grinder. Since the capacity of grinding of the two powder making lines cannot be enlarged to match the needed capacity for the future demand, an additional identical powder making line is installed.

The product mix shows how much fat and low fat cake is expected in the future situation. The total volume of fat cake for powder making is 8624 MT. The total low fat 12% cake is 36377 MT. The sum of fat and low fat cake equals 45000 MT. The total hours needed on the three powder making lines to process the cake is shown in Fig. 6.3.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

So the three lines also have sufficient capacity to meet the future production plan for the scenario in which the change over times and cleaning of the classifier cannot be aggregated.

Fig. 6.3 production time to process all the cakes at powder making

[redacted] This can be realized with a single Big Bag filling station. However, this limits the planning and scheduling options as only one powder making lines can process Big Bags at a time. In the future situation an additional Big Bag installation is installed for the case two powder-making lines are producing Big Bags simultaneously.

6.4 Blending

In chapter three the current blending function is examined and the flaws of the blending process were summarized. The integration of the blending function into the functions transport and grind resulted in an uncontrolled and unfulfilled blending function. An important requirement for the new production process is that the quality of the mixture must be examined before powder making. Therefore the function blending is differentiated. This ensures the degree of blending can be controlled before grinding into powder. First, the function blending is examined to determine its capacity. Secondly this paragraph discusses the amount of blenders, needed to process all the blends.

The cake silos feed the blending function and the output of blending goes to one of the three powder making lines. The blending capacity must be equal to or larger then the capacities of the powder making line processing fat and low-fat cake. This ensures the blending function is not the new bottleneck. The capacity of the blender feeding powder making is equal to the maximum capacity of powder making, which is 4 MT/hour. The capacity must be turned down to 2 MT/hour in the case a fat cake is blended. A blender can only feed one powder making line at a time.

Not all blends can be made by one powder making line, as the capacity of a single powder making line is insufficient to process al the blended cakes. On average, 69 MT (divided over multiple fat and low fat blends) is blended each day. Furthermore, 59 percent of the total processed cycles on powder making are blends. If all powder-making lines are equally utilized, more than half of the time two blends are made simultaneously. Thus, two blenders are needed in the new production system.

The design of the function blending does not answer which equipment is used for blending in the production system. The productmix and blend ratio gain as input for the choice of blending equipment. The process design, concerning the type of resource assigned for the function blending and the main decision for the mode of operation (batch or continuous) are discussed in chapter 7.

6.5 Cake storage

In the first and second paragraph of this chapter the production strategy and order processing are discussed. Alternating products on cake making and powder making evens out the imbalance between these stages, which is caused by a difference in capacity. By limiting the cycle lengths and batch sizes, while alternating fat, low fat and blended products, the necessary intermediate storage of cake to keep both processes running is limited.

The number of cake silos and their capacities are discussed in this paragraph. The number and capacity of the silos depend on the different cakes processed each interval and the ingoing and outgoing flow of cake in cake buffering. Increasing the number of silos and the capacity provides greater flexibility for planning and scheduling but also increases costs. Therefore, the intermediate storage is limited and based on the assumptions made by planning and scheduling, the product mix, and the capacities of the adjacent functions. Furthermore, the number and capacities of the already installed cake silos are reviewed in this paragraph to see if these are fit for the future production system.

6.5.1 Input and output of cake buffering

The ingoing process of cake buffering consists of production cake and imported cake. The input of cake buffering is highly standardized, due to the standardized production runs discussed in paragraph 6.2. The liquor making lines feeding the presses are dedicated to specific liquors. [redacted]

In two days the presses can alternate between the products needed for powder making and in a two-day interval the presses can produce amounts for these products. Therefore, the average flow of cake per two days is chosen. The functions, discussed in the previous paragraphs, and average two-day product flow derived from the product mix are shown in Fig. 6.5 and appendix B.

[redacted]

Fig. 6.5 Functions, equipment and capacities

The productmix shows average quantities per type of cake. The presses are able to produce more than the average demand for the Red 12%, MB 12%, Red 24%, MB 24% and [redacted] [redacted] cakes. The presses are dedicated to a cake type and alternate between these cakes. The maximum production of each press-set for each cake type in the two-day interval is shown in table 6.1. [redacted]

[redacted]

The imported cake is fed to cake storage via dumping stations. The design of the dumping stations is not included in this research. However, some assumptions are made concerning the capacities of the dumping stations, as it is an ingoing process of cake buffering. The capacity of the dumping stations is sufficient to provide the silos with cake when needed. This assumption can be made since the capacity of the dumping stations is limited by pneumatic transport that is able to exceed 4 MT/hour. A container of 20 MT and bags containing imported cake can be fed to cake storage. More than one dumping station is installed in the future situation ensuring continuous import of cake while changing imported cake bags. Two dumping stations make it possible types of imported cake can be imported simultaneously.

In the silos the cake is translated into batches for blending and powder making. The productmix shows that the average amount of batches is 1364/year. The amounts of cake for each type and the corresponding number of batches are shown in table 6.2. For the determination of batches, standardized batch sizes of 20 and 40 MT are used for standard alk and natural batches. For the [redacted] batches the average batch size of these powders in 2015 is used, which is 26 MT.

Table 6.2 average batches for each powder product

	MT	Batches	Average Batches/2days
Low fat alk blend	18697	467	2,7
High fat alk blend	4514	226	1,3
High fat alk (no blend)	2360	118	0,7
[redacted] (no blend)	5000	192	1,1
Natural (no blend)	14430	361	2,1
Total	45000	1364	7,9

On average 7,9 batches every two days are made on the three powder-making lines. On average 4 batches of the 7,9 batches are blended and 4,7 of the 7,9 batches are produced with standard cakes. Thus, the four standard cakes, produced by the presses are used once or multiple times during the two-day interval to establish the blends. Powder making uses cakes from these silos alternately to produce different batches and customer orders. The maximum amount of blended batches processed with two blenders (in line with two powder-making lines) is 6,8 and the maximum amount of batches produced on three powder-making lines in two days is 10,2. The overcapacity of the powder making lines provides flexibility to ensure all the silos are emptied on time while producing customer powder orders.

6.5.2 Dedicated silos

The previous subparagraph showed that on average half of all the powder batches are blended and these cycles are established with standardized cake coming from the presses. These four standard cakes (12% MB, 12%Red, 24% MB and 24%red) are needed to produce blends and represent 75 percent of the total volume of pressed cake. Including standard alk cake directly processed on the powder-making lines on average 4,7 batches of the 7,9 in a two-day interval are made with standard cakes. Furthermore, to produce a single blend of MR 22% powder three to four of these standardized cakes are needed. The cakes in these silos are blended to order, used on a daily basis and often needed simultaneously. Therefore dedicated silos are allocated to store these standard cakes: Red 12%, MB 12%, Red 24%, and MB 24%.

The dedicated silos are replenished before complete emptying. The system allows a silo to be filled and emptied simultaneously. During the two-day period a silo holding a basic cake can be assigned to establish a batch of powder more than once. Alternating the cake production automatically alternates the type batches on blending and powder making, and the dedicated silos that are used to feed cake for these cycles.

Dedicated silos may result in loss of flexibility. However, the assignment of storing product with dedicated silos improves operational simplicity and removing some flexibility does not need to result in decreasing production performance. The presses can continue pressing, maintaining a high utilization. Coordinating standardized pressing batches and standardized powder making batches prevents blockages and starvation. In the remainder of this paragraph the capacity of the dedicated silos, import cake silos, and storage capacity for [redacted] cakes is determined.

6.5.3 Standard Red and MB silos

[redacted] The maximum size is 40 MT, which is equal to the maximum batch size of cake making and powder making. [redacted]

[redacted] The cake silos for 24% Red and 24% MB (9 and 10 in Fig. 6.6) are able to buffer 20 MT of cake produced by the presses in a two-day interval before blending and powder making, which is similar to the standard batch size of powder making.

6.5.4 Import silos

The imported cake consists of alkalized and imported cake. The alkalized imported cake is blended with the four standard production cakes. The natural imported cake is mainly unblended. The imported cake is transported to the factory in containers of 20 MT and or Big Bags of 800 kg. A requirement of the product quality department is that a full container of 20 MT of cake can be emptied in a silo. Two silos of 20 MT each (1 and 2 in Fig. 6.6) are assigned to store imported alkalized cake similar to MB and Red cake for blending. These two silos ensure imported alkalized cake can be fed to the blenders simultaneously. Two silos of 20 MT (3 and 4 in Fig. 6.6) are assigned to store natural cake for the case a natural cake is blended simultaneously with the production of natural unblended cake. The cakes are fed to the silos on a JIT basis.

6.5.5 [redacted] silos

[redacted] cakes are not blended and the production runs of each function depend solely on the customer order. The average batch size of [redacted] is 26 MT and on average every two days one [redacted] cake is processed on the powder making lines. Only partial dedication of the silos is possible and not all of the 40 [redacted] cakes can be assigned a dedicated silo. However, all [redacted] cakes are buffered in two silos assigned to [redacted] cakes of 20 MT each (11 and 12 in Fig. 6.6). These two silos have sufficient capacity to store the average batch size and decouple cake and powder making. There are two silos for [redacted] and [redacted] cakes each with a capacity of 20 MT. Two silos provide more flexibility than 1 silo of 40 MT as with two silos two different [redacted] cakes can be buffered between cake making, and blending and powder making.

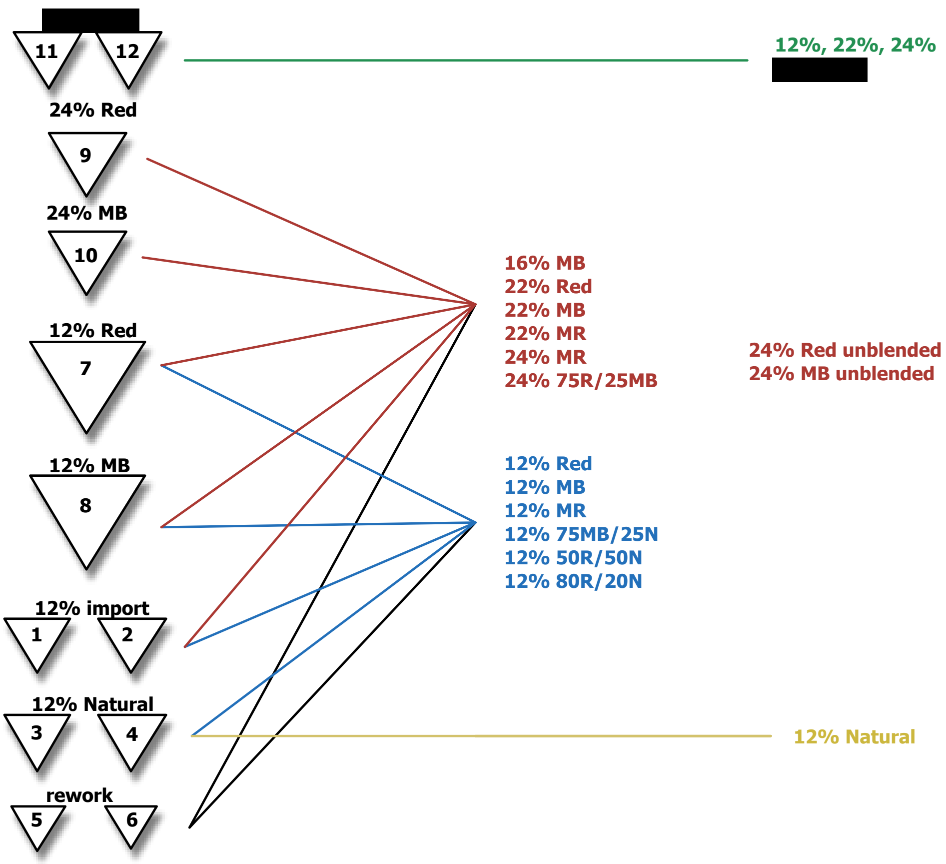


Fig. 6.6 Overview all silos used for production and blended and unblended products.

Silos 5 and 6 in Fig. 6.6 have sufficient capacity to process the rework. The four currently installed cake silos (silo 1 to 4) of 20 MT have enough capacity to be used for the future design. However, these need to function without flow obstructions. Additionally, four silos of 20 MT (A3, A4, A5, A6) and two silos of 40 MT (A1 and A2) are installed to meet the new demand of cake.

6.6 Control

In the previous paragraphs the new strategy and functions of the production system are described. This paragraph will issue the necessary control over the different functions to meet the forecasted output in terms of quality and quantity.

6.6.1 Propermodel

To control the system, we distinguish two types of control. These are function control and process control [4]. The function control controls cocoa processing in order to satisfy the stakeholders of the company, meeting the requirements. This research does not include investigating and adjusting function control. However, the research question is derived from function control, which states that a different type and quantity of product should be produced by a different type of production system. The requirements for the new production system are:

- The expected increased powder output must be realized
- The quality of the blended cakes must be controlled

Function control initiates standards for the production system and evaluates results, but does not react to disturbances. Process control controls each function within the production system with the occurrence of disturbances on the production process level. Process control uses feed forward and feedback control. Feed forward measures the disturbance in the input of a function or during throughput. The intervention can take place upstream or downstream of the measurement. Feedback is used to measure the output, the consequence of the disturbance, and intervention takes place upstream [4].

Fig. 6.7 shows the control functions and the three aspects it controls. The order flow and product flow are already discussed in this chapter. The resource flow, containing people and means, is added at the bottom. The resource flow contains the equipment needed for the functions blending, powder making and storage. These resources are discussed in the previous paragraphs as functions and further examined in the next chapter bulk solid equipment. The model in Fig. 6.7, containing the order, product, and resource transformation is called the process performance model, or Propermodel [4]. In Fig. 6.7 the function control providing standards to and evaluating results of the order, product and resource flow is shown at the top.

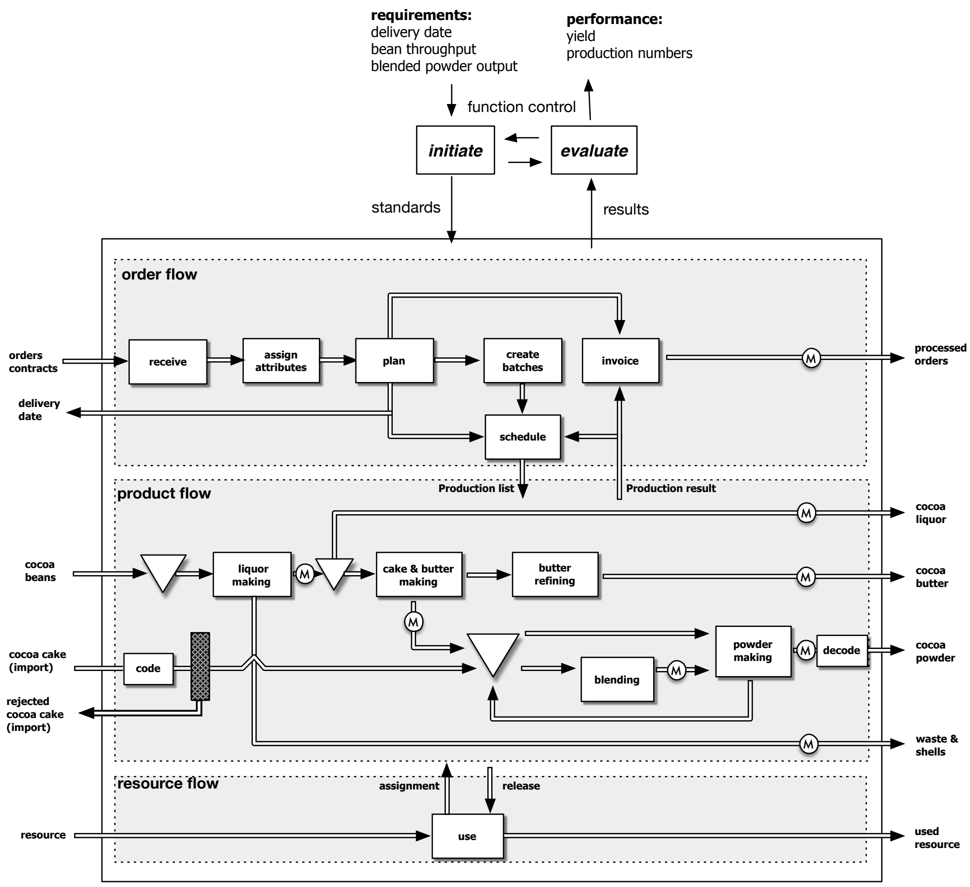


Fig. 6.7 Propermodel showing the order, product and resource flow

The Propermodel is used to clarify and define the interaction between the aspects order, product and resource flow. The remainder of this paragraph uses the Propermodel to describe the physical flows inside the function cocoa processing and the information flows used for production and control.

