Delft University of Technology

FACULTY MECHANICAL, MARITIME AND MATERIALS ENGINEERING
Department Marine and Transport Technology

Mekelweg 2
2628 CD Delft
the Netherlands
Phone +31 (0)15-2782889
Fax +31 (0)15-2781397
www.mtt.tudelft.nl

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Author:	L.M.C. van der Spek

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Initiator (university):	prof.dr.ir. G. Lodewijks
Initiator (company):	G. Peeters
Supervisor:	dr. ir. H.P.M. Veeke
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the Netherlands
Phone +31 (0)15-2782889
Fax +31 (0)15-2781397
www.mtt.tudelft.nl

Student:	L.M.C. van der Spek	Assignment type:	Master project
Professor:	Prof. dr. ir. G. Lodewijks	Creditpoints (EC):	35
Supervisor (TUD):	Dr. ir. H.P.M. Veeke	Specialization:	TEL
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Subject: **Improving the production logistics at Cargill Premix & Nutrition**

Introduction

Cargill Premix & Nutrition (CPN) develops, manufactures and sells customized animal nutrition products and services for customers primarily focused pork, poultry and ruminants. CPN Rotterdam manufactures roughly three types of products: premixes, concentrates and specialities (milkreplacers, piglet feeds). These products are delivered to farmers, feed millers and traders in small bags on pallets, big bags or by bulk truck. Daily, an average of 350 MT of animal feed is produced and packaged in the facility. This is done by dosing the ingredients in 6 paddle mixers after which the products can be pelletized on one of the 2 presses. At last they are packaged on one of the 6 packaging lines. Between the different steps, products are temporarily stored in silos.

Problem definition

Due to an increasing focus on the West European market (instead of a worldwide market), the factory of Cargill Premix & Nutrition in Rotterdam is producing a more diverse and concentrated product portfolio with smaller order sizes. This has a negative impact on the productivity of the factory, resulting in late deliveries, unsatisfied customers and declining sales. Besides, daily production quantities are varying a lot. It is not clear what determines the variation in production quantity. These developments gave reason to study what determines the productivity of the plant and how this can be improved.

Research goal

To investigate the variables determining the production output and how to change the system control, input or layout such that the productivity of the system increases. This must be done by taking into account physical, financial and regulatory limitations.

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Approach

- Analyze the current situation using the Delft System Approach
- Determine various solution paths with the aid of expert knowledge and literature
- Simulate these solutions using Discrete Event Simulation
- Analyze the results of the simulation experiments
- Develop implementation methods for the proposed changes in control, input and layout
- Study relevant literature

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

The professor,

Prof. dr. ir. G. Lodewijks

Preface

This report was commissioned by the faculty of Mechanical, Maritime and Material engineering (3Me) of the TU Delft as a completion of the master Mechanical Engineering with the specialization Transport Engineering and Logistics. The report is written for the members of the examination committee, TU Delft and Cargill.

Thanks go out to Alexander Peeters, Toine Stigter, Jochem van den Brink and Dick Schouten for their guidance during my graduation assignment at Cargill Premix & Nutrition. Furthermore, I would like to thank Erik Kwast and all the other operators who shared their knowledge and enthusiasm.

I would also like to thank Hans Veeke and Gabriel Lodewijks for their guidance throughout the course of my graduation assignment. They were always open for discussion and requests for advice.

L.M.C. van der Spek
Rotterdam, October 2016

Samenvatting

Cargill Premix & Nutrition (CPN) ontwerpt, produceert en verkoopt klantspecifieke veevoeders en diensten voor klanten die opereren op het gebied van varkens, kippen en herkauwers. De fabriek in Rotterdam produceert drie typen producten: premixen, concentraten en specialiteiten als melkvervangers en biggenvoeren. Deze producten worden afgenomen door boeren, veevoerproducenten en handelaren. De producten worden afgeleverd in kleine zakken op pallets, big bags of in bulk vrachtwagens. Dagelijks wordt er gemiddeld 350 MT veevoer geproduceerd en verpakt. Het proces start met het doseren van de batches in één van de zes mengers. Vervolgens kunnen de producten worden geperst op twee persen. Als laatste worden de producten ingepakt op één van de zes menglijnen. Tussen deze productiestappen worden de producten opgeslagen in silos. Op jaarbasis produceert Cargill ongeveer 84.000 MT veevoer met een gemiddelde ordergrootte van 10.7 MT. Deze orders worden voor productie opgesplitst in batches van 2.4 MT.

In het verleden waren de producten die geproduceerd werden in Rotterdam bestemd voor de hele wereld. Recentelijk is er echter een verandering merkbaar in de productie doordat de orders in verre landen worden overgenomen door lokale fabrieken van Cargill. De focus van de fabriek in Rotterdam is nu meer gevestigd op producten voor de locale markt. Deze markt heeft vooral behoefte aan hooggeconcentreerde producten (de 'vitamine pil' van veevoer) die in kleinere hoeveelheden verkocht worden. Dit zorgt voor een grotere invloed van omsteltijden en een toegenomen productcomplexiteit. De productiviteit van de plant in Rotterdam is daardoor drastisch gedaald. Dit zorgt voor late leveringen en ontevreden klanten. Daarnaast is de strategie van Cargill toegespitst op het verhogen van de productie in de fabriek van Cargill. De plant in Rotterdam is 4.5 volle dagen operationeel, een toename in productietijd is erg kostbaar en daarom is gevraagd hoe de productiviteit van de plant met de huidige product portfolio kan worden verhoogd.

Om deze vraag te beantwoorden is het productiesysteem geanalyseerd met behulp van de 'Delft System Approach' [13]. Het productieproces is opgesplitst in drie functies: mengen, pelleteren en

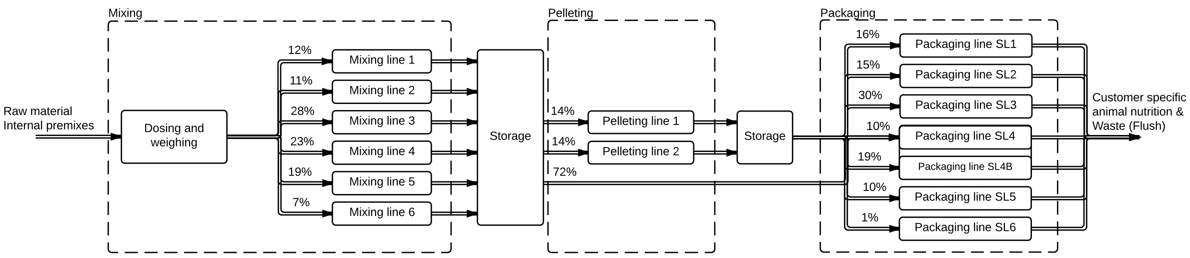

Figure 1: Functies van het proces, de percentages geven aan hoeveel MT er historisch gezien geproduceerd is over de lijn

inpakken. Deze functies en de productielijnen die gebruikt worden om de functies te vervullen kunnen gevonden worden in figuur 1. Capciteiten en variabelen die deze capaciteiten bepalen zijn gekwantificeerd en productstromen in kaart gebracht. Met behulp van de 'Theory of Constraints' [6] en een visuele representatie van de capaciteiten van de verschillende productiestappen zoals geïntroduceerd door Paulo Piero zijn de bottlenecks van het proces in kaart gebracht. Door middel van het bestuderen van literatuur, logisch beredeneren, brainstormen met experts en het interviewen van KSE (Het bedrijf achter de automatiseringssoftware van het proces [3]) zijn er verschillende haalbare oplossingsroutes in kaart gebracht voor het verhogen van de productiviteit:

- Het veranderen van de prioritisering van inpakorders van 'First Come First Serve' naar 'Critical Path Priority'
- Het uitbesteden van de productie van producten met Coccodiostatica (een medicinaal ingrediënt) aan een andere fabriek van Cargill
- Het verbinden van de silos van menglijn 3 met menglijn 1
- Een combinatie van de twee voorgaande aanpassingen

Om deze oplossingen te analyseren is Discrete Event Simulation gebruikt. De logica achter het proces, de verdelingen van order grootte en route en de verdelingen van de productiecapaciteiten zijn bepaald en in een model bij elkaar gebracht. Voor het ontwerpen van dit model is het programma Siemens Plant Simulation gebruikt. Het model is geverifieerd en gevalideerd met behulp van blackbox en whitebox validatietechnieken. Hierna zijn de voorgestelde oplossingsroutes gemodelleerd en de resultaten geanalyseerd.

Alle oplossingsroutes resulteren in een verhoogde productiviteit van de fabriek. De percentuele verhogingen en kosten van de oplossingsroutes zijn gegeven in tabel 1.

Sensitiviteitsanalyses zijn gebruikt om onvoorziene veranderingen in de product portfolio te analyseren. Een sensitiviteitsanalyse van de toename van orders per route door de fabriek laat zien dat een verhoging op de routes waarbij de SL4 of menglijn 1 worden gebruikt de meest negatieve gevolgen heeft voor de productiviteit. Een sensitiviteitsanalyse naar een verdere daling in ordergrootte laat zien dat de productiviteit steeds sneller zal dalen naarmate de gemiddelde ordergrootte daalt. Daarnaast kan door de voorgestelde aanpassingen de voorgenomen productiviteitstoename nog steeds worden gerealiseerd als de gemiddelde ordergrootte tot 30% verder afneemt.

Table 1: Kosten en productieverhogingen van de verschillende oplossingsroutes

Oplossingsroute	Vaste kosten	Variabele kosten (€/jaar)	Prod. vrh.
1. Critical Path Priority	Minimaal	Geen	4.30%
2. Uitbesteden Coccodiostatica	Geen	€106.704,- + Log. kosten	15.50%
3. Verbinden silo's	€130.000,-	€106.704,-	13.40%
4. Combinatie exp. 1-3	€130.000,-	€106.704,- + Log. kosten	20.30%

Summary

Cargill Premix & Nutrition (CPN) develops, manufactures and sells customized animal nutrition products and services for customers primarily focused on pork, poultry and ruminants. CPN Rotterdam manufactures roughly three types of products: premixes, concentrates and specialities (milkreplacers, piglet feeds). These products are delivered to farmers, feed millers and traders in small bags on pallets, big bags or by bulk truck. Daily, an average of 350 MT of animal feed is produced and packaged in the facility. This is done by dosing batches (average 2.4 MT) of ingredients in 1 of the 6 paddle mixers after which the products can be pelletized on one of the 2 presses. At last, they are packaged on one of the 6 packaging lines. Between these steps, products are temporarily stored in silos. On annual basis, Cargill produces around 84.000 MT of animal feed with an average order size of 10.7 MT. These orders are split up in batches of 2.4 MT for production.