6.6.2 Quantity and quality control

In the new production system, the standards are set to 50 MT of liquor, 25 MT of cake and 45 MT of powder for each production shift of 8 hours. Because the employees and the shift leaders are responsible for the realization of these standards it is important that they accept these [9]. In the new production system, liquor making and cake making are highly standardized and blending and powder making alternates between batches of high fat and low fat on the three powder making lines, ensuring constant standards provide an unambiguous picture of the performance.

The schedule dictates the sequence and amounts for each production step and is used to initiate actions. All the products in the sequence should be made within the week since the planned amount is feasible. Scheduling the products alternately ensures that the powder making lines empty the silos in order to store a new batch of cake from the presses. And that the powders are made on time to fulfill orders. The performance of all the functions is measured and compared with the schedule. Unfulfilled orders are postponed and scheduled for next week. There is overcapacity available to produce some of the products of the preceding week if due to unforeseen circumstances the production was below standard. The source of the disturbance causing the unforeseen daily in products must be investigated and eliminated ensuring the process stays in control. The investigation can also show the problems are on the level of function control. For example infeasible standards used in the production process.

Rescheduling takes place in the current production practice if a liquor or cake is not available for processing or can be processed before the schedule states. In the new situation liquor making is highly standardized as well as pressing of the liquor into cake and butter. This ensures that the intervals and quantities of cake making are predictable and less influenced by disturbances. The result is that rescheduling of cake making is not daily practice anymore preventing this type of decision-making that disrupts the weekly schedule.

The liquor destined for blending cakes is made in cycles on a weekly forecast. The production sequence and the level of liquor in the tanks trigger the production of liquor making for standardized cocoa. Dedicated liquor tanks for Red and MB ensure that liquor is always available and can be fed to the presses when needed.

Using standardized batches makes it easier to evaluate the production schedule and to examine where problems occur. In combination with the downtime analysis, the production process is evaluated in order to improve it.

After cake breaking a sample of cocoa cake particles is taken. The sample is measured and if the fat percentage deviates from the standard, the duration of pressing is adjusted to increase or decrease the residual fat percentage in the cake. This feedback control loop already exists in the current production system and is graphically shown in Fig. 6.8. Deviations in the duration of pressing, and thereby capacity in MT/hour, is also measured and evaluated by function control.

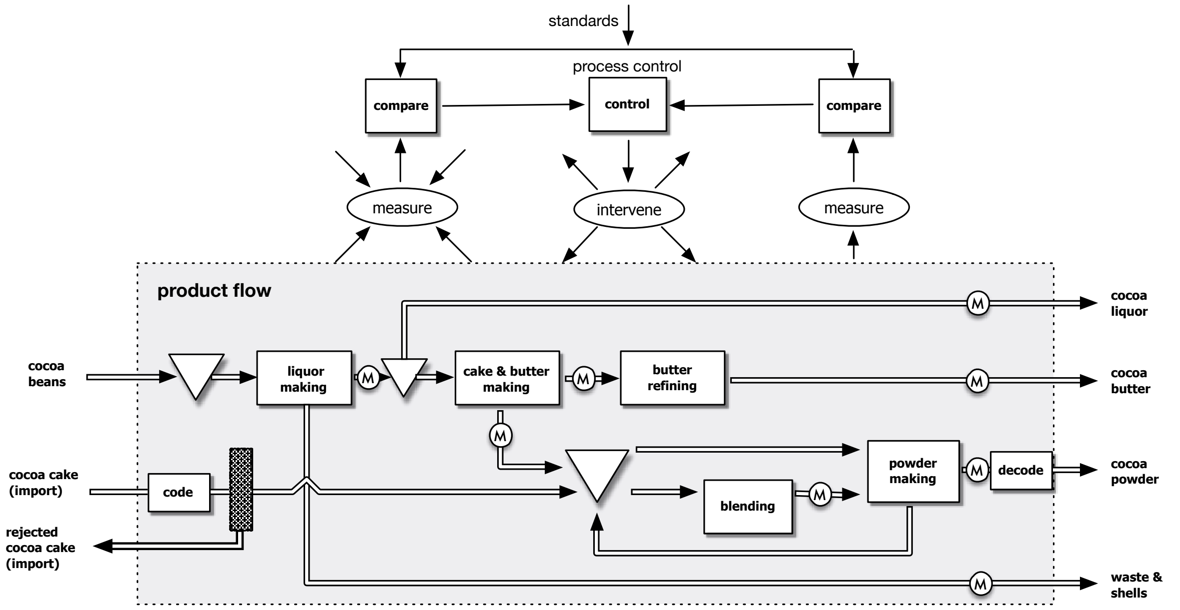


Fig. 6.8 Product flows and process control. The feedback loop of process control is used to control the quality of the cake after pressing and blending.

The imported cocoa cake is measured to determine if the delivered product meets the quality standards. The quality filter of cocoa cake is depicted in Fig. 6.8. Furthermore, measuring the input flow of cake is used to finalize the blend ratio.

After blending, a sample is taken to see if it meets the standard. Process control intervenes by adjusting the blend ratio and or blending duration if the standard is not met. For the sampling procedure, Allen (1981) proposes two golden rules of sampling: samples should be taken from a moving stream and samples should be randomly taken from throughout the whole mixture [17]. Sampling takes place during discharge of the blender or with a lance inside the blender. The feedback loop of process control adjusts the blend ratio and blending times when the output does not match the standard. The smaller the deviation from the standard, the better is the mixture. For sampling, the sample size, the number of samples and the sampling procedure are important. The size of the sample should match the scale of scrutiny of the mixture. That is the amount of material at which homogeneity is desired and should meet the application in which the mixture is used [18]. If the chosen sample size is small, one must take many samples to reduce the uncertainty in mean mixture. In practice, the number of samples is limited by the capability of analyzing the sample [18].

The quality filter for powder is situated inside the function powder making. If the cake does not meet the standard, the cake is rejected or is reworked. The decode function after powder making labels the pellets containing powder bags and adds transport documents.

6.6.3 Resource flow

The resources needed for the production flow need to be assigned to the product flow. Resources that are used in the production process include energy, people and production equipment. Just like the other aspects, standards are issued to the resource flow and output is measured to control the resource flow. These standards, for example electricity used in the production process are not further investigated in this research. The equipment and the design of the equipment used in the production process are examined in the next chapter.

6.7 Summary of the future system design

To summarize, the redesign of the cocoa production process consists of a new production strategy and additional equipment.

Based on strategic principles and improvements:

- Postponement of product differentiation
- Move CODP to cake silos
- Standardization of liquor and cake making
- Limitation and standardization of batch sizes
- Alternating orders
- Assign dedicated silos to basic products
- Differentiation of the function blending
- Quality and quantity control

Equipment:

- New powder making line
- Big Bag filler
- Two blenders
- Four cake silos of 20 MT and two cake silos of 40 MT

7. Bulk handling equipment

In the previous chapters the current production system is analyzed and the specifications of functions for the new product flow are determined. This chapter zooms in on the resource aspect and the equipment that is assigned to the functions cake storage and blending.

As mentioned in the analysis, a common problem in the production system is the obstruction of flow from the cake silos. In chapter three several causes for the downtime due to cake storage problems are mentioned. This chapter first examines the flow properties of cocoa cake by measuring samples of cake in a Ring shear cell tester. The test results give insight in the aspects affecting the flow behavior of cocoa cake. These results are further used in this chapter for the design of silos to store cocoa cake. The expense to measure the bulk solid properties that are necessary for the design of the silo is small compared to the costs arising due quality problems, shutdown, adjustment and replacement of the silo [11].

The analysis also showed the problems that occur with the current blending method and the lack of blending equipment.

The first paragraph of this chapter provides theory and information on testing flow properties of bulk solids. In the second paragraph, the input of the experiments is discussed. The third paragraph shows the results of the experiments and the influence of the aspects on the flow behavior. The outcome of the cocoa cake tests, the capacities of the silos determined in logistic chapter 6 and proven design procedures found in Powders and Bulk Solids [11] are used to determine the appropriate geometry of the silos in fourth paragraph. In paragraph 7.5 the current silos are reviewed using the knowledge of the cocoa cake measurements and the silo design principles. In the last paragraph of this chapter, a choice is made for the blending equipment.

7.1 Flow properties testing of bulk solids

The difference between a fluid and a bulk solid is that a bulk solid can build up strength when a consolidation force is exerted on it. This has a huge impact on the handling of bulk solid materials. Different bulk solids show different flow characteristics when forces are applied on them and therefore measurements are conducted to gain knowledge about the bulk solids. Since, the literature does not contain any research regarding flow characteristics or shear cell measurements of cocoa cake, cake is tested on a computer-controlled Ring Shear Tester RST-01.pc at Delft University of Technology.

The test procedure simulates the behavior of cocoa cake inside the silo. The cocoa cake is compacted first (preshear), like cake that is consolidated in a silo. After that, the cake inside the test ring is sheared under a lower smaller normal stress until the specimen fails and incipient flow occurs [19]. This yield limit of a bulk solid at a certain consolidation stress is shown in a yield locus, like the example in Fig. 7.1. The graph also shows Mohr stress circles representing the normal and shear stress in one particular cutting plane of a bulk solid specimen. The center of each Mohr stress circle is located at the σ-axis and the intersections of the Mohr stress circle and the σ-axis show the major (vertical) principle stress and minor (horizontal) principle stress.

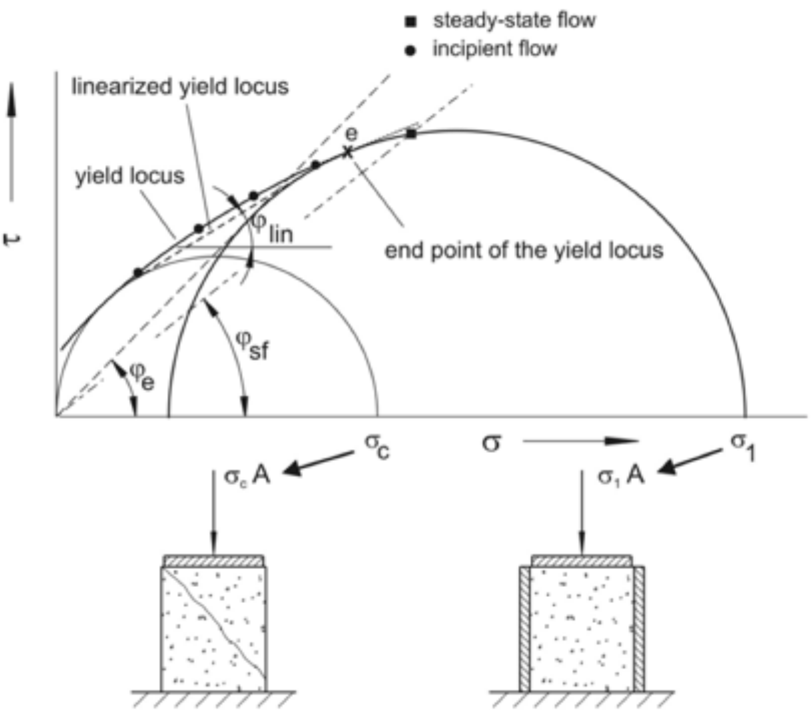


Fig. 7.1 Yield locus and principle stresses [19]

The major principle stress of the larger Mohr stress circle represents the stress state at steady state flow, which is the major consolidation stress (σ_1 in Fig. 7.1). The major principle stress of the smaller Mohr stress circle represents the unconfined yield stress (σ_c in Fig. 7.1). This is the stress that causes flow, located on the Mohr stress circle with a minor principle stress through the origin.

If the magnitude of consolidating is changed, a different yield locus appears. With several different yield loci, a flow function (FF) is established. The FF is the relationship of the major consolidation stress (σ_1 in Fig. 7.1) and the unconfined yield stress, the stress that causes flow (σ_c in Fig. 7.1) [11]. The flow function shows the flow behavior of a bulk solid material and can be classified as not flowing, very cohesive, cohesive, easy flowing, and free flowing. The flow behavior and an example of a flow function (A) is shown in Fig. 7.2

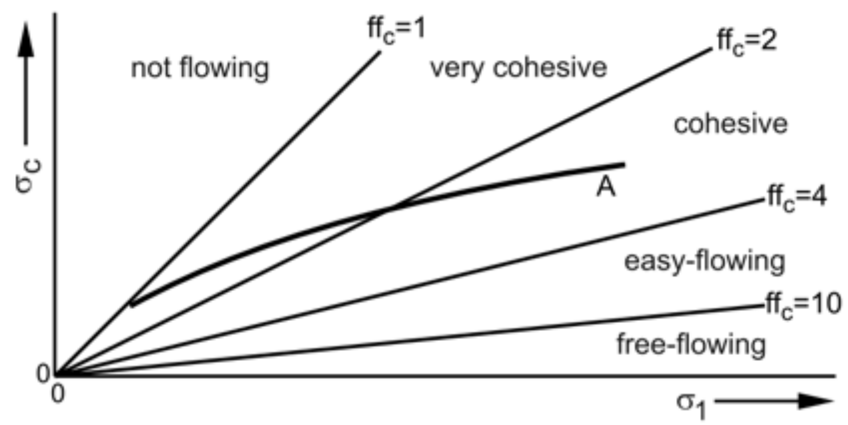


Fig. 7.2 flow behavior bulk solid materials [11]

The flow ability ratio (ffc) is used to characterize the flow ability numerically. It is the ratio between the consolidating stress and the unconfined yield stress [11], shown in Fig. 7.3.

$$ffc = \frac{\sigma 1}{\sigma c}$$

Fig. 7.3 Flow ability

7.2 Measurements of cocoa cake

Cocoa cake, especially the fat cake, can be sticky and it is expected to be a cohesive bulk solid material. With cohesive bulk solid materials problems during storage and handling are likely to occur. The measurements in this paragraph need to verify if the cocoa cake is cohesive and which aspects influence the flow behavior. The theory from the previous paragraph and the mentioned aspects, fat percentage, temperature, and particle size that might influence the flow behavior are used to set up the shear cell measurements.

The fat percentage is the first aspect that is tested. The low fat and fat cake are both heated to 30-35° Celsius and tested. At this temperature the butter inside the cake is melted [12]. This temperature range resembles the temperature of the cake, after the cooling step, when it is transported to the cake silos. The expectation is that a higher fat percentage increases the cohesiveness of the cakes.
The low-fat and fat cakes are also tested on a higher temperature to see if the cake behaves differently at a temperature above 35° Celsius. For this higher temperature, the cake is heated to 55° Celsius resembling the highest temperature measured inside the cake storage room. Above this temperature the transport of cake to the silos is stopped. The low fat cocoa cake is also tested at 19° Celsius, with solidified butter to simulate the behavior of low fat imported cake. The expectation is that a higher temperature increases the cohesiveness of the cakes.
Finally, the influence of the aspect particle size is tested. The particle size is important for handling bulk solid materials and can be influenced in the production process, for instance by adjusting the hammer mills that break the cake after pressing. The influence of the particle size on the flow behavior is tested by comparing cake samples with particles up to 8 mm with samples of cake containing particles that are not larger than 1 mm. The expectation, based on literature [11], is that a smaller particle size increases the cohesiveness of the cakes.
If a bulk solid is stored for longer periods of time, time consolidation effects (caking) might occur increasing the strength of the bulk solid material. Additionally, time consolidation tests are performed to see if this phenomenon can affect flow behavior during production.

Since the flow ability of the bulk solid depends on the stress level, appropriate stresses for the yield locus tests have to be selected. It is important to use consolidation stresses that are similar to the actual stresses inside the silo. Unlike fluids, the horizontal stress is less than the vertical stress due to the wall friction [11]. The stresses in a silo depend on the height-to-diameter ratio, the roughness of the wall and the state since stresses are different during filling and emptying. For calculation of the appropriate stresses in the vertical part of the silo Janssen's equation [11] is used, shown in Fig. 7.4. For calculations of stresses in the vertical and hopper section of the silo, the stress tool provided by Schulze [20] is used.

$$\sigma_v = \frac{g\,\rho_b A}{K\ \tan\varphi_x U} \cdot \left[1 - e^{\frac{-K \tan\varphi_x U z}{A}} \right]$$

Fig. 7.4 Janssen's equation for the calculation of stress in the vertical section of the silo

For comparative tests identical stresses for normal and preshear are chosen. If the variables, like consolidating stress, are held constant the influence of the temperature, the fat percentage and the particle size of the cake can be determined. During the shear cell tests, normal stresses should not be greater than 80% of the normal stress at preshear. The lower limit of normal stress is specified to be 30% of the preshear, which represents a slightly cohesive or cohesive bulk solid material. [11] The third middle point of the yield locus is the mean value of the lowest and highest normal stress.

The stresses are a result from gravity acting on the bulks solid and depend on the bulk solid density and the mass of the bulk solid in the silo. The bulks solid density is always less than solid density, due to the voids between individual particles of a bulk solid [11]. To determine the appropriate stresses in the silo table 7.2 is used.