Historically the products produced in the plant in Rotterdam were delivered all around the world. Recently, production became more focussed on the local market (West Europe) because of other, local factories of Cargill took over the export market of Rotterdam. Since the West European market demands concentrated products (the 'vitamin pill' of animal feed) and the export market was more focussed on complete feed, an increase in concentrated products was observed. As a consequence, order sizes declined. Due to set-up times and increased product complexity, this had a negative effect on the productivity of the plant which makes it increasingly difficult to satisfy customer demand. Because Cargill its strategy is to increase sales and thereby production in this particular plant, a production capacity deficit is foreseen. The plant is already operating 4.5 full days a week and since working during the weekends is expensive and unwanted the productivity must increase to satisfy customer demand.

The system is analysed using the Delft System Approach. The production process has been broken down into three functions: mixing, pelleting and packaging. These functions and the lines used to fulfill these functions are represented in figure 2. Capacities and variable determining production

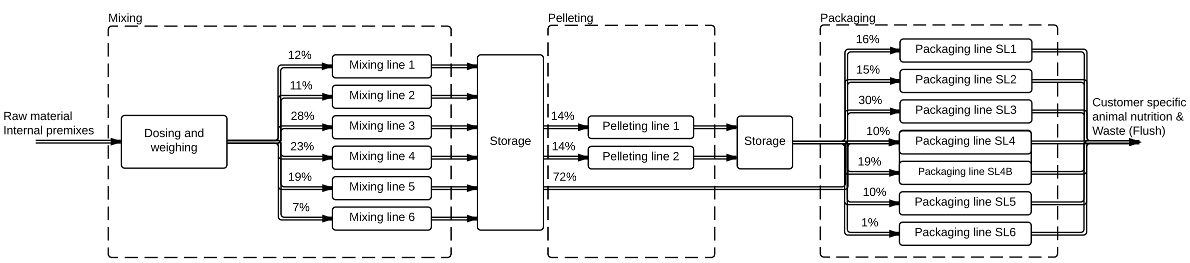

Figure 2: Functions of the production process, percentages represent the ratio of total production weight

capacity are quantified and product streams are mapped. Using the theory of constraints [6] and a visual representation of production capacity introduced by Paulo Piero the bottlenecks within production are determined. By studying literature, logic thinking, brainstorming with the production experts at Cargill and interviewing KSE (the company behind process automation in this particular industry[3]), various solution paths to increase the productivity have been determined:

- Changing sequencing strategy of packaging orders from First Come First Serve to Critical Path Priority
- Outsourcing products containing Coccidiostats (a medicinal ingredient) to a different plant of Cargill
- Connecting the silos of mixing line 3 to mixing line 1
- A combination of the previous two solution paths

To analyse these hypothetical changes Discrete Event Simulation is used. The process logic and distributions of order size, order route and mixing, pelleting and packaging capacities have been determined and put into a model using Siemens Plant Simulation. This model is verified and validated using black box and white box validation techniques. Next, the solution paths have been modelled and the results analysed.

The solution paths all result in an increase in productivity of the plant. The productivity increases and corresponding costs of the solution paths are shown in table 2.

Using the model sensitivity analysis to changes in product portfolio are performed to see how unforeseen changes would affect the productivity of the system. A sensitivity analysis to the increase of orders on a particular route through the factory shows that packaging line SL4 and mixing line 1 contain the most severe bottlenecks. A sensitivity analysis to a further decrease in order size shows an increasing decline in productivity. Besides, a further 30% decline in order size in combination with the 10% productivity improvement would still be possible due to the proposed adjustments to the system.

Table 2: Costs of the different solution paths

Solution path	Fixed costs	Variable costs (€/year)	Prod. impr.
1. Critical Path Priority	Minimal	None	4.30%
2. Outsourcing Coccodiostats	None	€106.704,- + Log. costs	15.50%
3. Connecting silos	€130.000,-	€106.704,-	13.40%
4. Combination exp. 1-3	€130.000,-	€106.704,- + Log. costs	20.30%

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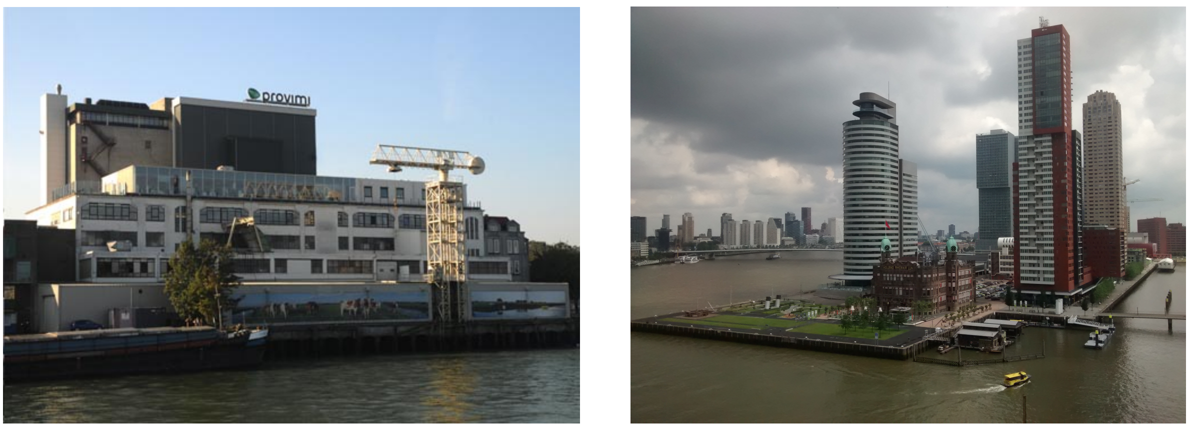
Introduction

Cargill Premix & Nutrition (CPN) develops, manufactures and sells customized animal nutrition products and services for customers primarily focused on pork, poultry and ruminants. The plant in Rotterdam manufactures roughly three types of products: premixes, concentrates and specialties (milk replacers, piglet feeds). These products are delivered to farmers, feed millers and traders in small bags on pallets, big bags or by bulk truck. An impression of the plant is given in figure 1.1.

Historically the products produced in the plant in Rotterdam were delivered all around the world. Recently, production became more focussed on the local market (West Europe), because other, local factories of Cargill took over the export market of Rotterdam. Since the West European market demands concentrated products (the 'vitamin pill' of animal feed) and the export market was more focussed on complete feed, an increase in concentrated products was observed. As a consequence, order sizes declined. Due to set-up times and increased product complexity, this had a negative effect on the productivity of the plant which makes it increasingly difficult to satisfy cus-



(a) Plant

(b) View from the roof

Figure 1.1: Exterior and context of the plant

tomer demand.

Because Cargill its strategy is to increase sales and thereby production in this particular plant, a production capacity deficit is foreseen. To be able to satisfy future customer demand the following research question is proposed:

> Can the input, control and layout of the production system of Cargill Premix & Nutrition be adjusted in a cost efficient manner such that the productivity is increased by 10%?

Productivity is defined as value adding production in mass per time unit. To answer this question, the products and production process are further explained in chapter 2, whereafter the system is analyzed using the Delft System Approach [13] in chapter 3. In chapter 4 the research question is posed and various solution paths proposed. To be able to determine the consequences of these solution paths, the system is modeled in 5. Results of the experiments performed using this model are stated in 6 and an implementation plan is given in chapter 7. The research report is closed by stating the conclusions and recommendations in chapter 8.

2

Situation description

This chapter focusses on describing the products, production process and related subjects as observed during the first months at Cargill. Estimations of capacities and product flows are given and production procedures described.

2.1. Products

Cargill Premix & Nutrition produces around 84.000 MT of animal feed per year. This aggregated number can be broken down into around 1100 formulations (the 'recipe' for the animal feed) which can be packed in several ways resulting in a portfolio of 1700 types of end products.

The products are categorized by animal species and concentrations. Animal species are roughly categorized under pork (piglets, sows and hogs), poultry (meat, egg), ruminants (cattle for beef and dairy, small ruminants) and small amounts of rabbit and fish feed. Products are produced in the form of powder (rescuemilk / milk replacers), mash, pellets or crumble and packaged in small bags, big bags or bulk trucks. Examples can be seen in figure 2.1. All these products are made in different concentrations. Concentrated products are mixed with additional (mostly cheap and bulky) ingredients like maize or soya by the customer. Feed millers use the concentrated products to make their own products and farmers mix the concentrates with an additional ingredient of choice. Concentration varies from 0.1% to 100% of the complete feed. Some product categories are named after the concentration they have:

0.1-2.5%	Premixes
2.5-5%	Base mixes
5-20%	Concentrates
20-100%	Not made
100%	Complete feeds

(a) Mash

(b) Pellets

(c) Crumble

(d) Packaging methods

Figure 2.1: Products

Complete feeds can be categorized under:

- Specialities
- Starter Nutrition
- Milk Replacers

Because Cargill CPN is increasingly focusing on the local market (Europe) and this market demands more concentrated products, a shift towards smaller orders is observed. Another shift in demand is seen in the packaging method. Originally, this plant mostly produced products packaged in small bags for the export market. Now customer demand is more and more shifting towards packaging in big bags (from 1% to 21% of the tons produced).

Formulations are determined by the Formulation department. This department is very knowledgeable when it comes to animal nutrition. The factory was previously owned by Provimi, a company internationally known for their expertise in animal nutrition. Cargill acquired the company and its knowledge five years ago. The price of Cargill's products (which are still sold under the Provimi brand) are a lot higher than the simpler feeds which are not customer specific. Because resulting animal growth and productivity are significantly higher, there is a business case for the customer. This business case is constantly recalculated by the formulation department. Revenues by extra growth or animal productivity are weighed against the cost of having the animal, the difference minus a margin can be invested in the animal feed responsible for the benefits. Factors like the price of milk and meat are also an important variable. Low milk prices will result in less use of sophisticated animal feeds because the profits obtained by increased animal productivity are much lower. To be able to answer customer demand, new formulations are introduced and unused formulations removed. This requires flexibility within the production process and supporting processes.

2.2. Production process

The factory produces an average of 350 MT per day divided into (on average) 32.7 production orders. This gives an average of 10.7 MT per product order. These production orders are divided into batches of around 2.4 MT. The production process can be divided into the following steps:

- Dosing the raw materials
- Controlling the weight of the dosed materials
- Mixing the raw materials into a product
- Controlling the aggregated weight of the product
- Pelleting the products (optionally)
- Packaging the products in bulk trucks, big bags or small bags

These steps and the machines used to perform these steps are graphically represented in figure 2.2. To really understand production, the methodology must be explained in more detail. The dosing installation of the system (consisting of step 1 and 2 in figure 2.2) is a shared component for most of the mixing lines. This installation doses a batch of one order alternately with the batches of other orders on other mixers. First, a batch is dosed in mixer 1, then a batch in mixer 2 and when the dosing installation dosed the last mixer, it will start with the first mixer again. This sequence depends on the amount of mixers used at that point in time. Each mixer makes its own type of product. Product types are assigned to a particular mixer at a particular time for contamination or compatibility reasons. Therefore, it is not always possible to operate all six mixers parallel. The parallel operation of mixers is called 'Gelijktijdigheid' within Cargill.

2.2.1. Dosing

The raw materials are dosed in a variety of dosing volumes and tolerances in batches of around 2.4 MT (depending on the density of the materials dosed). 'Carriers' like grains, soy, chalks and some other minerals are dosed in big quantities with wide tolerances. Finer materials like crucial minerals are dosed in small concentrated quantities with very small tolerances. The amount of these materials found in end products are often legally limited. Dosing fine materials happens on separate dosing stations and scales. Big quantities are dosed using a screw feeder (figure 2.3a) into weighing scales with capacities ranging from 0.5 MT to 3 MT (figure 2.3b). Finer dosings are dosed using an

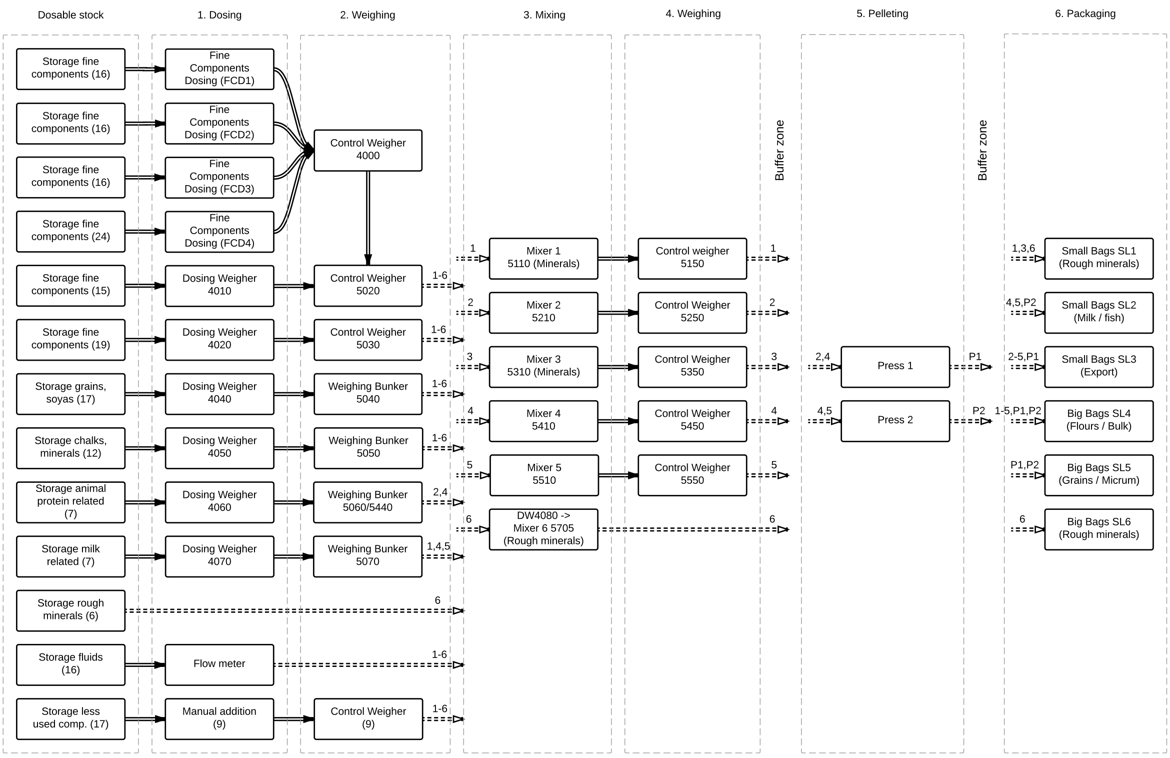
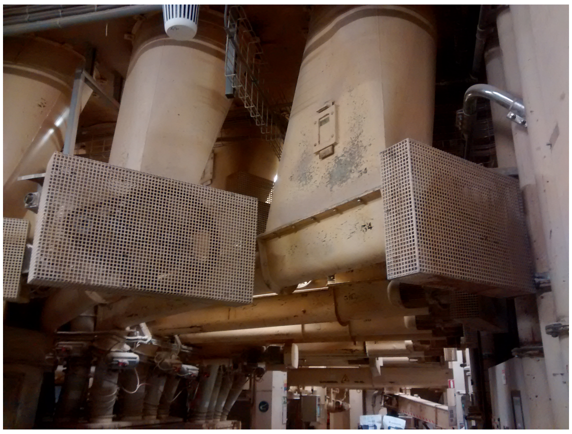


Figure 2.2: Detailed layout of production

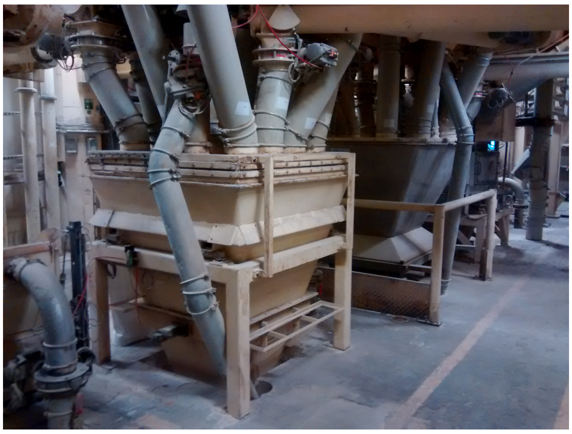
Alfra dosing slide (figure 2.3d) on an Alfra FCD unit (figure 2.3c). The Alfra FCD unit has movable weighing scales in which dosings from different silos can be dosed. A weigher-in-weigher concept is used to allow different weighing capacities in the same configuration. Dosing time (and therefore capacity) is strongly depending on dosing tolerances, type of material and dosing amount. Because the dosing installation is a shared component, products produced parallel to a product are also determining the dosing capacity. With the current product portfolio, the average time for dosing a batch takes 6:40 minutes. This makes the current capacity of the total dosing installation 9 batches (21.6 MT) per hour. After dosing, the weight of the dosed materials needs to be checked again to make sure the primary weighing scale is functioning correctly and materials do flow through the system. This happens before all ingredients come together in the mixer. All these steps have their own cycle times and ingredients from the same batch can have different positions in the system. The dosing step is finished when all ingredients of a batch are ready to be dumped in a weighing scale.

2.2.2. Mixing

Mixing is performed in six mixers. Mixer 1 and 3 are strengthened versions of mixer 2, 4 and 5. This makes them capable of handling minerals, these materials are in general more abrasive. Mixer 1-5 are all paddle mixers (figure 2.4). Mixer 6 is a course mineral mixer, this type of mixer is suitable for very abrasive course minerals. Mixer 1-5 have an estimated average mixing time of 14 minutes. Each of these mixers can produce 4.2 batches (10 MT) per hour. Mixer six has an estimated average mixing time of 30 minutes and a capacity of 2 batches (4.8 MT) per hour. The weighing scales before



(a) Screw feeder



(b) Weigher

(c) Alfra FCD unit, source [1]

(d) Alfra dosing slide, source [2]

Figure 2.3: Dosing equipment

the mixers only start dumping when all ingredients are present. This way, products do not get mixed for too long when an ingredient is delayed. First, all the solids fall into the mixer. When mixing, fluids enter the mixer via nozzles. After mixing, the batches of product are transported to the highest (7th) floor of the facility using blowpipes (figure 2.5). Only two blowpipes can be used simultaneously because there are only two compressors available. On average, these compressors blow the material up at a rate of an estimated 13 MT per hour. The product is blown into the product silos which are situated from the 4th to the 7th floor. From this step, the process is more continuous and less batch oriented. Batches of the same product run come together in the silos and are then regarded as a single production order.

2.2.3. Pelleting and packaging

The different batches of a product come together in this buffer zone before packaging and/or pelleting. The buffer zone contains 47 product silos in 7 clusters with a combined capacity of 831 m^3. The layout of these silos combined with the presses, mixers and packaging lines can be found in figure F.1. First, there is the option of pelleting the material. This happens in a press using a round die (figure 2.6b) and rotary rollers. These rollers push the material through the die. There are two identical presses with an estimated average capacity of 5 MT per hour. As with most machines in the

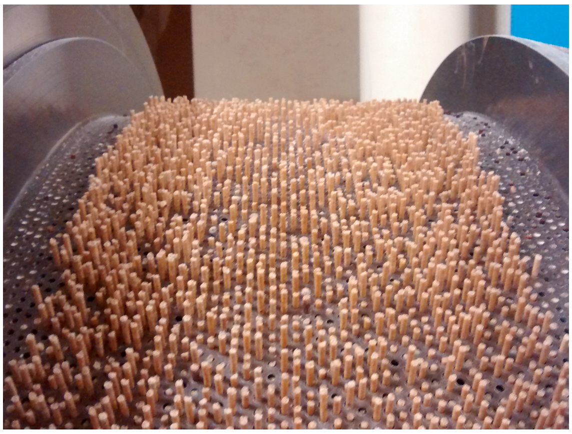
(a) Mixers 1-5

(b) Paddles inside mixer

Figure 2.4: Mixing equipment

Figure 2.5: Blowpipes used to transport material from mixing to product silos

(a) Press



(b) Die

Figure 2.6: Pelleting equipment

(a) Small bag packaging line SL3

(b) Small bag packaging line SL1,SL2

(c) Bulk packaging line SL4

(d) Big bag packaging line SL6

Figure 2.7: Packaging equipment

production line: the composition of the product determines the machine capacity. Some products are pressed easily while others take more time.