TABLE 7.2 CONSOLIDATION STRESSES APPLIED TO BULK SOLIDS FOR DIFFERENT DENSITIES [11]

bulk density ρ_b [kg/m^3] from... to	0 ... 300	300 ... 800	800 ... 1600	1600 ... 2400	> 2400
lowest consolidation stress $\sigma_{1,min}$ [kPa]	ca. 1	ca. 2	ca. 3	ca. 4	ca. 5

The bulk density lies in the range of 300-800 kg/m^3. The smallest consolidation stress is therefore 2 kPa. To determine the flow function 3 to 4 yield loci are measured, with consolidation stresses around 4, 8 and 16kPa. During the shear cell experiment multiple yield loci for each aspect are measured in this range. An overview of the tested cakes and aspects is found in table 7.3

TABLE 7.3 TESTED CAKES AND ASPECTS

	Temperature (°Celsius)	Particle size	Time consolidation
Low-fat cake 12%	19, 30-35 and 55	-	-
Fat cake 24%	30-35 and 55	<1 mm	18 hours

7.3 Results

In this paragraph the results of the Ring shear cell measurements are discussed. In order to expose the influence of the aspects fat percentage, temperature, and particles size the yield loci of the measured cake samples are analyzed in the subparagraphs. Furthermore, the wall friction angle is measured to simulate the interaction between cake and silo wall. In the presented yield loci in this paragraph, the useful information, to assess the flow behavior and bulk solid characteristics is added in the top of the figures. From the yield loci the following information is derived:

- σ1: Major consolidation stress (shown in Fig. 7.1)
- σc: Unconfined yield stress (shown in Fig. 7.1)
- FFC: Flow ability ratio (Fig. 7.3)
- RHOB: Bulk solid density (in kg/m^3)
- φ-e: Effective angle of internal friction (shown in Fig. 7.1)
- φ-lin: Slope angle of linearized yield locus (shown in Fig. 7.1)
- φ-sf: Angle of internal friction at steady-state flow (shown in Fig. 7.1)

7.3.1 Fat percentage

The first aspect that is considered is the fat percentage of the cake. The low fat and fat cakes are tested at the same temperature, to see if the fat percentage influences the flow behavior. The yield loci, presented in Fig. 7.5, show that a cake with a higher fat percentage (24%) has a lower flow ability ratio (ffc) and is more cohesive than a low fat cake (12%).

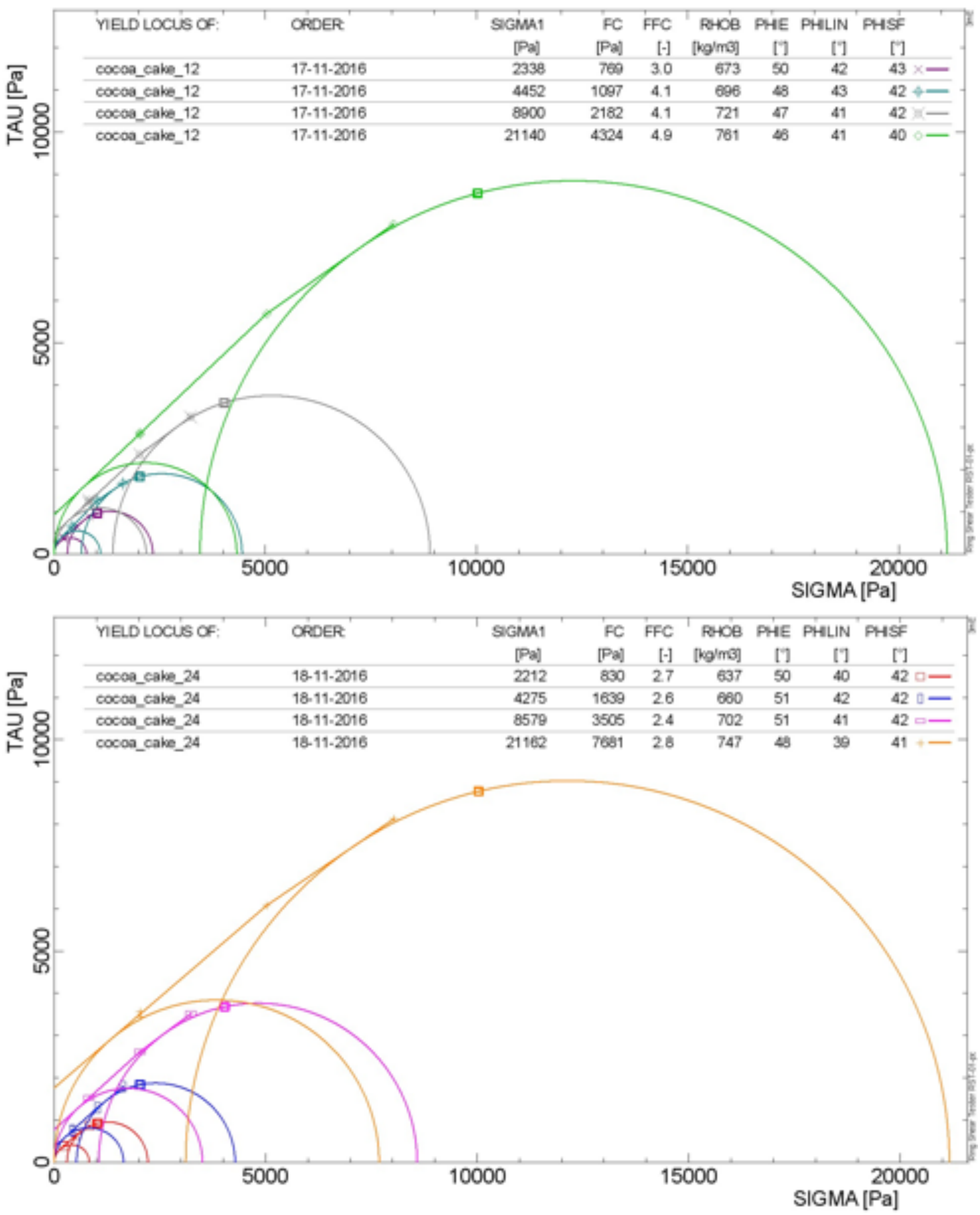


Fig. 7.5 Aspect fat percentage

7.3.2 Temperature

The influence of the temperature on the flow behavior of the cake is tested next. The 12% cocoa cake at 19 °C, with solidified butter, showed different results than 12% cocoa cake heated to 35 °C. This is shown in figure 7.6. Cold imported 12% cocoa cake is freer flowing than heated production cocoa cake.

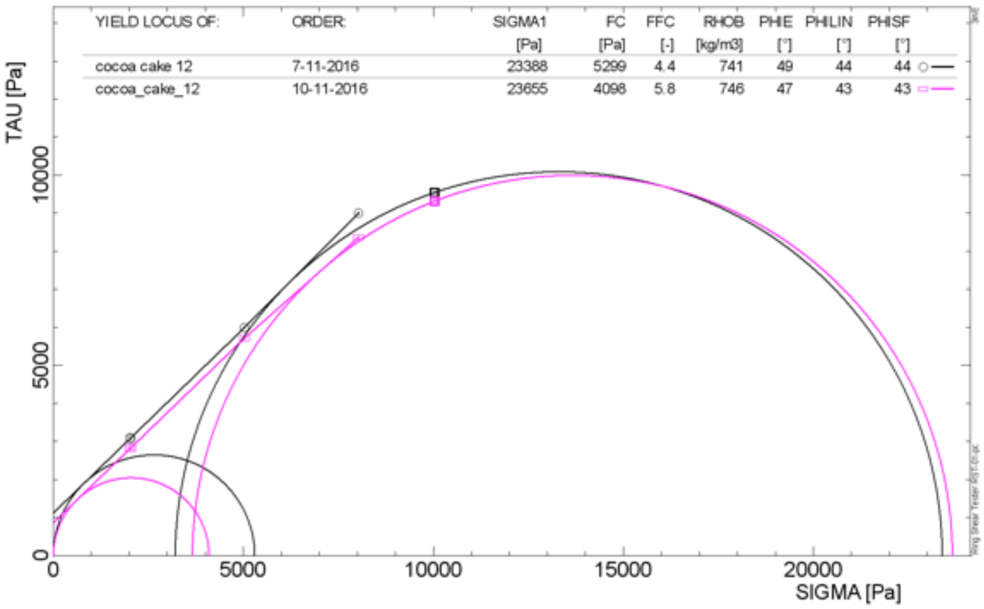


Fig. 7.6 Aspect temperature low fat cake

Cocoa butter melts in the temperature range of 23 to 36 °Celsius [12]. After breaking, the cake is cooled to a temperature of 30-35° Celsius, but it is not uncommon for the temperature inside the silo room to reach 55° Celsius. Low fat and fat-cakes are tested in the range of 30-35 °C and 50-55 °C to examine the influence of different temperatures to the flow ability of the cake.

The cake is heated to 35 °C and 55 °C in a controlled oven, to melt the butter in the cake.
The difference between fat cake heated up to 55 °C (black) and 35 °C (red) is shown in Fig. 7.7 below.

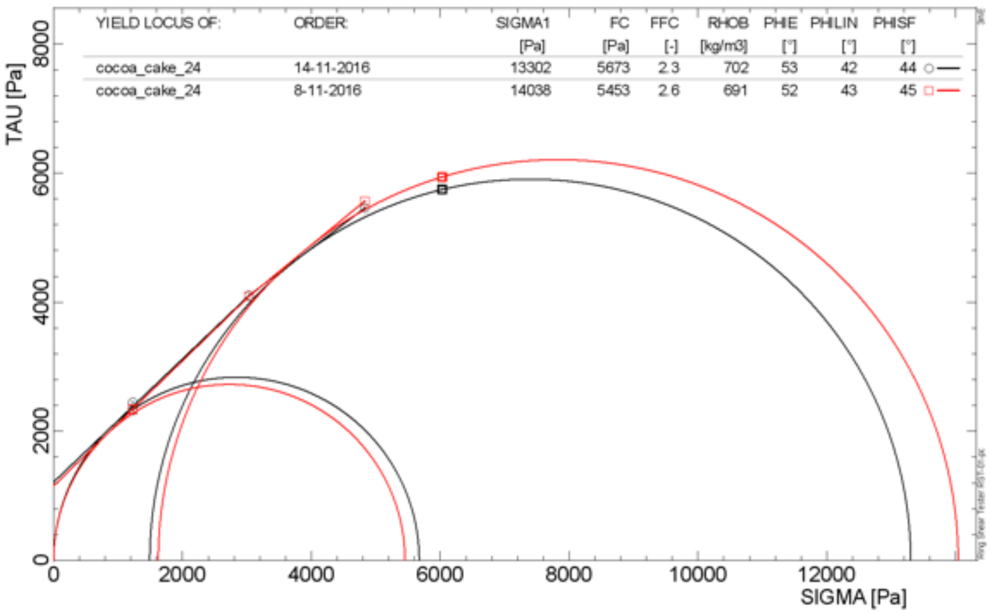


Fig. 7.7 aspect temperature high fat cake

The tests show minor differences in flow behavior for the cakes tested at 30-35 °C and 50-55 °C. At both temperatures one can assume that the butter inside the cake is liquid and therefore shows similar flow behavior. This can be seen in the overview of flow functions in Fig. 7.9

The shear cell ring with which the tests are conducted, is not temperature controlled. The samples are heated to 35 °C or 55 °C, tested and temperature is measured again after the test. During the tests the temperature of the surface of the cake dropped on average 2 °C, so the sample is not tested at a specific constant temperature. However, product specialists of [redacted] ensure that the solidification of butter does not occur during the time it takes to perform the measurements. Liquid bridges can affect the flow properties and might worsen flow behavior for fat cakes [21]. During the tests a sample with a higher temperature showed more stick-slip behavior.

7.3.3 Particle size

The influence of adhesive forces increases when the particle size of the bulk solid decreases[11]. Due to limitations of the shear cell tester, only particles smaller than 10 mm can be tested and the tested samples contain cake up to 8 mm. In reality the is more free flowing, as cake particles up to 6 cm are transported to the cake silos.

To show the influence of the particle size, another flow function is established by measuring yield loci for fat 24% cocoa cake samples containing cake particles equal or smaller than 1mm. The tests show that cake particle sizes smaller than 1mm are far more cohesive than measured cake in the range up to 8mm. The flow function of 24% fat cake established with samples containing particles smaller than 1 mm is added in Fig. 7.9.

7.3.4 Time consolidation

It is possible that cake is buffered some time before processing and therefore time consolidation effects are investigated. To examine possible time consolidating effects, a ring shear cell containing a sample of cake is placed inside an oven for a period of time. To simulate the conditions of cake inside the silo, a load is exerted on the top lid of the shear cell. The weight on the sample, 30,7 kg, corresponds to sigma 1 and is calculated with the help of the RST controller. The temperature inside the oven resembles the temperature inside the cake silo room of 55 °C.

To see if time consolidation or caking effects occur the sample has to be stored for the same period of time resembling the time the bulk solid is stored in the application under consideration. As these tests are time consuming and the cake is not stored for a specific amount of time, a general time consolidation test is performed with duration of 15,5 hours. The actual total time inside the oven was 18 hours. The unconfined yield stress did not increase after storing for 18 hours. This is important for production, as the bulk solid does not show any increase in strength after storage for longer periods of time. The result is shown in Fig. 7.8.

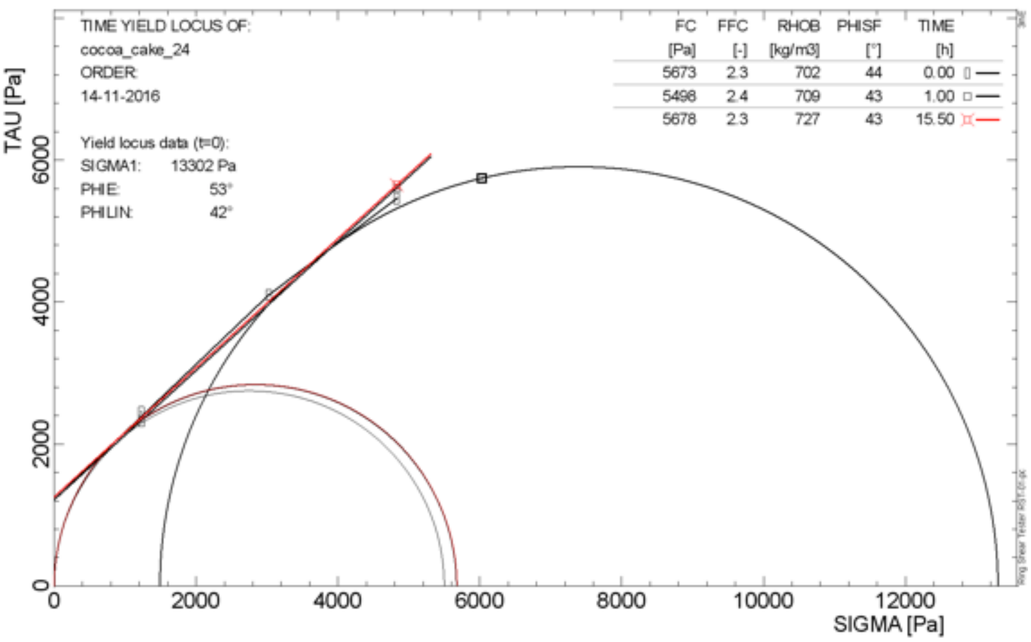


Fig. 7.8 Aspect time consolidation

7.3.5 Overview flow functions

A summary of all flow functions, established with the measured yield loci, is presented in Fig. 7.9. Straight linear lines are drawn through the points of the yield loci. The applied consolidation stress does not seem to alter the slope of the flow functions. The linear functions are used in chapter 7.4 to determine the minimum critical diameter of the silo outlet.

The results show that cocoa cake 12% heated and cold are in the easy-flowing region while 24% cocoa cake is categorized as cohesive. The 24% cocoa cake with particles equal or less than 1 mm is very cohesive. Cakes heated to 35 °C or 55 °C show similar behavior.