Products are packaged into small (ca. 25kg) or big (500-1500kg) bags on pallets or are directly dumped into a bulk truck. This happens on six packaging lines. 3 fully automated packaging lines are used to package the goods in small bags. A robot fills and closes the bags and another machine stacks the bags on pallets (see figure 2.7a and 2.7b). The operational capacity of these packaging lines varies from 7-12 MT per hour. However, there are (long) change over times involved. Different packaging materials (pallets, bags, stickers, sealing etc) are used for different products and these need to be replaced for each type of product. The big bags are filled in the three other packaging lines. One of the other packaging lines is also used to fill bulk trucks (only one function can be used at a time). Packaging in big bags is labor intensive: every big bag needs to be moved away by a forklift truck and the new bag and pallet need to be manually applied. Filling big bags is happening at a rate of around 6-8 MT per hour. However, this is strongly depending on the amount of manual actions necessary. Some products need to be packed as ADR ('Accord européen relatif au transport international de marchandises Dangereuses par Route') products. This involves sealing, stamping and other manual handling. Figure 2.2 shows the configuration of the packaging lines within the total production line. The packaging lines are configured as follows:

SL1 This line is used for packaging mineral products from mixing line 1,3 and 6 in small bags.

SL2 This line is used to package 'dirty' products in small bags. These products contain animal proteins and Coccidiostats traces.

SL3 This line was originally used for export products only. Nowadays, it is used to package products in small bags from all mixing lines except lines 1,6 and press 2.

SL4 This line is used for packaging products from all mixing lines except line 6 in bulk trucks or big bags.

SL5 This line is used for packaging products from the presses in big bags.

SL6 This line is used for packaging course mineral products from line 6 in big bags.

There are three shifts of three packaging operators. Therefore, only three packaging lines can be used parallel. SL4 is used for big bags throughout the night because during day time the bulk trucks get loaded on this line.

To conclude, the initial estimations of the nominal capacities made by the operators and historical proportional throughput are given in table 2.1. The estimations of the nominal capacities are later quantified in more detail in chapter 3.

Table 2.1: Initial estimation of nominal capacity and historical proportional throughput per line

Production step	Line	% of total tonnage	Estimated capacity (MT/h)
Dosing	Dosing line	100%	21.6
Mixing	Mixing line 1	12%	10
	Mixing line 2	11%	10
	Mixing line 3	28%	10
	Mixing line 4	23%	10
	Mixing line 5	19%	10
	Mixing line 6	7%	4.8
Pelleting	Pelleting line 1	14%	5
	Pelleting line 2	14%	5
	Not pelletized	72%	
Packaging	SL1	16%	7-12
	SL2	14%	7-12
	SL3	30%	7-12
	SL4 (Bulk)	19%	6-8
	SL4 (BB)	10%	4-8
	SL5	10%	6-8
	SL6	1%	6-8

2.3. Contamination

Contamination between production runs are a big concern and affect the production configuration of the system and the sequencing of products. Contamination issues are forestalled by the Food Safety and Quality Regulation (FSQR) department. The problem arising is the residue of (a component of) a product left in the system when a product run is performed. Variation and allowance of components of other products are limited and therefore this residue should be taken into account. Contamination risks are ruled out using three methods. Products are separated from other contaminating products by (in order of effectiveness):

1. assigning them to a particular mixing and/or dosing line
2. allowing them to be produced next to only a few other products
3. not allowing them to be produced after each other on a mixing/packaging line

There are several critical aspects of products when it comes to cross contamination:

Concentration Concentration differences between products determine the sequencing of production orders, residues of highly concentrated products have a big impact on low concentrated products, however, a product with an average concentration can be used between the product batches such that the system does not need to be flushed. Some products are so vulnerable to contamination that they can only be produced next to a few other products. (Methods used: 1, 2 and 3)

GMO Traces of Genetic Modified materials are sometimes not allowed in products. After producing a GMO product the line should be flushed with a GMO allowing non-GMO product or using non-GMO soya. (Method used: 1)

Coccidiostats Coccidiostats are a substance to retard the growth and reproduction of coccidian parasites. They can only be used in mixer 2. The coccidiostats are manually inserted in the mixer. If there is a different or no coccidiostat in the next production run, the mixer must be flushed. (Methods used: 1 and 2)

Animal proteins Ruminants are strict vegetarians. Animal proteins may not be found in their food because it ìncreases the risk of getting Boviene Spongiforme Encefalopathie ('Gekke koeienziekte'). Therefore animal proteins are dosed from a particular dosing line into mixer 2 and 4 (1 and 3 are used for ruminant feeds). (Methods used: 1 and 2)

Milk Milk products can not be used for some export countries (Russia and Iran). These countries have strict regulations regarding milk traces in animal feed. Because the production for these countries is decreasing rapidly, this rule is not very actual anymore. Milk components are still dosed from a separate dosing line.

2.4. Raw materials

There are around 430 types of raw materials. The raw materials can roughly be categorized under:

- Fine components, a variety of vitamins and minerals
- Grains and soy (GMO or non-GMO)
- Fishmeal related components
- Milk related components
- Coccidiostats
- Course minerals
- Fluids

Raw materials are delivered in small bags, big bags (together around 15%) or bulk trucks (around 85%). The materials are, in the case of solids, stored in stock or dose silos or on the production floor. Filling the bulk silos from bulk trucks is done by blowing the materials into the bulk silos through a blowpipe up to the 7th floor (figure 2.8a). Most other ingredients are manually dumped into the dose silos (figure 2.8b). Not all ingredients can be dosed from silos. Less used, or materials very sensitive to contamination are weighed and dosed manually in a dumping pit which is directly connected to the mixer. The request for a dump is given via the automation software. There are four types of silos in the production facility:

Stock silos 1 cluster containing 16 silos with a combined volume of 3648 m^3 used to store ungrounded soy and grains

(a) Raw material supply by bulk truck

(b) Dumping the fine components in silos

Figure 2.8: Dumping raw materials in silos

Dose silos: 11 clusters containing 152 silos with a combined volume of 2330 m^3 used to store dosable materials

Product silos: 7 clusters containing 46 silos with a combined volume of 831 m^3 used to store materials within the production process

Fluid silos: 9 clusters containing 16 silos with a combined volume of 216 m^3 used to store dosable fluids

The stock silos contain ungrounded materials like (GMO) soy and grains. These ungrounded materials are grounded in a hammer mill. The grounded materials are stored in a silo. This process is performed parallel to production. An overview of the product silos within the routing in the factory is given in appendix F.

2.4.1. Internal premixes

Within the factory, internal premixes are made. These premixes are handled as normal products, but after packaging, they are dumped into a dose silo and used for the production of other product. Internal premixes are made for a few reasons:

- To reduce the amount dosings. If a certain combination of raw materials is often used, it takes less time when one big batch is mixed, which in turn is used as a raw material for many other batches
- To decrease the number of manual dosings. Manual dosings are slow and labor intensive. By making a premix of various ingredients and automatically dosing this premix, less manual dosings are required.
- To decrease the dosing tolerances. A 'carrier' is introduced in which the to be dosed material is mixed. When the combination of the fine material and the carrier is dosed, the weighing tolerances can be bigger
- To reduce the number of dose silos used. By mixing several raw materials, only one silo has to be used for several raw materials. This can only be done when these raw materials are used often in the same proportions

2.5. Product release

Initially, most products are make to order (MTO). This demanded too much of production (no buffers, peaks and lows in production) and consumers wanted a shorter lead time. Therefore, Cargill made some products make to stock (MTS). Because there is not enough storage space in the factory, a third party (Neele-vat Logistics) collects and temporarily stores the finished products (MTS and MTO) and delivers them to the customers when ordered. A safety stock is contained for the MTO products and orders are automatically generated when this safety stock is used. This shortens the delivery time for most products from 5 to 2 days. Bulk trucks and export containers do not go through Neele-Vat. They are directly collected at the factory.

2.6. Conclusions

The product portfolio at Cargill Premix & Nutrition is highly diverse. This diverse product portfolio can not always be produced parallel or serial due to contamination risks. An order is produced in batches which are alternately dosed by a shared dosing installation in a mixer together with the parallel produced batches for the other mixers. These batches are collected in a silo after which they are pressed and packaged. Routes through the parallel lines for these 3 steps cross in many cases. Individual line capacities can be quite easily estimated, however, together they form a complex network of which the variables determining the overall capacity are unclear.

3

System analysis and conceptual model

This chapter defines and analyses the system as described in chapter 2. Using the Delft System Approach [13], a combination of soft and hard systems approach, the system is mapped, quantified and all relevant subjects addressed. The soft system approach is used to define the right problem, while the hard system approach is used to solve the problem in the right way. All activities are described as functions. This results in a conceptual model because the functions are not explicitly fulfilled. The general function of the system is firstly described using the black box approach, only the in- and output is defined while the transformation process is undefined. By zooming in the black box is opened and more, less aggregated functions of the system will be found. This method is used to go into detail at the right pace, without neglecting relevant subsystems while zooming in.

3.1. Data

Sources The data used for quantifying the processes of the system are gained from the process automation software package. Promas registers when dosing is started and when the product batch has entered the buffer zone between mixing, pelleting and packaging. It does the same for the pelleting lines, the packaging lines and the manual addition of materials in the dumping pits. The time

	A	B	C	D	E	G	H	I	J	K
1	Procescel	Blender	Gestart	Gereed	Prod opdracht	Artikelnr	Artikelnaam	Gewenst	Gedoseerd (kg)	Locatie
2	BL1	R2	4/1/2016 12:05:57 AM	4/1/2016 1:06:02 AM	00362014:5	F401302116000	23303 SPRINT GRO	2705	2704.8	E102
3	BL1	R3	4/1/2016 12:09:36 AM	4/1/2016 1:30:33 AM	00361732:1	F401308311000	33203 ABZ PREMIU	2655	2657.4	E806
4	BL1	R5	4/1/2016 12:29:08 AM	4/1/2016 1:21:52 AM	00361779:1	F401301417000	52303 EASYPIG 4 -	2400	2391.9	E704
5	BL1	R6	4/1/2016 12:47:58 AM	4/1/2016 2:13:29 AM	00361979:1	F401308896000	61203 RUVITAL MA	2125	2102.8	E810
6	BL1	R1	4/1/2016 12:57:44 AM	4/1/2016 1:30:58 AM	00361744:1	F401300399000	13203 PR 0399: 80	2050	2050.5	E706
7	BL1	R2	4/1/2016 1:01:32 AM	4/1/2016 1:43:47 AM	00362014:6	F401302116000	23303 SPRINT GRO	2705	2703	E102
8	BL1	R3	4/1/2016 1:09:11 AM	4/1/2016 2:31:00 AM	00361732:2	F401308311000	33203 ABZ PREMIU	2655	2655.3	E806
9	BL1	R5	4/1/2016 1:15:29 AM	4/1/2016 2:27:46 AM	00361779:2	F401301417000	52303 EASYPIG 4 -	2400	2393.8	E704
10	BL1	R6	4/1/2016 1:49:48 AM	4/1/2016 2:59:02 AM	00361979:2	F401308896000	61203 RUVITAL MA	2125	2103.1	E810
11	BL1	R1	4/1/2016 2:03:08 AM	4/1/2016 3:06:24 AM	00361744:2	F401300399000	13203 PR 0399: 80	2050	2053.6	E706
12	BL1	R2	4/1/2016 2:06:20 AM	4/1/2016 3:30:55 AM	00362014:7	F401302116000	23303 SPRINT GRO	2705	2706.7	E103
13	BL1	R3	4/1/2016 2:45:19 AM	4/1/2016 3:25:27 AM	00361766:3	F401301617000	32203 GESTANTI 3	2425	2425.8	E801
14	BL1	R6	4/1/2016 2:49:29 AM	4/1/2016 4:12:29 AM	00361981:1	F401308894000	61203 RUVITAL VR	2125	2117.6	E809
15	BL1	R1	4/1/2016 2:54:35 AM	4/1/2016 4:02:33 AM	00361701:1	F401300291000	13203 FCD 0291: P	2500	2499.6	E706
16	BL1	R2	4/1/2016 3:03:15 AM	4/1/2016 3:59:39 AM	00362014:8	F401302116000	23303 SPRINT GRO	2705	2706.2	E103
17	BL1	R3	4/1/2016 3:15:20 AM	4/1/2016 4:10:08 AM	00361754:1	F401302088000	32203 SWINE FATT	2000	1990.2	E707

(a)

	B	C	AO	AP	AQ	AR	AS	AT	AU
1	Day	Time	Mixl. 1	Mixl. 2	Mixl. 3	Mixl. 4	Mixl. 5	Mixl. 6	Batches/30min
2	Tue	9/1/2015 0:00							
3	Tue	9/1/2015 0:30	1.5	1	1				3.5
4	Tue	9/1/2015 1:00	1	1	0.66667			1	3.66667
5	Tue	9/1/2015 1:30	0.66667	1	0.66667				2.33333
6	Tue	9/1/2015 2:00	0.66667	0.66667	0.66667				2
7	Tue	9/1/2015 2:30	1	0.66667	1	1		0.5	4.16667
8	Tue	9/1/2015 3:00	1	1	1	1		0.66667	4.66667
9	Tue	9/1/2015 3:30	1.33333	1.33333	1			0.33333	4
10	Tue	9/1/2015 4:00	1.5	1.5				0.66667	3.66667
11	Tue	9/1/2015 4:30				2		0.5	2.5
12	Tue	9/1/2015 5:00				2	1		3
13	Tue	9/1/2015 5:30				2	1		3
14	Tue	9/1/2015 6:00				1.66667			1.66667
15	Tue	9/1/2015 6:30				2			2
16	Tue	9/1/2015 7:00				2.66667			2.66667

(b)

Figure 3.1: (a) Raw batch data from Promas (b) Edited, time oriented data

records for the packaging lines are depending on when the operator releases the product order. The original batch data gives the following properties for every individual batch or, when applicable, order:

Process cell	This variable indicates what particular step (Dosing/Mixing, Pelleting, Packaging, Manual dumping) is recorded
Mixing line	This variable indicates which mixing line is used
Start time	Starting time of the process step
End time	End time of the process step
Production order	This is the identifier of the production order, this run is divided into batches of (on average) 2.4 MT, records are based on these batches for the mixing lines, this order number is related to the SAP system
Product number	A product number is a unique number for the formulation, or the formulation with the applied packaging form, this number is also used in the ERP system
Product name	This is the product name corresponding to the product number
Wanted (kg)	This is the amount of material that should be dosed
Dosed (kg)	This is the amount of material that is actually dosed
Location	This variable is used to indicate the destination silo of the batch

Data method This data is converted to a time-oriented instead of batch-oriented table. This is done by plotting the start and end times in discrete time buckets. The number of batches is also inserted and multiplied by the batch weight to get the input per time bucket.

$$Q_{input}(t) = n_{batch}(t) * w_{batch}(t) \tag{3.1}$$

Where Q_{input} is the input of the system time bucket, t is the bucket index, n_{batch} the number of batches dosed in a time bucket and w_{batch} the weight of the batches dosed. These discrete time buckets do not give the right representation of the average input of the dosing lines at that time because the frequency of the start times might be close to the time bucket frequency, which causes unrealistic variations of the input Q_{input}. To avoid this phenomena a moving average is used. It is assumed that the input changes gradually over time:

$$Q_{input,ma}(t) = \frac{\sum_{i=t-\frac{m}{2}}^{t+\frac{m}{2}} n_{batch}(t=i) * w_{batch}(t=i)}{m} \tag{3.2}$$

Where $Q_{input,ma}$ is the average input of the m time buckets and t indicates the current time bucket. Now the data can be used to analyze production capacities and look what variables like lead time, parallel operation, product formulation and mixing lines have on the mixing capacity. An example of the raw and rewritten data is given in figure 5.7. Behind the product number, the ingredients can be found using a Bill Of Materials database from the ERP system. By combining this data with the specific workstation the ingredient is dosed from, it is possible to determine which workstations are used to produce a formulation. Using 'R', an open-source programming language for statistical analyses, the data is converted into readable and meaningful diagrams and numbers.

3.2. Context and definition of the system

First, the root definition of the system is formulated using the CATWOE method [5]. A root definition is a structured description of the core activity of a system. Defining the system' root definition helps to define the boundaries and function of the system while paying attention to the context of the system. The different aspects of CATWOE are formulated as:

C Consumer: farmers, feed millers and traders

A Actors: operators and the SCM department of Cargill

T Transformation process: transforming raw materials to customer specific animal nutrition

W Worldview: to make productive food for animals such that animal protein as a nutrient is available to everybody

O Owner: Cargill

E Environmental constraints: Food safety and quality (FSQR), environmental, health and safety (EHS) regulations

These aspects can be brought together in the root definition of the system:

> *A system owned by a private company named Cargill, to convert raw materials to customer specific animal nutrition for farmers, feed millers and distributors using equipment, the operators and the SCM department of Cargill while taking into account quality and safety regulations.*

The system boundaries for this particular case are drawn around the production facility where the actual transformation occurs. This includes the supply chain management (SCM) department which controls this function, but it excludes the environment, safety and health (EHS) department, food safety and quality regulations (FSQR)department, the formulation department and sales department. These departments make requirements (standards) for the function of the system and will be left outside the system scope. The main function of the system is to transform raw materials into customer specific animal nutrition. The physical in- and output of the system are raw materials and packaging materials, the physical output of the system consists of customer specific animal nutrition. While transforming raw materials to customer specific animal nutrition, requirements from customers, governments and Cargill international are translated into feasible standards by the FSQR, EHS and SCM departments (The control function) The most important requirements are quality, On Time Delivery (OTD) and safety. These requirements translate into standards like a production schedule, safety regulations and quality regulations. The system delivers results. These results are translated into performance indicators by the production control. The most important performance indicators are: Overall Equipment Effectiveness (OEE), the number of non-conformities (defects), operator FTE's, production costs and OTD. A function black box of the system is visually represented in figure 3.2. The transformation process is an industrial process:

- The process is repetitive. Cargill produces many different types of animal nutrition and does so in a repetitive way.

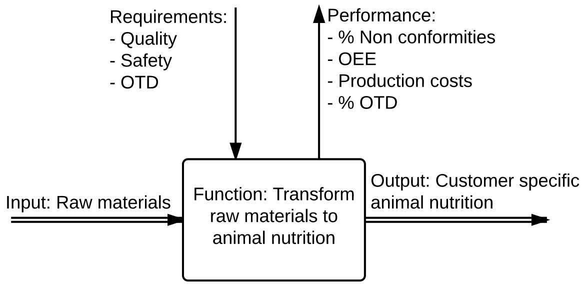


Figure 3.2: Function black box of the system

- The system controls the making of a series of products. In this case, the system is static while products travel through it, which means the system is controlling the making of a series of products.
- The system has many repetitive processes. For example, Cargill simultaneously handles orders, makes products and uses equipment repetitively. These are called aspects of the system.

According to Veeke et al. (2006) three aspects should always be present in an industrial system:

- Products should flow through the system as elements to be transformed. In this case, the raw materials are transformed into animal nutrition by flowing through the system.
- The transformation takes place using resources like personnel and factory equipment. These resources are used and discarded after their lifetime.
- Orders are transformed into handled orders. Without customers ordering animal nutrition, there would be no flow through the system.