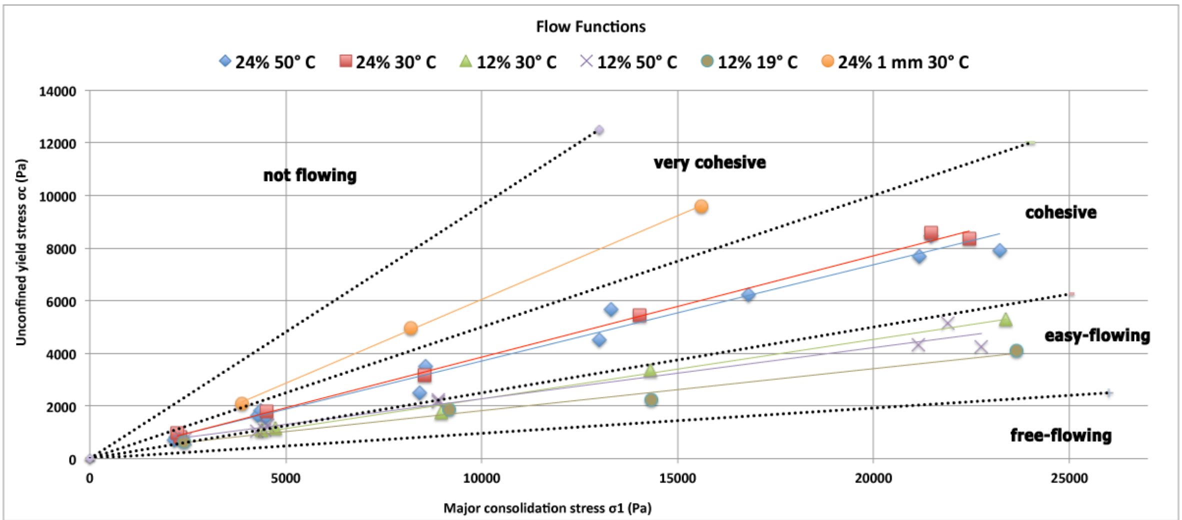


Fig. 7.9 Overview flow functions

7.3.6 Wall friction angle

The internal friction angle is derived from the cake on cake measurements. The wall friction angle is the relationship between normal stress acting between the cake and a solid surface, like a silo wall, and the shear stress under flow conditions [22].

Unlike the cake-cake tests, the literature does contain research on the interaction of cocoa powder and stainless steel. Cocoa powder low fat 10/12% powder and fat 20/22% powder are tested on wall material in the temperature range of 20 – 50° Celsius [21]. The relationship between the temperature and measured wall friction angle, for polished stainless steel 1.4571, is shown in appendix C. As seen in [21], cocoa powder containing more fat shows a lower wall friction angle in the temperature range of 20-40° Celsius. The literature states that the fat content has a lubricating effect when it is still solid. However, when the temperature rises, the butter melts and this decreases the flow behavior. This result is also seen in the cake-cake tests, comparing cold cocoa cake 12% cake and heated cocoa cake 12%. The viscosity of the butter at 50° Celsius is low and liquid bridges can degrade easily for powders with low fat (butter) percentages. For the powder with the higher fat content, the butter escapes the powder and is able to build bridges worsening flow behavior [21]. That would explain the higher wall friction angle for 20/22% powder compared with the 10/12% powder. Since the temperature is important for the interaction of cocoa powder and wall material, it is also expected to influence the wall friction angle for cocoa cake.

For the wall friction tests, a test ring is made out of hot-rolled SA2.5 steel (Fig. 7.10), which is the same material as the inside wall of the silos currently in operation at [redacted] The measurements simulate flow of cake across the silo wall and the corresponding wall friction angle. The internal friction angle and the wall friction angle are used to determine the conditions of flow in the next paragraph.

Fig. 7.10 Hot-rolled SA2.5 steel ring shear sample

The wall friction is measured at normal stresses similar to the stresses acting between wall surface and the cake inside the silo [11]. Since wall friction angle might be stress dependent, the normal stress is varied. For each test, six or nine normal stresses are applied, shown in Fig. 7.11. The low fat 12% cakes are tested at 19° Celsius (cold imported cake), 35° Celsius, and 55° Celsius. The fat cake is tested at temperatures of 35° and 55° Celsius. Fig. 7.11 shows the results for 55° Celsius 24% cake. The red line in the right graph of Fig. 7.11 shows 24% cake with particles smaller than 1 mm).

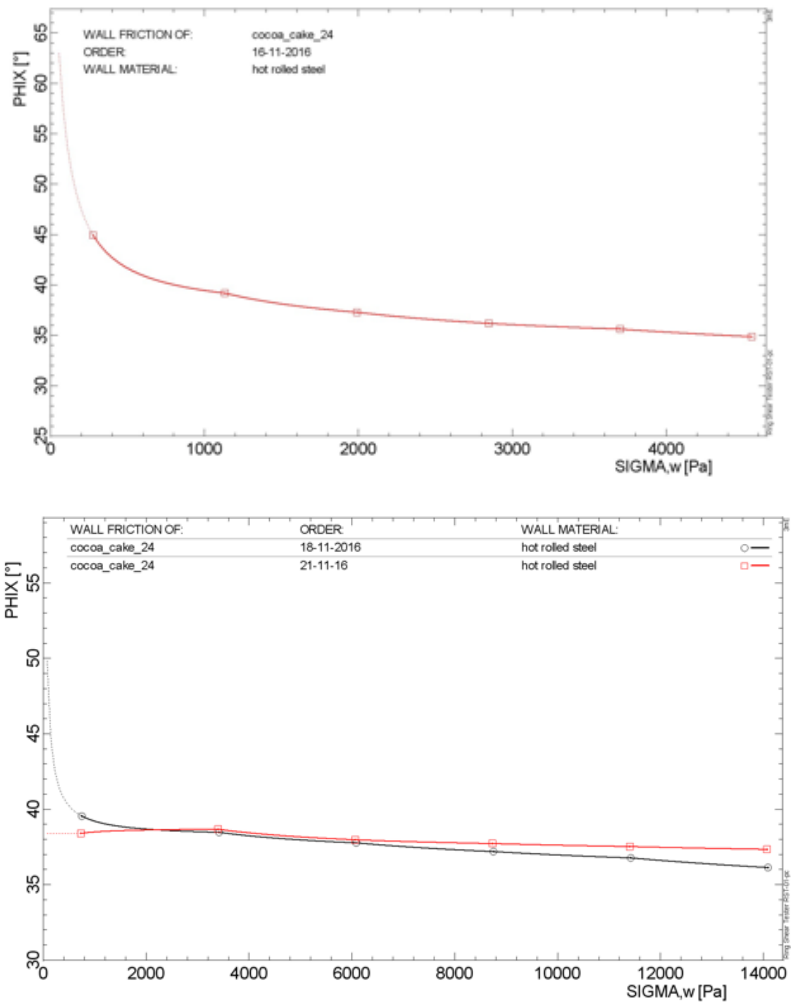
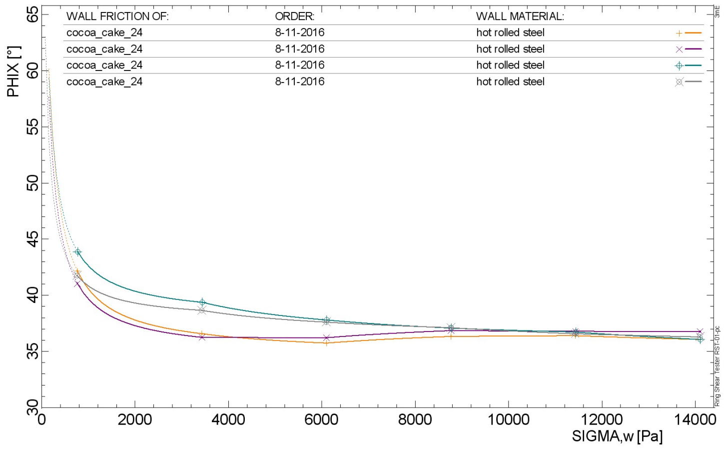


Fig. 7.11 wall normal stresses and angles

Fig. 7.12 shows 24% cocoa cake heated to 35 °C and 55 °C. The purple and yellow lines are samples heated to 35 °C, the green and grey lines are samples of cake heated to 55 °C before testing. The wall friction angle of the 55 °C cakes is slightly higher than cakes tested at 35° Celsius.
Fig. 7.12 also shows the 12% cake heated to 35 °C and 55 °C. The red and black lines are samples heated to 35 °C, while the blue and pink lines are samples of cake heated to 55 °C before testing. The test show that the wall friction angle for 12% cocoa cakes heated to 35 °C are slightly higher than for 12% cocoa cakes heated to 55° C.



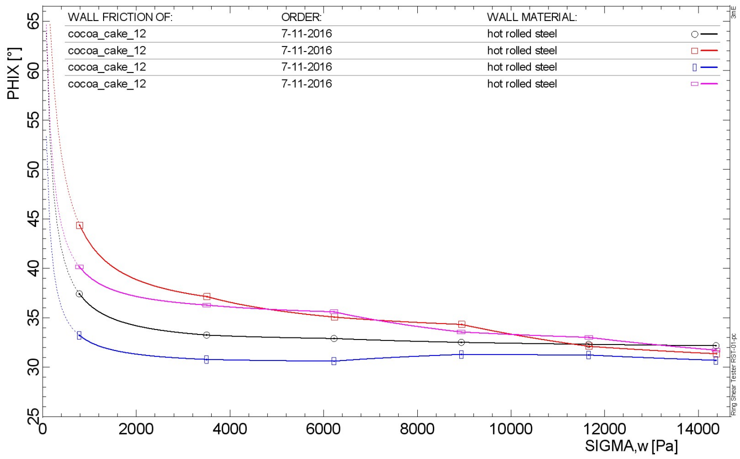


Fig. 7.12 Wall normal stresses and angles 24% cake (top) and 12% cake (bottom)

Testing 12% low fat cold cocoa cake shows the lowest wall friction angles. The wall friction angle for 24% cocoa cake is on average slightly higher than the wall friction angle for 12% low fat cake.

7.4 Design of storage equipment

The bulk solid properties determined in the precious paragraph, are important for either small scale or large-scale bulk solid handling equipment, as the basic processes are the same [11]. The outcome of the cake measurements, the information from cake storage paragraph in the logistic chapter, and design principles presented by Schulze [11] are combined in this paragraph to design silos that are capable of storing 20 and 40 metric tons of cake.

Flow inside the silo can be classified as mass flow, funnel flow or a combination of both called expanded mass flow [11]. The goal of the design procedure is to design a silo that promotes mass flow, in which all the bulk material inside the silo is in motion. In contrast with a mass flow silo; in a funnel flow silo the material close to the silo axis flows out of the silo first while product in the stagnant zone is not in motion. It is even possible that the material in the stagnant zones never leave the silo resulting in product degradation and contamination with other batches. The mass and funnel flow patterns are shown in Fig. 7.13.

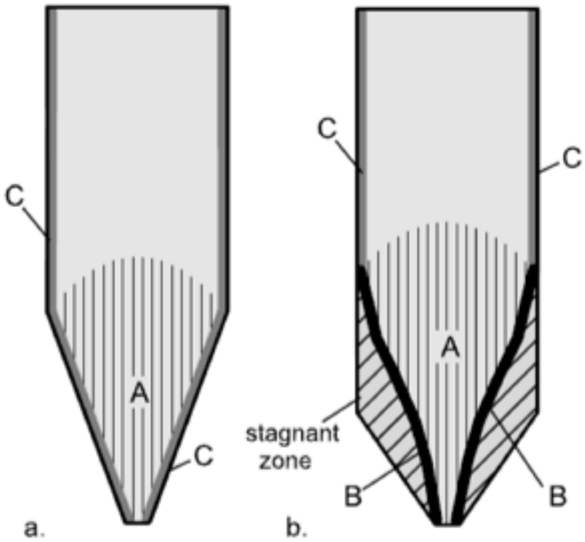


Fig. 7.13 Mass flow (a.) and funnel flow pattern (b.) [11]

When cake is blown into the silo, segregation takes place due to segregation mechanisms like fluidization and momentum [18]. Due to momentum, fines will remain closer to the silo axis and coarse material will gather near the silo wall. Mass flow is the preferred flow patterns for this design as it aids in remixing the segregated cake. In a mass flow silo all the material is in motion, so the fines and coarse particles will remix close to the outlet opening. Mass flow ensures the first in first out principle is met, preventing ageing of material inside the silo and making it suitable for traceability. That is, one can approximate when cake, which has been fed at the top, emerges from the silo at the bottom, making it possible to distinguish different cake batches while replenishing silos with cake.

The flow pattern, mass or funnel, inside a silo depends on the bulk solid material, the silo wall material, and the geometry of the silo. Funnel flow can be caused when the hopper wall angle is too small and or when the hopper wall material is too rough [11]. In a funnel flow silo the core will exit the silo first, followed by the stagnant zones resulting in product segregation. Another disadvantage of funnel flow silos is the material that is fed may not have the time to de-aerate and will flood out of the silo causing a lot of dust and flooding of the feeder [11].

7.4.1 Hot-rolled sample

The silo is designed to achieve a mass flow pattern and to let the bulk solid flow due to the force of gravity. The bulk solid flows out of the silo and hopper if the stresses acting on the bulk solid are larger than the strength of the bulk solid. For the design of the silo the cake with the worst flow ability (heated 24% cocoa cake) is chosen. If the silo is designed for the storage of this cake, it is also suitable for storage of the other cakes.

As stated earlier, the bulk solid material, the wall material, and the silo dimensions influence flow inside the silo. The bulk solid material and the wall material are tested with the shear cell, to determine the internal friction angle and wall friction angle. The internal friction angle, φ_e, is derived from the yield loci and is 50°. The wall friction angle, φ_x, is 37°. This is the highest wall friction angle for cocoa cake 12% heated (35 °C and 55 °C) and cocoa cake 24% heated to 35 °C. The critical cone angle, Θ_c, of 8° does not include a safety margin correcting for errors in the establishment of this angle. Including a safety margin of 2-3° [11], the critical cone angle is 6°. Applying these results in Fig. 7.14, the critical cone angle to promote mass flow, is obtained. The silos is not designed for 24% cocoa cake heated to 55 °C (similar to the temperature in the cake storage room) as the wall friction angle of 40°, results in a cone angle of 0°.

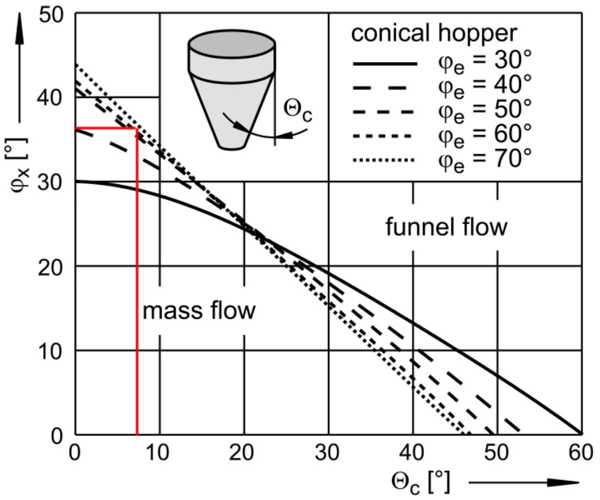


Fig. 7.14 Determination of the critical cone angle for a wall friction angle of 37° and an effective angle of internal friction of 50° [11]

Flow problems usually occur close to the outlet opening, where especially in the passive (discharge) state stresses are small and independent of the filling height [11]. For the flow in the hopper, the hopper flow factor (ff) is used. This factor, relates the stresses developed at a particulate solid in the converging part, at the point of discharge, with the consolidating stress acting in a hopper (ff = σ_c / σ_D) [22].

The flow function (FF) depends purely on the characteristics of the material. It is the relationship of the consolidating stress and the unconfined yield stress at which flow occurs. A high value of the flow function (FF) means high flow ability. The hopper flow factor (ff) depends on the material and the geometry, representing the relationship between the consolidating stress and the developed stress in the hopper. In contrast with the flow function, a high value of the flow factor means low flow ability.

The hopper flow factor is obtained using the wall friction angle of, the critical cone angle (Fig. 7.14), the internal friction angle. For a wall friction angle of 37°, a cone angle of 6°, and an internal friction angle of 50°, a hopper flow factor of 1,2 is obtained in figure 7.15.

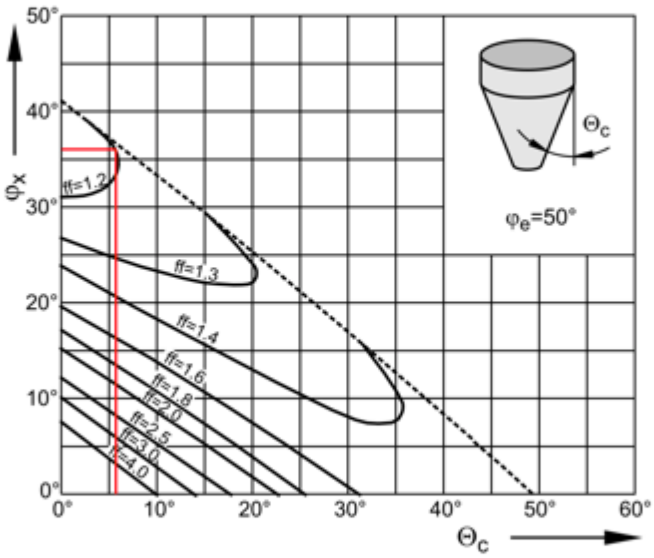


Fig. 7.15 Relationship of cone angle, wall angle, internal friction angle, and hopper flow factor

Combining the design principles and the bulks solid properties, the critical cone angle (**Θ_c**) and the hopper flow factor are determined. The cone angle can be used directly in the design of the silo, as it is the angle between the vertical part of the silo and the hopper. This is shown on the top right in Fig. 7.15. Bulk solid materials can form cohesive arches as a result of consolidation and inter-particle adhesive forces [11]. The hopper flow factor is used in silo design to determine the diameter of the outlet opening, which is sufficiently large to prevent arching.