These aspects come together in a basic Conceptual model for Industrial Systems (CIS) [12] which, for this particular situation, is graphically represented in figure 3.3. To further explain the interaction between the different aspect models 'Handle', 'Produce and 'Use' a list of information and automation systems used at Cargill is given:

SAP Enterprise Resource Planning (ERP) system. Used to automate many back office functions related to technology, services and human resources. All customer orders and physical goods are registered in this system.

Promas ST Process automation system: Most equipment is controlled and automated using this system. Has an interface with SAP (figure 3.4).

Actemium System used to print labels for finished / premixed products. Collects data about goods produced from SAP.

AS400 This is a software package developed by a Cargill employee. The software is used to determine whether the production sequence (per individual line) is allowed. It looks at nutrient level whether the residue left by a product is allowed in the next product. It does not determine the sequence.

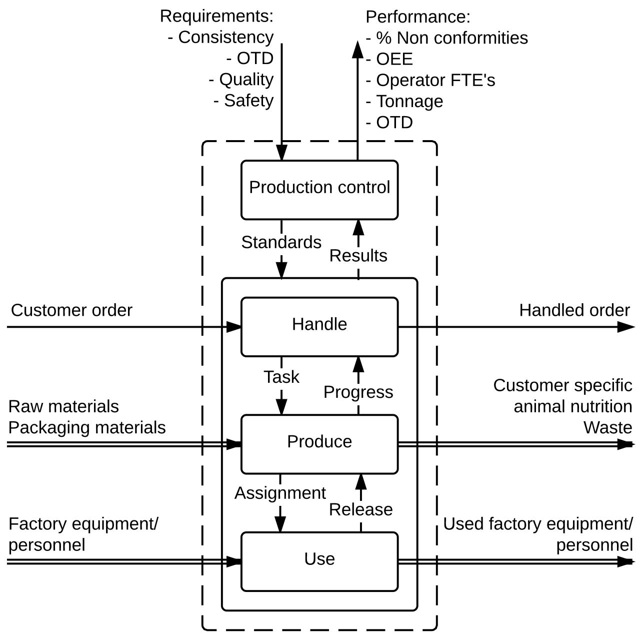


Figure 3.3: Basic conceptual model for industrial systems (CIS) for Cargill CPN

Figure 3.4: Promas ST, the process automation software package

By zooming in one level the three aspect models 'Handle', 'Produce' and 'Use' can be distinguished. These aspect models show the different flows through the system. Orders are handled and transformed to handled orders, customer specific animal nutrition is produced using raw materials and packaging materials and to realize this production equipment and personnel is used.

3.3. Planning hierarchy

At the strategic level, planning of production is performed in an aggregated way with a long horizon. The supply chain management department recently changed from a full MTO system to a mixed MTO/MTS system. Another development is the implementation of Sales and Operation Planning. By forecasting the sales based on historical data, operation planning can be better anticipated by breaking the Sales and Operation Planning down into a Master Production Schedule. This Master

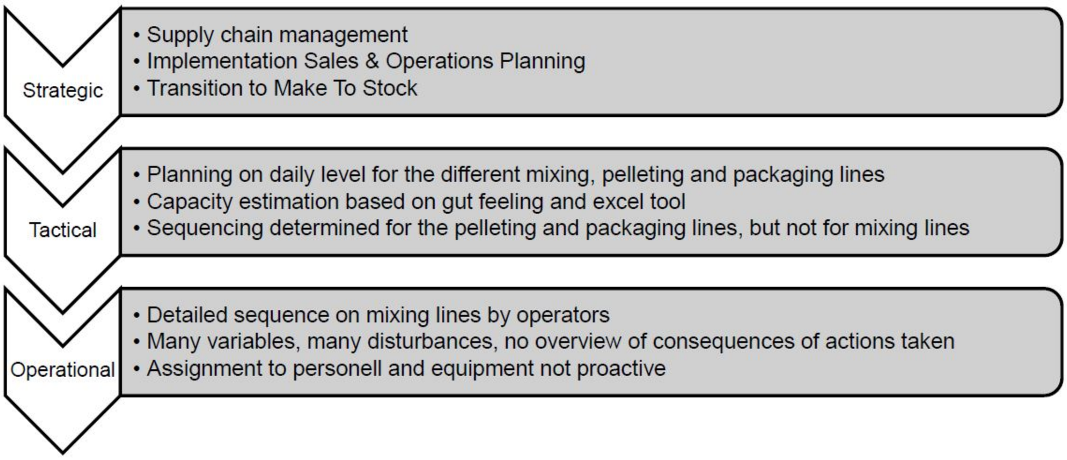


Figure 3.5: Main characteristics of planning hierarchy

Production Schedule plots the forecasted demand on the available capacities and corrects the Sales and Operating Planning where necessary [14]. This results in a feasible planning.

At the tactical level, tasks are initiated by a customer order and passed on to the production control via the production planner. The production planner is an employee of who knows the system very well, he has a good 'gut feeling' of what the capacities of the different elements and aspects in the system are. An Excell template is used to fill the 'buckets' of the different lines (6 Mixing lines, 2 pressing lines, 6 packaging lines). This is done by forward operations scheduling, which means that the jobs with the earliest due dates are scheduled first. A rough estimate is automatically made of the capacity needed for every particular order. The production planner then generates a sequence plan for the pressing lines (which have long setup times in case of a die change) and packaging lines (this plan is mostly ignored by the operators). The production planner asks for later ultimate delivery dates if necessary, and shifts jobs between days to get a manageable schedule. The results are communicated to the operational personnel using an excel sheet with all the orders and printed overviews for the sequence of the pressing and packaging lines.

At the operational level, production control consists of three shifts of operators. Night shifts consist of 2 operators while the day shifts consist of 4 operators. Every afternoon the operators receive the excel file with the tasks scheduled for the following day. In general, the operators can choose from orders planned for the current and next day. The A-operators assign the tasks to the operators and equipment. The tasks assigned to operators are packaging tasks, changing the press die, cleaning, maintenance tasks, filling silos, manually dumping materials in the mixers, and weighing the to be manually dumped materials. The assignment to the equipment is performed using Promas. The operators determine the detailed sequence of production assignments using the contamination indicating tool (AS400) and then assigns the production tasks to the mixing lines by releasing the tasks in Promas. The operators determine the packaging sequence based on the occupation of the buffer between the mixing, pelleting and packaging lines. The sequence of packaging is mainly determined by the due date of the particular product. Since the jobs are scheduled by the due date at a tactical level, this results in First Come First Serve (FCFS) sequencing. A similar manner of communication is used for the assignment of manual dosing jobs (both dumping in silos and mixers). Promas indicates materials needed for the scheduled orders. However, most of the times only a few orders are already scheduled, which results in surprises. In general, the operator scheduling the jobs has to take many variables into account: raw materials levels, end product silo availability, press die changes, ultimate delivery dates, routing and contamination rules. Many processes are not proactive because there are disturbances in the system. Together with an increasing amount of product types made per day, it is a very complex puzzle to solve.

According to Van Wezel et al. (2006) this type of planning hierarchy is typical for medium sized enterprises in the food processing industry. Production planning is performed outside the ERP system without the use of an Advanced Planning System (ADS) like a scheduling algorithm.

Each of the three aspect models ’Handle’, ’Produce’ and ’Use’ are discussed in the following paragraphs.

3.4. Functions of ’Handle’

The subsystem ’Handle’ is crucial, but has a small part within the current system boundaries. Customer orders come in via the SAP system. Based on the location of the customer, the SAP system calculates an ultimate production deadline by taking into account the transfer to the Neele-Vat warehouse and the transportation from the Neele-Vat warehouse to the customer. The production planner gets these deadlines and converts them into production orders. When planning the production planner takes into account what the rough capacity of the considered mixing line, press, or packaging line is. Orders are almost always accepted, but in some cases, production capacity is not sufficient. The production planner then asks for a later ultimate delivery date. Finished (packaged) products are registered in SAP, making it a handled order. The lead time of the product from the order point is 5 workdays for make to order products and 2 workdays for make to stock products.

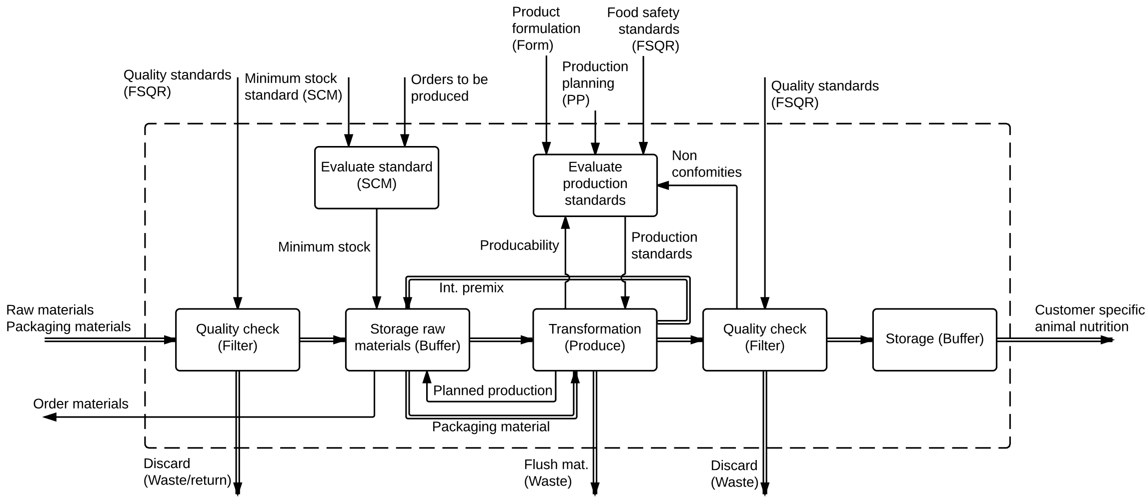


Figure 3.6: Detailed functional model of 'Produce'

3.5. Functions of 'Produce'

The functional model of the 'Produce' function of the system is represented in figure 3.6. The 'Produce' function contains three types of sub-functions: 'Quality check', 'Storage' and 'Transformation'. These subfunctions will be explained in the next paragraphs.