In order to find the minimum diameter of the outlet opening the flow function and hopper flow factor are plotted in one graph (Fig. 7.16). The point of intersection of the flow function and the hopper flow factor gives the critical values for developed, unconfined yield and consolidating stress. The critical values represent the flow properties at the outlet opening of minimum (critical) dimensions to avoid arching [11]. If the developed stress exceeds the yield stress, the material flows: $\boldsymbol{\sigma_D > \sigma_Y}$. The flow function of cocoa 12% 55° Celsius is chosen as it yields the highest critical stresses at the point of intersection with the line representing the hopper flow factor. The intersection of the flow factor (ff) and flow function (ffc) shows the transition from a stable arch, left of the intersection, to a guarantee of flow, right of the intersection.

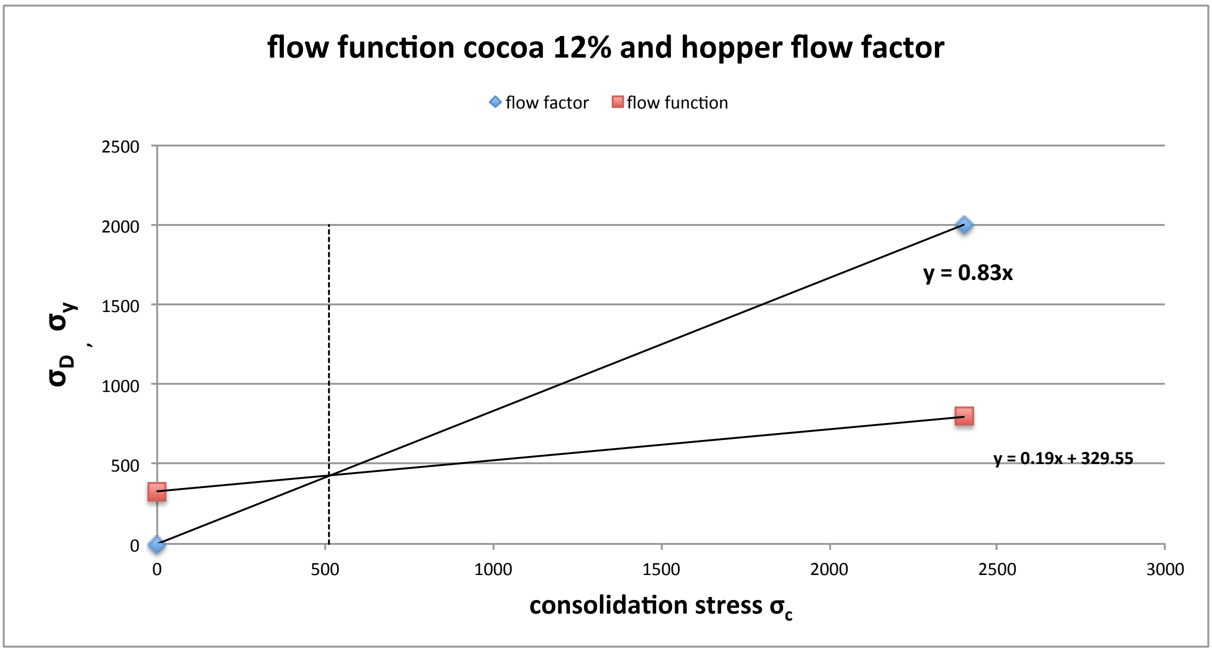
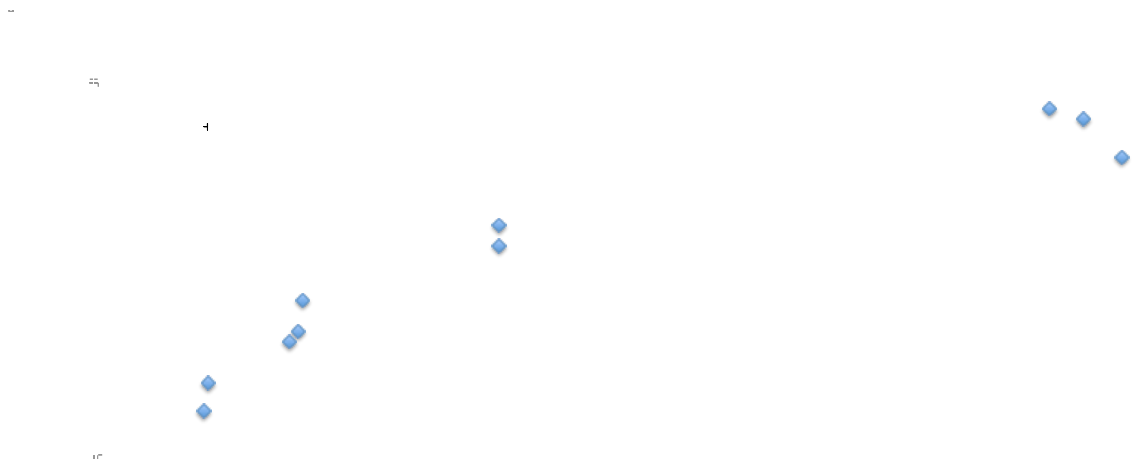
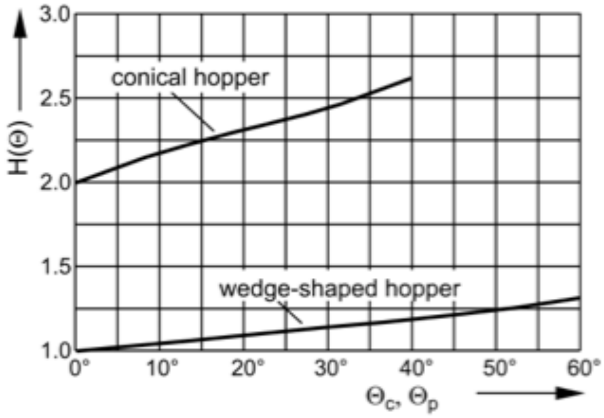


Fig. 7.16 Intersection flow function and hopper flow factor



With the critical consolidation stress and critical density, the minimum outlet opening can be determined with the formula for d_{crit} in Fig. 7.20. H (theta) in the formula takes into account the hopper geometry, conical or wedge shaped, and the wall inclination angle [11]. The function H theta is shown in Fig. 7.20 on the top.



$$d_{crit} = H(\Theta_c)\frac{\sigma_{c,crit}}{g\rho_{b,crit}}$$

$$d_{crit} = 2{,}1 * \frac{428}{(9{,}81*628)} = 0{,}15m$$

$$d_{crit} = 0{,}18m(+25\% safety)$$

Fig. 7.20 function H(theta) for conical and wedge shaped hoppers (left) and calculation of the critical outlet diameter (right)

Taking into account an additional safety factor of 25%, the critical diameter is determined to be 0,18 meter. With the critical diameter for the outlet opening and the previous determined critical cone angle of 6°, the silo can be designed. Coarse-grained bulk solids can build arches due to interlocking and wedging of particles. To avoid this, as a rule of thumb the diameter of the circular outlet should be at least 6 to 10 times the maximum particle size of the bulk solid [11]. Since the diameters of the cake particles vary from fines to particles of 6 cm, the minimum diameter is determined at a minimum of 36 cm.

7.4.2 Cold-rolled sample

The high wall friction angle for the hot rolled steel sample results in a steep cone angle in order to achieve a mass flow pattern. The steeper cone angle, resulting in a higher silo, is a disadvantage of a mass flow silo. This can be a problem if there are space constraints. The cocoa cake is also tested on a cold rolled steel sample to see how the choice of materials influences the wall friction angle and critical cone angle. If the hopper material is not cold rolled steel, the same effect can be obtained by placing cold rolled linings or similar coating reducing the wall friction angle. The results of 12% and 24% cocoa cakes heated to 55 °C are shown in Fig. 7.21. The wall friction angle is 19°.

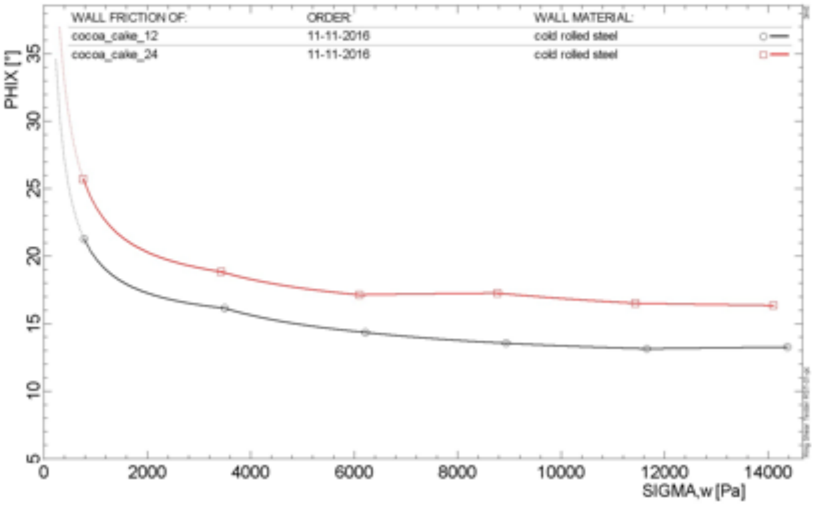


Fig. 7.21 Cold-rolled wall samples tested with cakes heated to 55 °C

The left graph in Fig. 7.22 shows that mass flow is obtained with a cone angle of 26° (extracting 2-3°[11] from the 29° as safety).

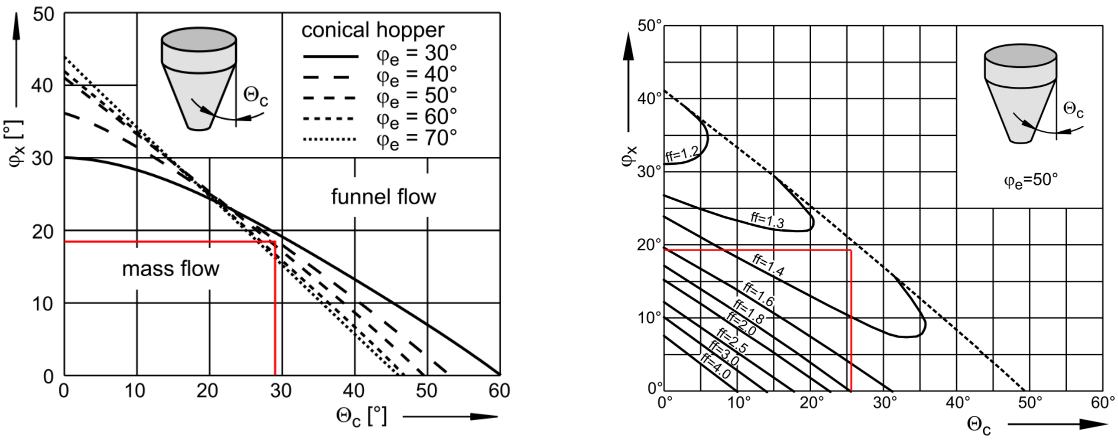


Fig. 7.22 Determination of the cone angle (left) and hopper flow factor (right)

The hopper flow factor is determined in the right graph in Fig. 7.22. A wall friction angle of 19° and a cone angle of 26°, results in a hopper flow factor of 1,34 after interpolation. With the hopper flow factor and flow function, the critical yield, density and H(theta) are established. For the cocoa cake 12% heated, the hopper flow factor is 1,36. The critical diameter is determined on 0,18 m. The calculations are shown in appendix D.

7.4.3 Dimensions of the designed silos

The input for the design of the silo:

- Angle of repose is measured: 40°
- Critical cone angle is 6° for hot rolled and 26° for cold rolled steel
- Minimum outlet diameter determined by particle size of cake: 6x60 mm = 360 mm
- Capacity 40 MT
- Bulk solid density 700 kg/m^3

The design of the silos is shown in Fig. 7.23. The filling height from outlet incl. heap is 17 meter for the 40 MT with critical cone angle of 6°. The diameter of the silos is 3,6 meters, which is the same diameter as the silos currently installed at [redacted] For the silo with the cold rolled wall and the critical cone angle of 26°, the silo height can be reduced to 6 and 9,5 meters for respectively 20 and 40 MT. The height of the 20 MT mass flow silo for the cold rolled hopper wall material is similar to the height of the currently installed silos.

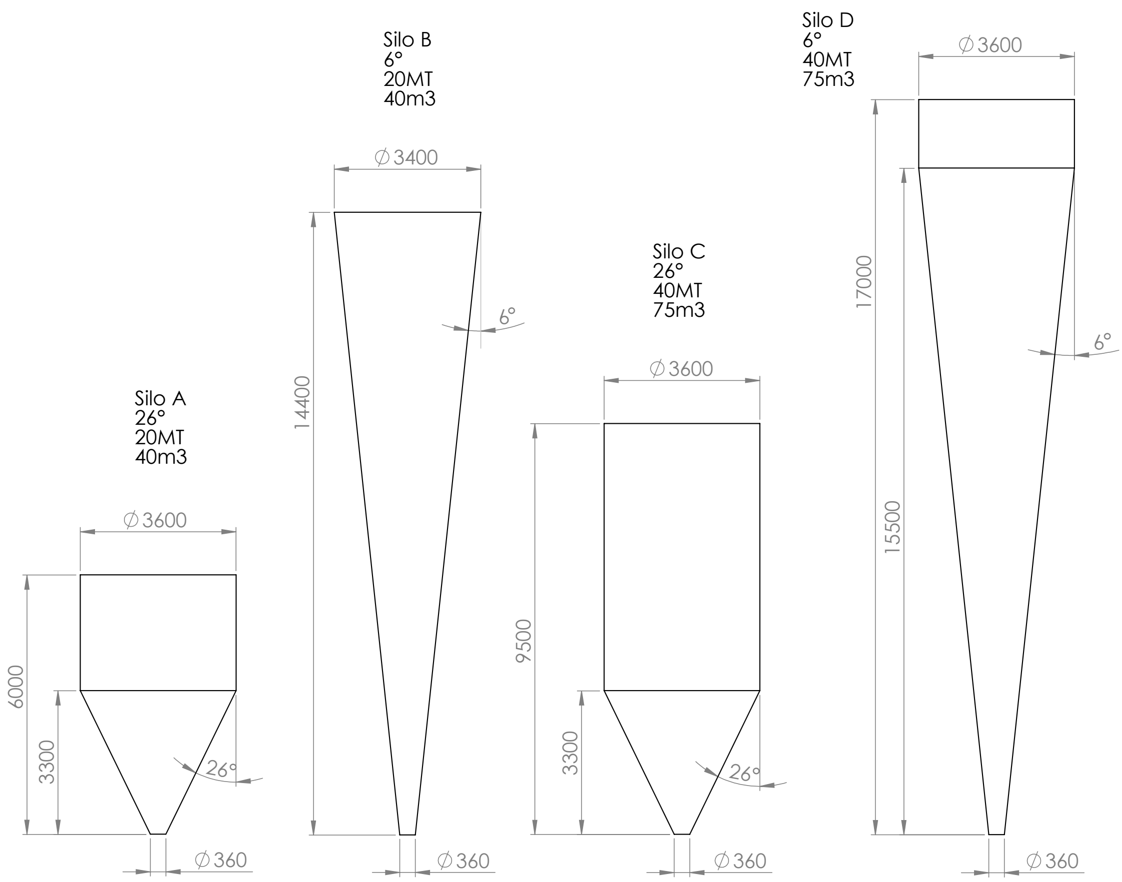


Fig. 7.23 Design for mass flow silos for capable of storing 20 MT and 40 MT of cake

7.5 Review of the current silos

The previous paragraph showed how the silos should be dimensioned in order to achieve a mass flow pattern. The goal of this paragraph is to review the silos currently in operation and use the information from the previous paragraphs to see what the causes are of the flow obstructions. This paragraph shows that the flow obstructions are the result of design of the currently installed silos and how the silos are used.

The dimension and design of the currently installed silos is shown in Fig. 7.24. The experiments show that the hopper angle of 21° is too shallow too deliver mass flow to the inverted cone discharge device [22]. The angles inside the currently installed silos, 21° for the hopper and 45° for the inverted cone section, are not steep enough for the cake to move due to gravity. This can be seen in Fig. 23 on the right. An inverted cone enlarges the diameter of the flow zone of a funnel flow silo, but a mass flow pattern is usually not attained [11]. The enlarged flow zone contains material from a larger cross-section of the silo. However, the material closest to the silo walls will come out last at the end of the discharging process.

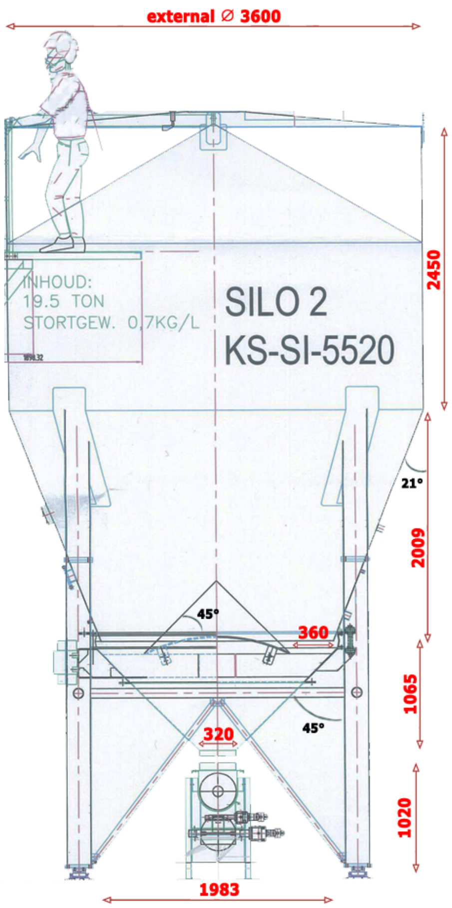


Fig. 7.24 Dimensions of the silos currently installed at [redacted] is shown on the left. The inside of these cake silos is shown on the right. Cake lies on the inverted cone and the shallow bin.

In the current situation cake arches are formed between insert and the silo wall (0,36m). The maximum particle size is 6 cm and as a rule of thumb the opening should be at least 6 to 10 times the maximum particle size [11]. Thus, it is not impossible that material gets stuck due to interlocking. The operators that break arches during production enforce this statement of interlocking as the arches consist of larger particles.

The silos are equipped with discharge aids. The cake flows out of the silo solely due mechanical and pneumatic discharge aids, respectively vibrating motors and air nozzles. However, these should not be employed as an alternative to good hopper design [22]. The bin activator is used to limit the height of the hopper. However, the previous paragraph showed that using a different material for the hopper, a mass flow silo with similar height is designed without needing discharge aids for flow.

Discharge aids have to be located so they can act at the source of the flow problem. The aeration nozzle is placed correctly: situated in the shallow bin, positioned above the possible arch. The injected air causes overpressure and the majority of the injected air tends to flow to the outlet opening where the pressure is lower [11]. The additional force on the bulk solid results in overcoming the wall friction and possibly destroying arches, thus promoting flow [11].

Vibrating inserts should not cause flow obstruction or act as the basis for a stagnant zone, which is often the case when they are not active. The supports required to carry inserts must be sufficiently steep to avoid the formation of stagnant zones, and cross-sections must be large enough to avoid flow obstructions due to arching [11]. The first condition, which is steepness of the supports, is met in the current silos, but the second condition might be a problem due to aforementioned interlocking of particles. The inverted cone and supports can also cause asymmetric stresses on the silo [11]. Therefore, a well-designed mass flow hopper, without an insert is preferred.

Also how the equipment is used, is reviewed. Hammer strikes are not allowed as they increase the wall roughness, making it even more difficult for the material to flow out of the silo.

If the yield limit is attained during vibration stable arches or ratholes are broken and the material starts to flow [11]. However, flow-promoting devices should only be used during discharge, else it further consolidates the bulk solid and increases flow problems. The effect of vibrations decreases with increase of fineness and compressibility of the bulk solid, because the latter enhances absorption of the vibrations[11]. Flow obstruction is more likely to occur with powders and fines. On the other hand, interlocking occurs when particles are too large. The hammer mills should be set to avoid breaking the cakes into fines or particles that are too big in order to prevent flow obstructions.

If downstream material, like a rotary valve underneath the silo, limits the flow of material from the silo, a possible result is the formation of an eccentric flow zone. [11] The flow zone is shown in Fig. 7.25. The stagnant material in the hopper, arched zone on the right in Fig. 7.25 becomes increasingly consolidated due to the effect of vibration. This also explains why the last metric tons of a stored cake batch only get stuck on one side of the cone during discharge of the silo. With a constant cake output of the silo the flow problems does not seem to occur, confirming the existence of an eccentric flow zone.

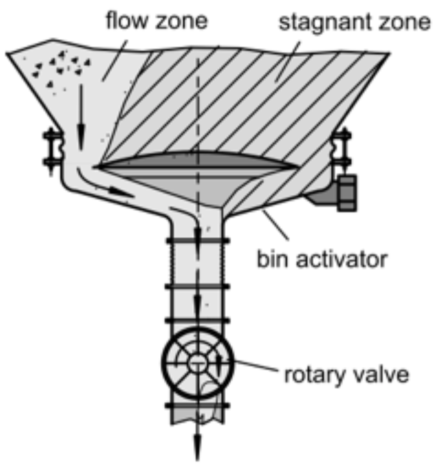


Fig. 7.25 The Eccentric flow zone is a result of limited flow from the silo. The stagnant zone becomes increasingly consolidated by vibrations.[11]

The aspects particle size, temperature and fat percentage of the cake are not the cause for the flow obstructions inside the current cake silos. The flow obstructions are caused by the design of the silos and the use. The angles in the currently installed silos are too shallow to promote mass flow and discharge aids and devices are necessary to promote flow. Interlocking of particles may be the result of insufficient distance between the wall and inverted cone, and the outlet opening. Furthermore, vibrations increase the bulk solid when it is not discharged and limiting the flow from the silo results in an eccentric flow zone.

7.6 Design of blending equipment

The capacity of the function blending and the number of blenders are discussed in paragraph 6.4. This paragraph looks at the equipment for blending and deals with the decision for the mode of operation of blending: batch or continuous. This decision is important, as it not only affects the quality of the product, but also the adjacent functions. First the different basic principles of blending and mixing are discussed. After that, batch and continuous blending is compared and a decision is made for the mode of operation. In the final subparagraph, a decision for the volume of the batch blender is made in order to achieve the right capacity.

7.6.1 Batch or continuous

Solid mixing can be quantified as shear mixing, diffusive mixing and convective mixing. The goal of the mixing mechanism is to reach an asymptotic limit of random mixing [18]. In a random mixture the probability of finding a particle of any component is the same at all locations and equal to the proportion of that component in the mixture [22]. Convective mixing is the preferred mixing mechanism as it is most likely to result in a random blend [17]. Nonetheless, the other mixing mechanisms, diffusive and shear are also found in convective mixing.
Horizontal convective mixers are widely used in the food industry [23]. A plow mixer or a paddle mixer, shown in Fig. 7.26 are both suitable convective mixers for cohesive powders and with added high speed choppers capable to break particles in the feed stream [18]. If the particle size is reduced, a more homogenous blend can be achieved. During blending the mixing aspect is controlled and the uncontrolled particle size reduction is a wanted side effect for reducing segregation and classifying downstream.

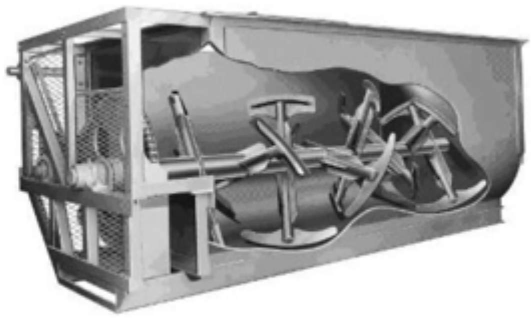


Fig. 7.26. Single shaft paddle mixer [18]

The most common convective blenders used in the food industry are batch blenders, but also continuous convective blenders are used. In a batch blender the ingredients are loaded into a closed vessel and agitated for a certain amount of time until a homogenous mixture is achieved [18]. In a continuous mixer the ingredients are mixed in a single pass. [18] The goal for blending is to design a robust mixing system, which allows the homogenized cake blend to be checked before powder making. Although both batch and continuous blenders can satisfy this goal, a comparison is made to see which mode is most relevant for blending in the future situation. Table 7.4 shows this comparison, listing the advantages (+) and disadvantages (-) of both modes of operation.

Table 7.4 Comparison Batch and Continuous mode of operation for blending

	Batch	Continuous
Flexibility [17]	+	-
Batch integrity [18]	+	-
Reliability [18]	+	-
Control costs [18]	+	-
Number of ingredients [18]	+	-
Residence time [17]	-	+
Segregation [17]	-	+
Mixing minor ingredients [18]	-	+
Size machine [17]	-	+
Labor, maintain and clean [18]	+	+

Batch blenders are preferred as they are more flexible in blend recipe, number of ingredients and in batch size [17]. In a batch blender it is easier to identify a batch for further follow-up [18]. Continuous mixing is preferred for processes where throughput is high, space is a constraint, storage of intermediates must be avoided or the material has the tendency to segregate. [18] Segregation may occur during discharge of a batch blender affecting the product quality. During the blending process size reduction occurs increasing the homogeneity of the blend. Although this reduces segregation down the line, small differences in particles size such as a ratio of 1.3 (small/big particles) already leads to segregation [18]. Thus, segregation is unavoidable downstream of the blend process with batch and continuous blending.

Batch blending is the preferred mode of operation. The critical part of continuous blending is the control of the flows feeding the blender. The reliability of the system depends on the metering, monitoring and intensive calibration making the automatic control of the feed more difficult and costly [18]. For continuous mixing the feeders must be precisely controlled and a continuous blending process is hard to realize with irregular flow and when stoppages occur. Throughput is more or less fixed for continuous blending, while for batch mixers the turndown ratio is quite high and it is easier to vary the production rate [18] [17]. This is necessary, as different fat percentages require different blending capacities while processing a batch on the power making lines. Also, the rest of the process is more batch-oriented and particle size reduction during blending is more likely to occur in a batch blender with longer residence time. The residence time in the batch blender, shown in Fig. 7.26, is approximately six minutes and in a continuous blender only 1-3 min [17]. Finally, the quality of the blended batch blend can be controlled before it is transported to powder making. If the problem with the silos is solved, flow is regular and large quantities of the same blend are produced, a continuous blender is the preferred mode of operation.

7.6.2 Volume of batch blender

The batch mixing cycle time is usually not the rate-limiting step in an overall batch process, and consequently, mixers are idle from time to time during production [17]. Thus, it is possible to use a smaller mixer for multiple times feeding the powder making lines. Consequently there is a trade off between mixer capital cost and labor operating costs as a smaller blender results in more weighing, filling and discharging [17]. The relative cleaning cost reduces while increasing the size of the batch blender and the cost of sampling is significant leaning towards an increase of the size of the batch blender [24]. On the other hand, cleaning is only necessary after product change over at the powder making lines. Furthermore, controlling the input material as discussed in the control paragraph 6.6, the possibility arises that sampling has less influence while it can be executed while the batch moves further downstream [24].

A smaller blender is chosen that is able to supply the powder making lines with a capacity of 4 MT/hour. For batch blenders the volume, filling degree and cycle time determine the capacity. The degree of filling is important for the product quality and blending efficiency. These aspects improve by making two well-sized batches rather than one over-filled batch. An under filled blender, especially a batch that does not fully engage the mixing does not mix uniformly [17]. To long mixing times, used to break particles, can also lead to segregation [18].

The exact time of batch and continuous blending to achieve a blend with homogeneity, at the used scale still, remains empirical [23]. The residence time to achieve a random blend is approximately 6 minutes for the paddle mixer shown in Fig. 7.27 [18]. Assuming a residence time of 6 minutes and the capacity of filling and emptying with 10 MT/hour, the graph in Fig. 7.25 is established.

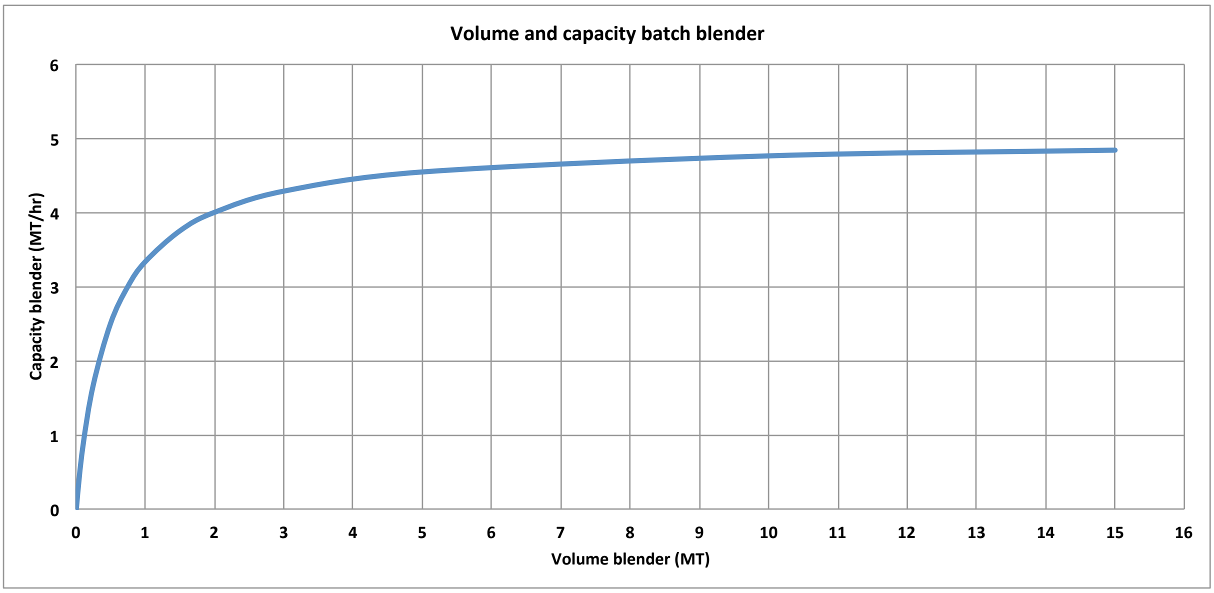


Fig. 7.27 Relationship of the volume and capacity of the batch blender

The capacity of the batch blender is determined by the volume and residence time, but also by the speed of filling and discharging. Fig. 7.25 shows the relationship between the cake volume inside the batch blender and the capacity at a constant filling and emptying speed of 10 MT/hour. Increasing the capacity of blending by increasing the size of the batch blender reaches an asymptotic value of 5 MT/hour at a filling and emptying speed of 10 MT/hour. Downtime due to cleaning is not taken into account in Fig. 7.25. The weight of cake inside the batch blender must exceed 2 MT to achieve a capacity over 4 MT/hour during uptime. To prevent the powder making lines from starvation, while a new batch is blended, the separator must be able to store 1,2 MT.

The total volume of the batch blender is larger than depends on the filling degree. Assuming a filling degree less than 70 percent [18] and a bulk density of 650 kg/m^3 the total volume of the batch blender should be at least 4,4 m^3.

8. Conclusion

In this research the transformation of cocoa cake into cocoa powder is investigated. This research has given an answer to the following research goal:

Redesign the production system for storage, blending and processing of cocoa cake, in order to meet the future demand of powder.

By adding additional equipment and using a different planning and production strategy, the expected increase of powder output of 200 percent can be realized.

An additional powder making line is added to increase the capacity of powder making. Three powder making lines can process the expected amounts of low-fat and fat cake. The function blending is differentiated to control the degree of blending and convective blenders are chosen as they promote a random mixture. For the mode of operation batch blending is chosen. Two batch blenders, each with a volume of 4,4 m^3, have sufficient capacity to process all the cakes that need to be blended.

The productmix and Pareto analysis show large amounts of standard production cake need to be blended with imported cake. Therefore, a new strategy production strategy is proposed. Liquor making and cake making become highly standardized in the new production system, maintaining a high utilization. Additional dedicated silos are installed before blending. The capacities of the additional silos are 20 MT and 40 MT. The silos decouple cake making and powder making and have sufficient capacity to store standardized batch sizes. The new production system, alternating production strategy and limited batch sizes prevent blockage of cake making and starvation of powder making.

The design of the silos and malfunctioning of the current silos is further investigated by conducting cake-cake and cake-wall Ring Shear Cell experiments. The tests show similar flow characteristics between cakes tested at 35 °C and 55 °C. Increasing the fat percentage increases the cohesiveness and the wall friction angle. Decreasing the particle size, makes the cakes very cohesive.

The cake tests are used to design new mass flow silos with a capacity of 20 MT and 40 MT and the silos are designed for cake with the worst flow behavior up to 35 °C. This ensures the silos can be used for all cakes if the production plan changes in the future. The silos are designed to prevent flow obstructions and promote flow without discharge devices. Using a different wall material for the hopper, like cold rolled steel, the cone angle can be increased to 26°. The same effect can be achieved when cold rolled linings or a coating, reducing the wall friction angle, is used in the hopper. This decreases the total required height to 6 m for a 20 MT mass flow silo, which is similar to the height of the cake silos currently in operation.