3.5.1. Quality check and storage raw materials

The input zone is the zone where raw materials are stored and correctness of raw materials is checked. Cargill takes samples of all supplied raw materials. The samples are send off to the laboratory where the materials are analyzed. If an input batch is discarded it will not be taken into production. This is a filter function of the system which guarantees the input elements agree to the quality standards. Figure 3.7 shows a more detailed, zoomed overview of the functionality of the input storage. As can be seen, some materials need to be grounded before use, these materials are primarily stocked in the

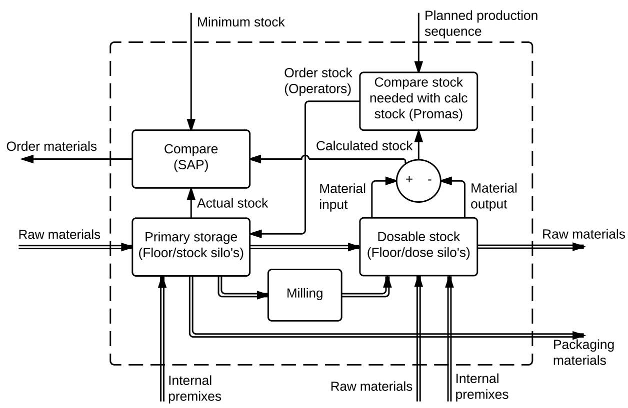


Figure 3.7: Detailed functional model of 'Storage raw materials'

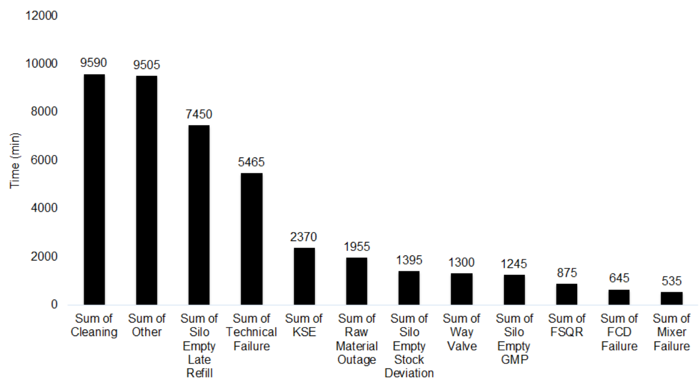


Figure 3.8: Reasons for downtime (8,94% of the operational time) in FY16

stock silos. The control loops for getting a minimum stock are based on minimal stock standard, at a certain order point an order will automatically be triggered towards the supplier. This order point is sometimes adjusted by Supply Chain Management if a certain raw material is used more often. A problem arising in this subsystem is the availability of dosable raw materials. Raw materials are very often available on the production floor, but before they can be dosed, the materials should be dumped in the dose silos. Figure 3.8 shows the main reasons for downtime in FY16. One of the main reasons for downtime and potentially for restricting production is 'Silo Empty Late Refill'. One of the operators has the task of dumping raw materials in the dosable silos and the dump pits next to the mixing lines for manual addable ingredients. These tasks are communicated by the operators using Promas. Promas gives a forecast of the levels of all silos by calculating the ingredients to be used by the scheduled products. Using this information, the operator who dumps the raw materials knows what to dump to maintain production of the scheduled orders. The main reason for the increase in downtime was that the operators have many parallel jobs and are not always available for dumping raw materials. To get a better utilization of the system, an extra operator is now hired who focusses on dumping raw materials. Besides, the bucket 'Other' is much too prevalent in the measurement of reasons for downtime. During the assignment, the feedback loop of disturbances is improved by making the list mutually exclusive and collectively exhaustive (MECE). Meaning that every subject is covered and the 'other' bucket is unnecessary. The result is the following list:

- Logistical failure
  - Late supply raw material
  - Late refill raw material
  - Stock deviation raw material
  - Silo empty calibration
  - Full product silos
  - No parallel production
- Technical failure
  - Dosing
  - Mixing
  - Pelleting

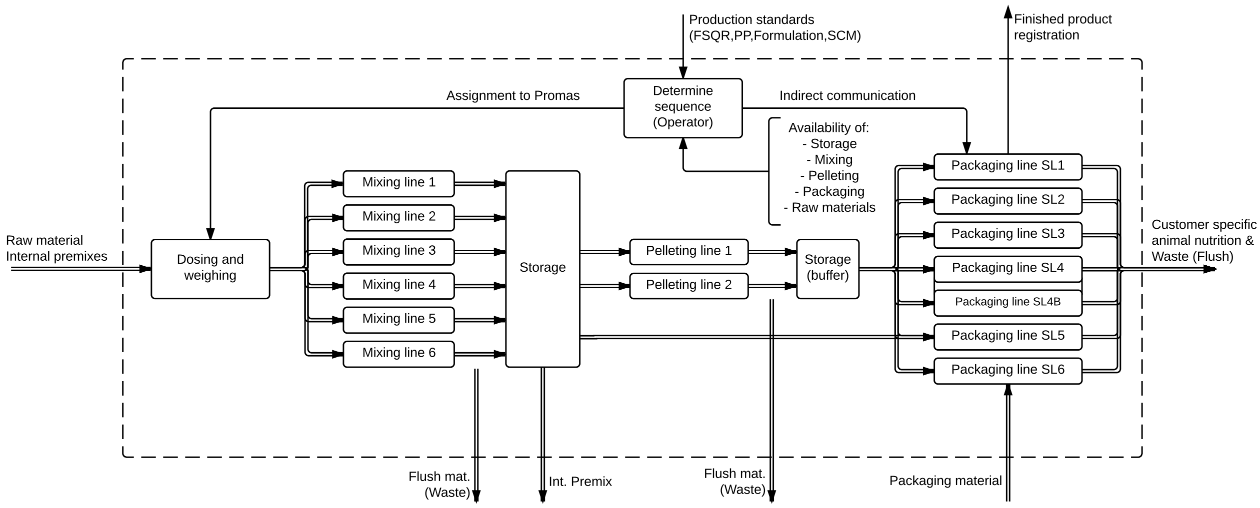


Figure 3.9: Functional model of 'Transformation'

- Packaging
- Material transport
- KSE

• Other

- Product test
- Cleaning
- Planned interuptions
- FSQR

Furthermore, an accompanying legend explains what the content of the buckets should be such that all operators put the downtime in the right bucket.

3.5.2. Transformation

The physical transformation of raw materials and packaging materials into customer specific animal nutrition is the main function of this subsystem. To realize this main function, five steps are distinguished:

1. Dosing the raw materials and controlling the weight of the dosed materials on the dosing line
2. Mixing the raw materials into a product and controlling the weight of the mixed materials on the mixing lines
3. Transporting the material to the product/press silos
4. Pelleting the products and transporting the products to the product silos on the pelleting lines (optional)
5. Packaging the products in bulk, big bags or small bags on the packaging lines

Dosing and controlling the weight of the dosed materials consist of a single flow (the dosing installation), which means that the product batches flows in a single series through the system.

Mixing and controlling the aggregated weight are separated in six parallel flows, pelleting in three parallel flows and packaging in six parallel flows.

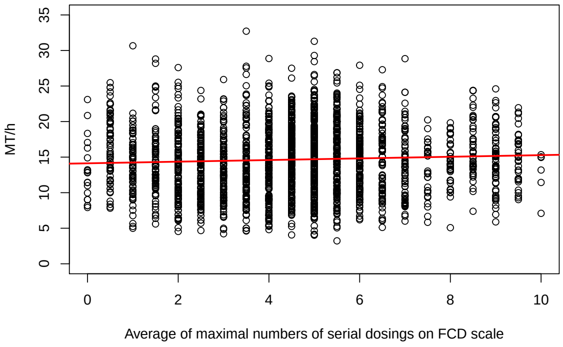
Dosing

Dosing and controlling the weight of the current product portfolio has an average maximum capacity of 21.4 MT/h. To get an idea of the impact of the dosing times on the overall output of the system, an analysis of the dosing times is performed. According to KSE [3], the manufacturer of the weighing scales and automation software, the dosing time is defined by the following variables (in order of importance):

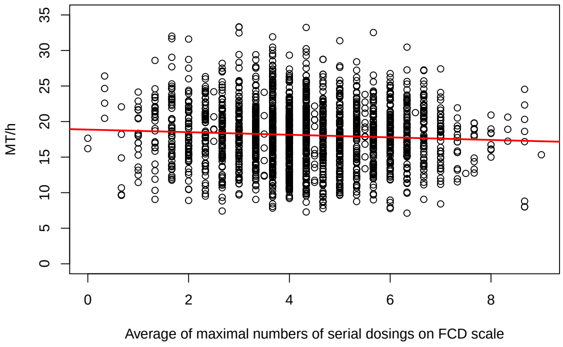
- Number of dosings in series, if a piece of equipment needs to dose a series of dosings, the tolerance must be met several times. Therefore, the number of dosings on a weighing scale is an important indicator.
- Dosing tolerance, the dosing equipment starts with a very high throughput but ends with a very low throughput, to make sure the material is dosed accurately. The higher the tolerance, the lower the throughput at the end and the longer the dosing time.
- Dosing amount, the amount of material to be dosed only determines some of the dosing time, but it has an effect.

First, the number of dosings for each weighing scale is determined for all 1000 formulations. Next, this data is used to look at what the effect is on the overall output of the mixing lines. Figure 3.10 indicates the output of the system as a function of average maximal serial dosings on an FCD weighing scale. As can be seen, this variable influences the output of the system only slightly and increasingly with more parallel operating mixing lines. This analysis is performed for all parallel weighing scales. It is observed that the number of dosings and amount of material dosed per station are of little influence on the overall output but becomes more important when the number of parallel operating mixing lines increases. In figure 3.11 the overall production output as a function of the amount of to be manual dumped material is visualized. The number of parallel produced products which require manual dumping does influence the overall output as can be seen in figure 3.12. This makes sense because this is done by one employee. If the number of dumps increases, this employee has too many jobs to do which results in waiting times. For figure 3.11 and 3.12 only the cases with three parallel operating mixing lines are used because the number of parallel operating mixing lines influences the output most (figure 3.14).