To meet the future demand of powder, a new production strategy is proposed. The new strategy focuses on improved flow due to alternating products and standardization. Equipment is added in the form of an additional powder making line, blenders and silos. The silos are redesigned to ensure mass flow, without discharge devices, and to prevent flow obstructions.

9. Recommendations

Investigate the productmix, blend ratio and customer demand. The assumptions made on these aspects are very important for the design of the production process. In this research the average demand and blend ratio are used for the design of the production process. The strategy determines the decisions made for the equipment and operational production process.

To determine the blend ratio, the aspects pH-degree and color need to be tested in a laboratory. Since blending influences all three aspects simultaneously, tests need to examine the possibilities of blending.

In the current system the focus lies on optimization of the individual functions. Standards for each function are held constant, without regarding the aspects of the products that are produced. Not only the daily quantities should be summarized, but also the operating hours and type of products. The total throughput time of the product can be established with this information and additionally this provides insight in the cost to produce the product. In the long run information concerning the throughput times and performance should be used to adjust order processing and installed capacity.

Standards and working procedures used in the production process should be accepted and complied with. The operators currently alter machine settings and or transportation speeds between processing equipment in order to improve the flow. These setting should be investigated and standardized preventing additional variations introduced by different operators.

Cleaning the presses and change over to another liquor to press can be aggregated. This increases the productivity of the cake and butter making function.

During the shear cell experiments the heated cake cools down, as the shear cell ring is not temperature controlled. The decreasing temperature of the sample during testing can influence the flow behavior. With a temperature controlled ring shear cell [21] the samples can be measured at a constant temperature.

It is best to test cake immediately after it is produced when the butter inside the cake is liquid. By heating up the cocoa cake to melt the butter, the moisture content is reduced and this can influence the flow behavior of the bulk solid material. Although the moisture content is around 2 percent, moisture can still influence the flow behavior [11].

Smaller particles are more cohesive while larger particles might interlock. Adjust the hammer cake breaking mills to prevent too large particles are stored in the silo.

The feeder underneath the silos, managing the discharge rate, is controlled with information provided by the load cells of the silo. The capacity of the feeder is adjusted to meet the right output by measuring the difference in weight each time interval and the rotational speed of the feeder. If the silo is filled and cake is discharged simultaneously, the load cells do not provide information to control the discharge rate. An additional metering or weighing system is needed to control the discharge rate.

The additional equipment needed for the new production system requires space. Investigate the possibilities to install a powder making line in the empty warehouse intended for future expansion. Furthermore space is required for the future intake of imported cakes and height is required to install the additional silos. Investigate the increase in traffic at and around the production site as more trucks are unloaded and loaded.

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Appendix A: Scientific Research Paper

Design of a Production Line for Storage and Processing of Cocoa Cake

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Abstract*—At [redacted] the customer demand for cocoa powder continues to grow. The response to this trend is that large amounts of cake are imported and blended increasing the input of powder making. In this paper the production system and its equipment are redesigned to cope with the increase in cake handling. The Delft Systems Approach is used to analyze the processes at [redacted] and to define the functions of the production system processing cake into powder. By adding additional equipment and using a different production strategy, the expected increase of powder output of 200 percent can be realized. The additional powder making line ensures all the cake is grinded into powder and the proposed production strategy aims at standardization and high utilization. Additional dedicated silos with a capacity of 20 MT and 40 MT that matches the standardized batch sizes are installed before blending. The production strategy and the silos prevent blockages of the presses and starvation of powder making lines. Blending of cake is differentiated and executed by two convective batch blenders of 4,4 cubic meters. To redesign the storage of cake and prevent flow obstructions, shear cell experiments are conducted. The shear cell experiments show the influence of the temperature, particle size and fat percentage of the cake. The cake tests are used to design mass flow silos with a capacity of 20 MT and 40 MT and the silos are designed for cake with the worst flow behavior up to 35 °C. Using a different wall material for the hopper, the cone angle can be increased from to 6° for hot rolled steel to 26° for cold rolled steel. This decreases the total required height to 6 m for a 20 MT mass flow silo, which is similar to the height of the cake silos currently in operation.

***Index Terms*— Bulk Solid Handling, Delft Systems Approach, [redacted] Silo Design, Cocoa Production.**

I. Introduction

[redacted] cocoa beans into cocoa liquor, cocoa butter cocoa powder. The beans are sustainable, certified and ethically produced and carefully selected to maintain a high quality product. The cocoa beans are processed according to different, often customer specific, recipes. [redacted] The cocoa products are produced on customer demand and all products are make-to-order. The storage of beans is located next to the [redacted] and the beans are transported in trucks to the factory on a just-in-time basis. First all beans are processed into cocoa liquor. Liquor making consists of several steps, in which the core of the cocoa beans, the nib, is separated from the shell, roasted and grinded into coarse and fine cocoa liquor. The liquors can be blended in this stage to obtain liquors with the right product specifications. Cocoa cake and butter are produced when cocoa liquor is pressed in hydraulic presses. The butter is refined and the cake is broken, cooled and pneumatically transported to the cake silos. The cake silos decouple the cake making process and the powder making process. Decoupling is necessary due to the difference in capacities of producing and processing low-fat and fat cakes. In the current production process, the presses are blocked and powder- making lines are starved decreasing the performance of the processes. Furthermore, obstruction of flow takes place inside the silos. This results in unplanned downtime on cake making and powder making. Several causes are mentioned for the malfunctioning of the silos, including the design of the silos and the aspects temperature, fat percentage and particles size of the cake. The powder making lines grind the cake into powder and pack the powder in different stock keeping units (SKU's).

The trend of recent years is that the customer demand for cocoa powders grows. This increase puts pressure on the processes liquor making, and cake and powder making. An alternative for increasing the powder output by pressing more cocoa liquor is importing high quality cocoa cakes as semi-finished product and grinding these cakes into powder at the production facility of [redacted] The imported cakes origin from other cocoa processing factories that are part of [redacted] This ensures the quality of the cake is controlled and the standards for a transparent and sustainable supply chain are maintained. To meet the powder characteristics of the customer orders, the cakes can be blended. The future prospect is that large amounts of cake are imported, blended, and processed into powder. It is expected that the powder output will increase from [redacted] to 45,000 MT, due to increased cake production, but mainly due to the import of 25,000 MT of cake. [redacted] is curious how this will affect the production process and equipment.

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II. Research Approach

A. The Delft Systems Approach

In order to design the production process that transforms the cakes into powders, the current production practices are investigated. The Delft Systems Approach presents a fundamental approach for the analysis and design of industrial systems, which emphasis a concept that can be used by all disciplines involved and makes a logical systematic combination of quantitative and qualitative modeling [1]. This approach is used to analyze the processes of [redacted] and to define the functions of the new production system.

B. Production data and expected increase

The production data of 2015 are analyzed and used to gain insight in the capacities of the currently installed equipment. This year is representative for the production trend and since no changes have been made regarding the resources and production practices, the production numbers of 2015 provide insight in the capacities and the performance of the production system. These numbers and renewed requirements are used to design the functions and equipment. One of these new requirements is the expected increase production quantities and import of cake.

C. Silo design principles by Schulze

The design of equipment focuses on the silo design. The cake silos are designed by using the properties of the bulk solid, in this research cocoa cake, and proven design principles presented by D. Schulze [2]. Since the literature does not provide information and test results about the flow ability of cocoa cake nor the influence of the aspects temperature, fat percentage and particle size, experiments are conducted. The samples of cocoa cake are tested on a computer-controlled Ring Shear Tester RST-01.pc at University of Technology in Delft. From the test the yield loci are obtained. With several yield loci the flow function is established that shows the flow ability of the cake. For the experiments appropriate stresses are assigned, similar to the stresses inside the silo. Identical stresses for normal- and preshear are chosen for the comparative tests and one aspect is varied each experiment to examine the influence of the temperature, fat percentage, and particle size. To examine the influence of the temperature of the cake, the samples are heated in an oven. The interaction between cocoa cake and silo wall material is also tested. For the wall friction tests, a test ring is made out of hot-rolled SA2.5 steel resembling the inside wall of the silos currently in operation at [redacted] [redacted]

III. Results

A. Product mix

To determine the expected increase in product handling for each step, the future product mix is determined based on the possibilities of blending, the product mix of 2015, and the expected production and import of cake. The residual fat percentages of the produced blended cakes are 10-12% and 22-24% and by blending these cakes with imported 10-12% cake all cakes in the range 10-22% can be made [3]. The blended cakes are made out of 2 liquors, Red and MB, of the total 27 liquors destined for pressing. The Pareto analysis [4] for the liquors is shown in Fig. 1. The liquors Red and MB represent 75 percent of the total volume of liquors processed on the presses.

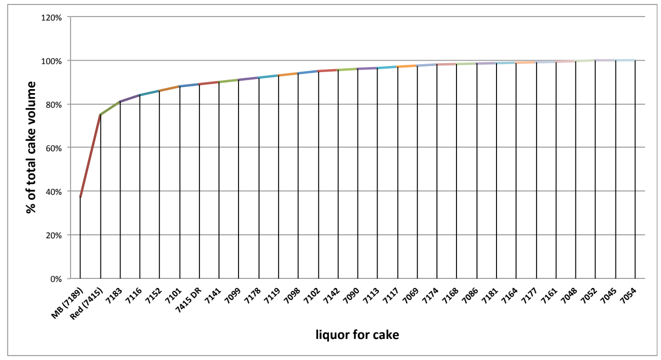

Fig. 1. Pareto Analysis of cocoa liquor for cake making

B. Strategy

A common development in the food industry that applies to [redacted] [redacted] is the tendency to restrict set-ups, batch sizes and produce economically using stable and repetitive cycles [5]. On the other hand the production process needs to be flexible reacting on customer demand. A strategy is to postpone the product differentiation activities [6] and stock intermediates which can be used to produce end products [7]. This strategy in combination with the decision to make 10-12% and 22-24% cakes for blending, leads to a standardized cake making process with a flexible blend to order strategy. This results in standardization of the liquor making lines, providing liquor for the presses. Dedicated presses and liquor making lines are assigned for production. The basis cakes are produced in standard cycles or imported and blended- to- order (BTO). The volume of these cakes is high and the variability in demand is low, this in contrast to the sustainable and [redacted] high-alkalized cakes remaining pure make-to-order (MTO) products. This results in a hybrid customer order decoupling point (CODP) [5].

C. Production system and functional design

Opening the black box cocoa processing reveals the functions transforming cocoa beans into liquor, butter and powder. These functions, shown in Fig. 2, are examined to see if the increase in product flows can be realized. The focus of this research lies on the functions within the red dotted line, indicating the system boundary.

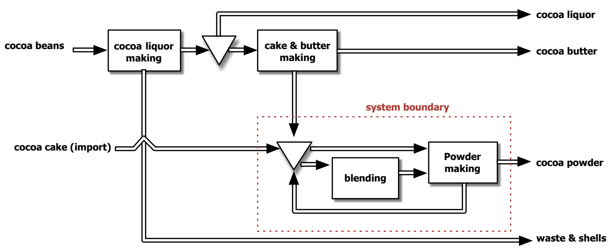

Fig. 2. System boundary of the redesign

The analysis of the production system shows that cocoa liquor making and cake making have sufficient capacity to generate the expected product output, while powder making has insufficient capacity to grind all the cake into powder. Furthermore, the cake silos have insufficient capacity and malfunctioning of the silos causes downtime.

The function blending is a side effect of transportation and grinding of cake. The degree of blending is not controlled in these processes. The goal of this research is to redesign the functions cake storage, blending, and powder making in order to meet the future demand of powder. This is discussed in the remainder of this paragraph.

The product mix dictates the amount of (blended) low-fat cake and fat cake that needs to be grinded into powder. This is important for the determination of the needed powder making capacity. Furthermore, the batch size of powder making influences the capacity of powder making as the change over time between two batches is 3 hours. By standardizing the batch sizes for blended powders, 20 MT and 40 MT for respectively fat and low-fat powders, the necessary 3-hour cleaning downtime can be aggregated with the product change over. An additional powder making line is added and the three powder-making lines have sufficient capacity to produce all the powder. The overcapacity of the powder making lines provides flexibility to ensure all the silos are emptied on time while producing customer powder orders.

The function blending is differentiated to control the degree of blending. Since blending should not be the bottleneck process, the capacity of blending should be at least 4 MT/h matching the capacity of low-fat powder making. Two blenders are needed to process all the cakes, since on average more than half of the times two powder making lines are producing blended powders simultaneously.

The silos must decouple cake making and powder making. Pressing fat cakes has a higher capacity than grinding fat cakes, while pressing low-fat cakes has lower capacity than grinding low-fat cakes. In the current production process, the presses are blocked and powder-making lines are starved due to lack of coordination and batch sizes that are not process oriented. The rework and imported cake are processed in silo 5 and 6 that have a capacity of 25 MT combined. The average daily quantity of imported cake is 75 MT and the buffers do not have enough capacity to store the difference in ingoing and outgoing flow. There is a capacity problem in cake storage and additional silos are needed for production.

For the four basic cakes, 12% Red, 12%MB, 24%Red, and 24%MB, dedicated silos are assigned. These cakes represent 75 percent of the total volume of pressed cakes, are needed on a daily basis, and needed simultaneously to produce certain blends. The liquor is made in standardized batches and the presses alternate between the four basic cakes every two days. Powder making ensures that the silos are emptied on time, preventing blockages of the presses. Due to the high and stable demand for blended powders, the power batches are standardized. The standardized production runs and batch sizes eases the scheduling procedure. By limiting the cycle length and batch size, while alternating fat, low fat and blended products, the necessary intermediate storage of cake to keep both processes running is limited.

The standardized ingoing and outgoing processes determine the capacity of the silos. Following the alternating strategy the presses produce a maximum of 40 MT of 12% Red or 12% MB cake every two days, which is stored in dedicated silos. The cakes in these silos are blended to order, used on a daily basis and often needed simultaneously. The capacity of 40 MT is also equal to the standard batch size of powder making for blended powders. For fat cakes, the standard batch size is 20 MT. To decouple the cake and powder making stage, the capacity of the dedicated silos for 24% Red and 24% MB is determined on 20 MT.

The imported cake is transported to the factory in containers of 20 MT and or Big Bags of 800 kg. A requirement of the product quality department is that a full container of 20 MT can be emptied in a silo. Two silos of 20 MT are assigned to store natural cake for the case a natural cake is blended simultaneously with the production of natural unblended cake. Two silos of 20 MT each are assigned to store imported alkalized cake similar to MB and Red cake for blending. The dumping stations are able to fill the cake silos on a just-in-time basis.

Only partial dedication of the silos is possible and not all of the 40 [redacted] [redacted] cakes can be assigned a dedicated silo. On average one [redacted] [redacted] cake is produced every two days. Two silos, each with a capacity of 20 MT are used to store [redacted] providing more flexibility than a single silo and making it possible to store two different [redacted] [redacted] cakes simultaneously. Additionally, four silos of 20 MT, and two silos of 40 MT are installed for the new production system.

Function control and process control ensure the production is controlled in terms of quality and quantity [1]. Function control initiates the standards for the production process and evaluates the results. The imported cake is measured providing information for the blend ratio. The feedback control loop, of process control, ensures the feed of cakes to the blender and or the time of blending is changed, when the sample does not meet the standard.

D. *Cocoa cake handling equipment*

Besides the previous mentioned capacity problems, there are flow problems inside the silo. Flow obstructions occur during production, causing downtime on the powder making lines and presses.

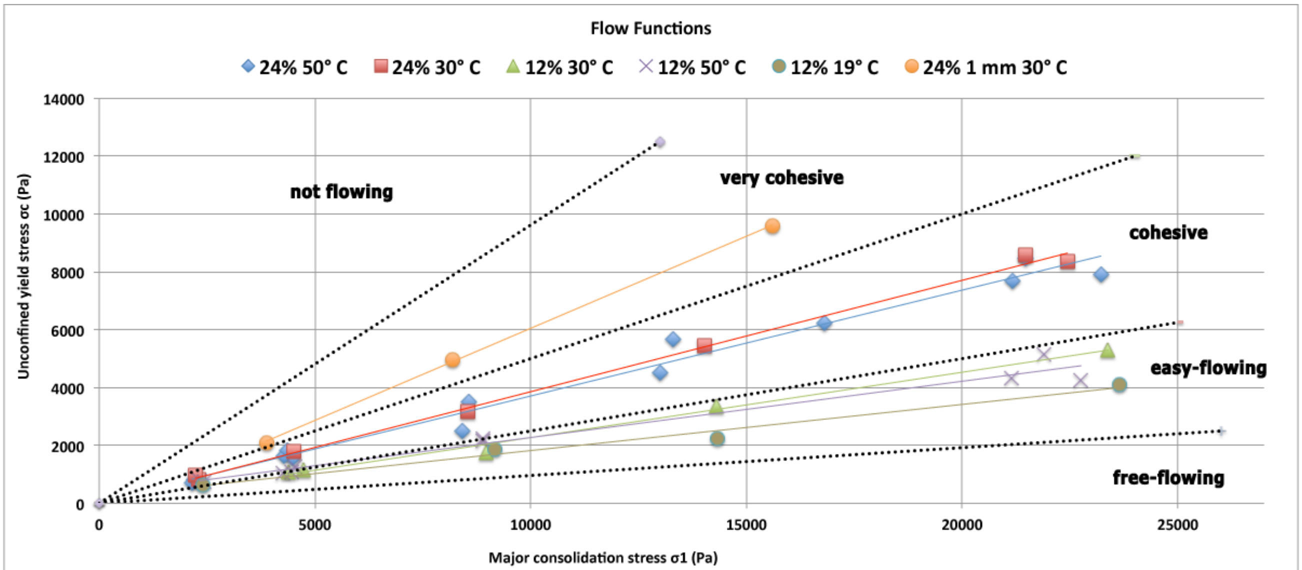

Fig. 3. Flow functions of tested cocoa cake

The operators mention several causes for the flow obstructions, like the temperature of the cake, particle size, fat percentage, and the design of the currently installed silos. The flow properties of a bulk solid material can be affected by particle size distribution, particle shape, chemical composition, moisture and temperature [2]. Therefore, experiments are conducted to investigate the influence of these cake aspects. Fig. 3 shows the flow functions, established with the yield loci, of the tested cakes and the influence of the fat percentage, temperature, and particle size. The flow functions show the cake is more cohesive if the fat percentage of the cake increases. Decreasing the particle size of the cake samples also increases the cohesiveness. Similar results are found for the cakes tested at 35 °C and 55 °C, temperatures at which the butter inside the cake is melted [8]. The low fat cocoa cake is also tested at 19 °C, with solidified butter to simulate the behavior of low fat imported cake. This cake is less cohesive than cake with melted butter. No time consolidation effects occur when cake is stored for longer periods of time. The corresponding internal friction angle, derived from the yield loci during the shear cell measurements, is 50°.

The influence of the temperature on the wall friction angle for low fat 10-12% cocoa powder and fat 20-22% powder is examined in [9]. This research shows different wall friction angles are obtained when the temperature of the powder samples varies.

The wall friction angles of 10-12% and 22-24% cocoa cake are measured with the hot rolled SA2.5 steel ring sample. The wall friction angle increases with an increase in fat percentage of the cake. Increasing the temperature of the test samples slightly increases the wall friction angles for 22-24% cake and slightly decreases the wall friction angle for 10-12% cakes. The wall friction angles for 22-24% fat cakes are shown in Fig. 4. The green and grey lines show the cake tested at 55 **°C** and the orange and purple lines are cakes tested at 35 °C. The wall friction angle is derived from the wall yield loci and determined on 37**°.**

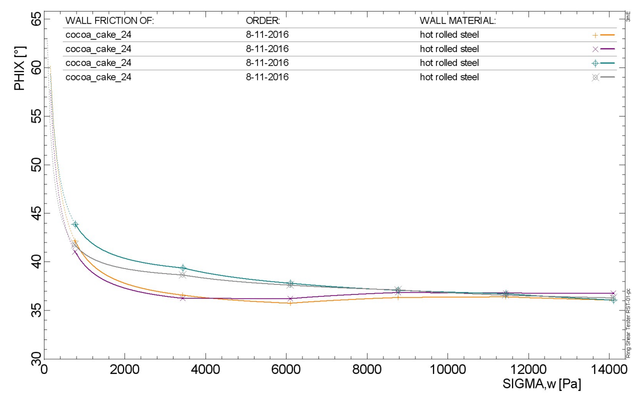

Fig. 4. Wall friction angles 22-24% cake on hot rolled steel SA2.5

The test results are used with the silo design principles presented by Schulze [2] to design mass flow silos with a capacity of 20 MT and 40 MT. The mass flow pattern is preferred, as it remixes the segregated material inside the silo. Furthermore, the first-in-first-out principle is met, making it possible to link the cake output of the silo back to the bean. In [2] the relationship of the internal friction angle, wall friction angle, and critical cone angle for mass flow is presented. Including a safety margin of 2-3°, the critical cone angle for mass flow is 6°, for an internal friction angle of 50° and a wall friction angle of 36° [2]. This information is used to derive the hopper flow factor, which is 1,2. The critical values are obtained from the intersection of the hopper flow factor and the flow functions. These critical values are used to calculate the minimum outlet diameter. The minimum outlet diameter obtained from the calculation is 0,18. The maximum particles size is 0,06 m and the design principles state that the minimum outlet diameter should be 6-10 times the maximum particle size to prevent interlocking [2]. Therefore, the minimum outlet diameter is 0,36 m. In order to design a mass flow silo of which the inside material is made out of hot rolled SA 2.5 steel, a steep cone angle, of 6°, is needed and an minimum outlet opening of 0,36 m.

The wall friction angle tests are repeated with a cold rolled steel sample, which is expected to result in a reduction of the wall friction angle, increasing the cone angle and decreasing the height required to obtain a mass flow silo. The resulting wall friction angles for 12% cake and 24% cake heated to 55 °C are shown in Fig. 5.

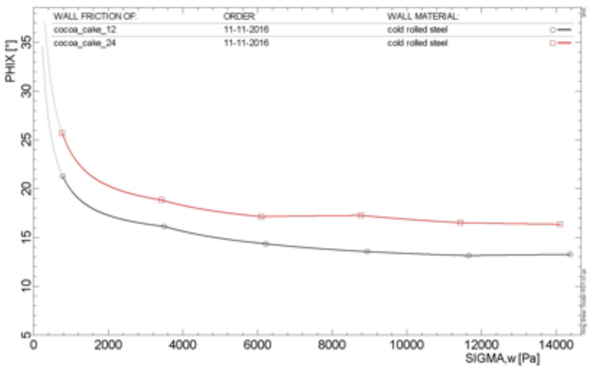

Fig. 5. Wall friction angles cold rolled steel

Using the design principles of mass flow silos [2] and a wall friction angle of 18° for cold rolled steel, the critical cone angle is 26°. Placing a coating or cold rolled linings inside a hopper made out of hot rolled steel can yield similar results [2]. The two mass flow silos, each with a capacity of 40 MT, are shown in Fig. 6.

Besides the equipment for cake storage, also equipment for the differentiated function blending is designed. For the function blending a convective batch blender is chosen.

The convective mixing mechanism is preferred as it is most likely to result in a random blend [10]. Batch blending is chosen for the mode of operation since the process is batch oriented and irregular flow and stoppages in the production system occur. Furthermore, batch blending is preferred over continuous blending, as the production rate of blending must be varied for low and high fat blends [10]. Finally, the longer residence time in a batch

blender ensures the high-speed choppers have more time to break the coarse particles, reducing segregation. Fig. 7 shows the relationship between the cake volume inside the batch blender and the capacity at a constant filling and emptying speed of 10 MT/hour. The weight of cake inside the batch blender must exceed 2 MT to achieve a capacity over 4 MT/hour during uptime. Assuming a filling degree less than 70 percent [10] and a bulk density of 650 kg/m^3 the total volume of the batch blender should be at least 4,4 m^3.

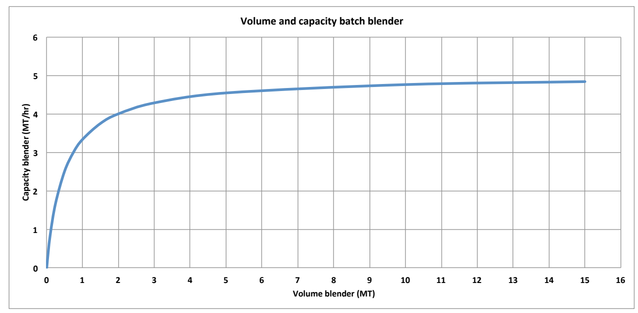

Fig. 7. Volume cake and capacity of the batch blender

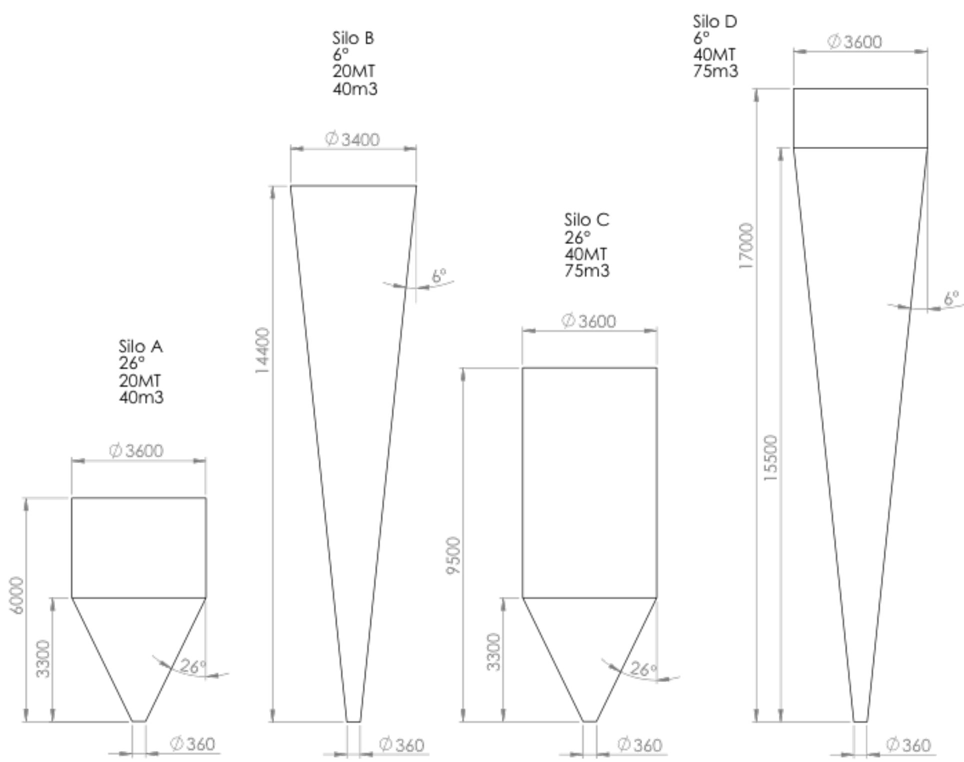

Fig. 6. 20 and 40 MT mass flow silos cold rolled (left) and hot rolled (right)

IV. Discussion

The combined blend-to-order and make-to-order strategy presented in this paper is based on the assumptions made for the product mix. The final product-mix and blend ratio's still need to be decided by company management and these strategic decisions influence the decisions made for the equipment and operational production process.

Standardization of the batches and production cycles reduces the variability and increase the utilization. Critical in this process is continuous improvement of the production process, which can be realized with function control [1].

The aspects particle size, temperature and fat percentage of the cake are not the cause for the flow obstructions inside the current cake silos. The flow obstructions are caused by the design of the silos and the use. The angles in the currently installed silos are too shallow to promote mass flow and discharge aids and devices are necessary to promote flow. Interlocking of particles may be the result of insufficient distance between the wall and inverted cone, and the outlet opening. Furthermore, vibrations increase the bulk solid when it is not discharged and limiting the flow from the silo results in an eccentric flow zone [2].

Due to limitations of the shear cell tester, only particles smaller than 1 cm can be tested and the tested samples contain cake particles up to 0,8 cm. This is different from the cake particles, stored in the production process that ranges up to 6 cm. The decreasing temperature of the sample during testing can influence the flow behavior. To obtain more accurate results for the yield loci and wall yield loci the test can be repeated with a temperature controlled ring shear cell [9].

By heating up the cocoa cake, the moisture content is reduced. The percentage of moisture inside the cake is measured at [redacted] and determined on 2 percent. The reduction in moisture can also influence the flow behavior of the bulk solid material [2].

V. Conclusions

To meet the future demand of powder, a new production strategy is developed. The new strategy focuses on improved flow due to alternating products and standardization. Equipment is added in the form of an additional powder making line, blenders and silos. The silos are redesigned to ensure mass flow, without discharge devices, and to prevent flow obstructions. The redesigned production system is capable of increasing the powder output with 200%.

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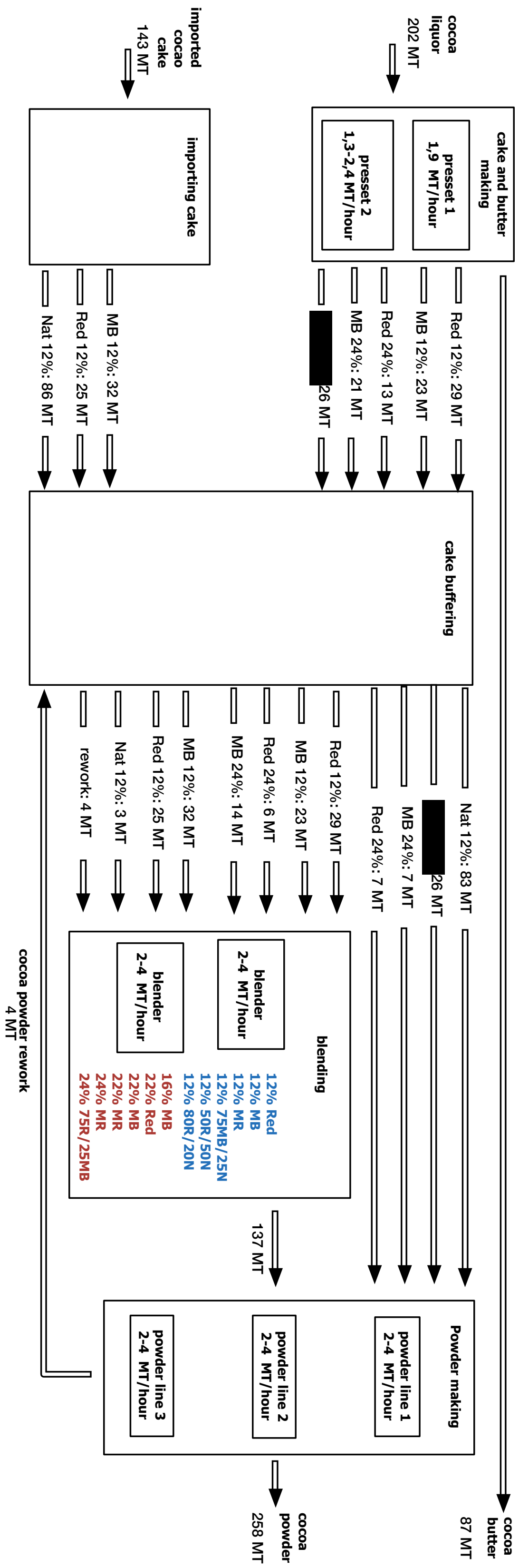
Appendix B: Average product flow for two days



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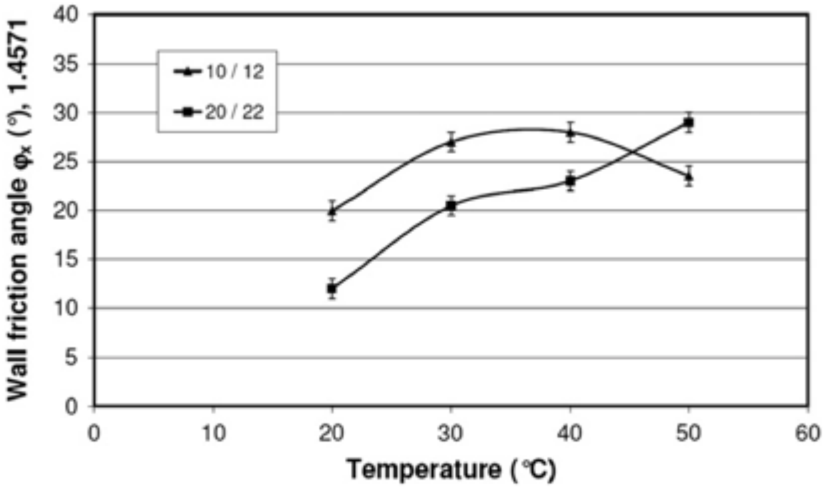

Ap en ix D: Ca cu at on fo m ni um cr ti al ou le d am te

$y_{h\ pp\ rf\,ow} \quad \frac{1}{1\ 36}$

y_f

$_{crit} = 605\,Pa$

$y_{crit} = 445\,Pa$

$$d_{crit} = H(\Theta_c)\frac{\sigma_{c,crit}}{g\rho_{b,crit}}$$

$$d_{crit} = 2{,}1 * \frac{445}{(9{,}81 * 629)} = 0,$$