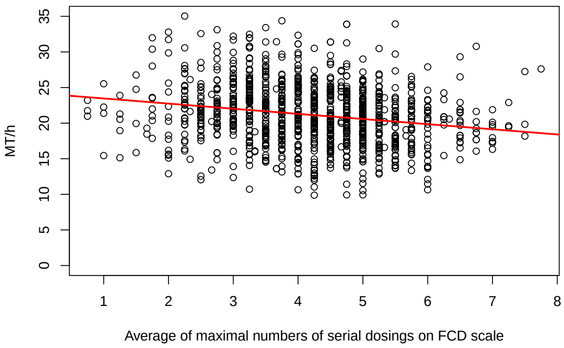
The output of the dosing installation is the input of six parallel flows (the mixing lines). These mixing lines are, when all lines are used, consuming the full capacity of the dosing lines. Using the production history the capacity of the system as a function of the number of mixing lines used is analyzed. The capacity as a function of the number of parallel operating mixing lines is given in figure 3.14. As can be seen, the average capacity of the system is highly depending on the amount of mixing lines used in parallel. Variation around this average capacity is mainly caused by differences between mixing lines and product concentrations as described previously. Mixing line 6 has a different dosing frequency because the cycle time of this mixer is longer.



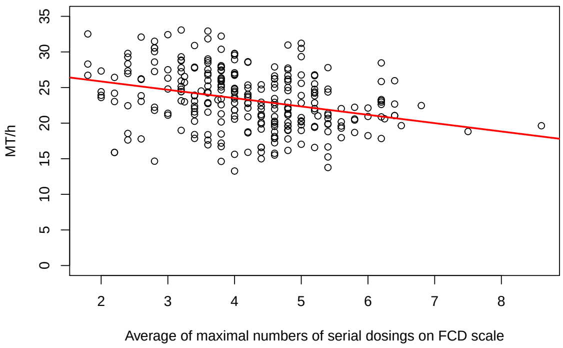
(a) With 2 parallel operating mixing lines



(b) With 3 parallel operating mixing lines



(c) With 4 parallel operating mixing lines



(d) With 5 parallel operating mixing lines

Figure 3.10: Input as a function of average maximal serial dosings on a FCD weighing scale

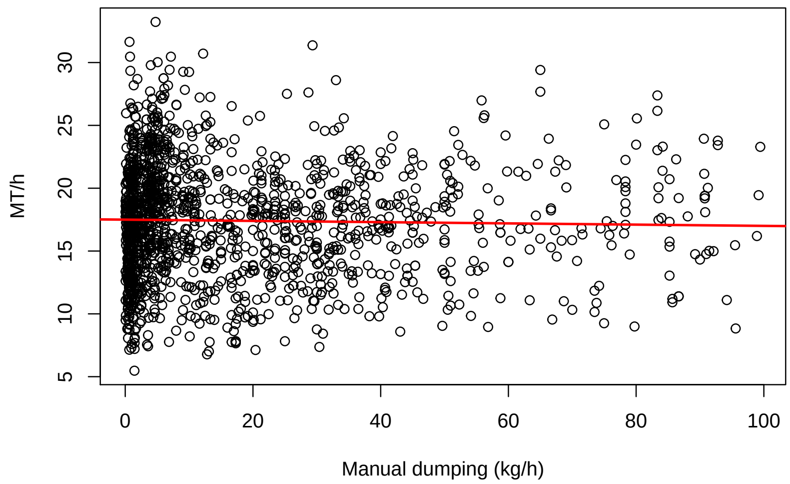


Figure 3.11: Input as a function of amount of manually dumped material

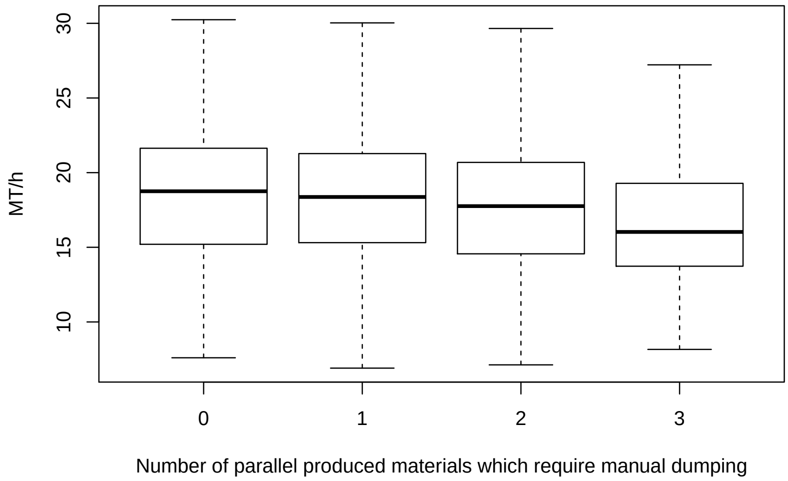


Figure 3.12: Input as a function of the number of parallel produced products which require manual dumping

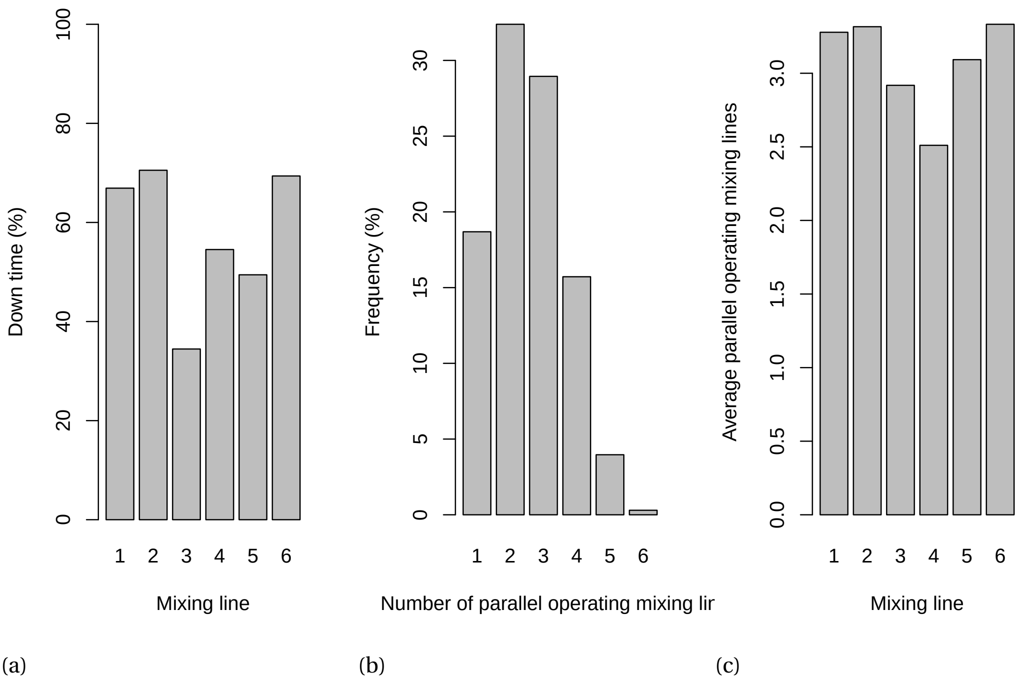


Figure 3.13: (a) Percentage downtime of individual mixers (b) Percentage of amount of parallel operating mixing lines (c) Average parallel operating mixing lines for each mixing line

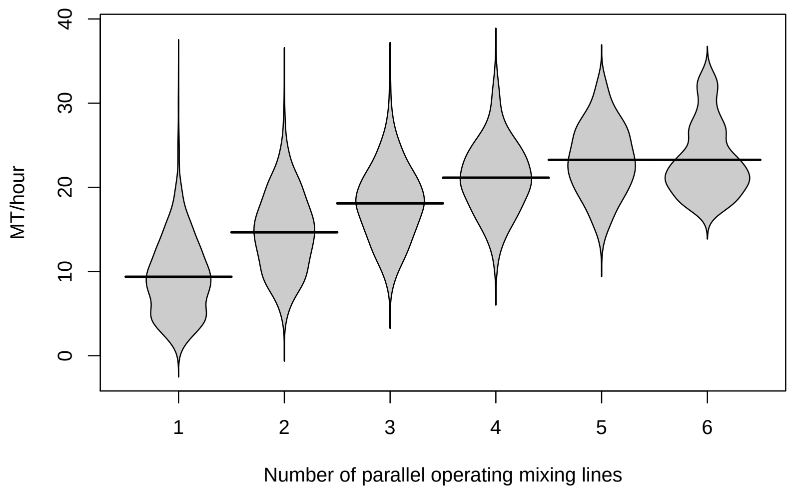


Figure 3.14: Capacity of production as a function of parallel operating mixing lines

Figure 3.13a shows the average downtime of the mixing lines. This the individual downtime excluding the overall downtime (8,94% of the operational time). As can be seen, mixing lines are poorly utilized (max 65% of the time). Individual mixing lines operate apart from each other. Figure 3.13b shows the frequency of the amount of parallel operating mixing lines. The average amount of parallel operating mixing lines is 2.55 mixing lines. When extrapolated from figure 3.14 this corresponds with an average output of 15.87 MT/hour. This number is confirmed by looking at historical output measures. It is clear that with more parallel production, the output will increase, for example: 4 parallel operating mixers give an average output of 21 MT/h (32% higher).

The reason for increasing production capacity with increasing number of parallel operating mixing lines can be explained when looking at the dosing sequence of the batches of around 2.4 MT in the different mixing lines. Figure 3.15a shows the dosing sequence when four mixing lines are utilized. When the dosing sequence of mixing line 1-4 is finished, the first mixer is just ready to receive another dosing. When the sum of the cycle times of the different dosing line ($t_{c,dl}$) are equal to the cycle time of the mixing line ($t_{c,ml}$), there are no waiting times (t_w) which results in a maximal utilization of the dosing installation. The equilibrium which is found is given in equation 3.3.

$$\sum t_{c,dl} = t_{c,ml} + t_w \qquad \forall \qquad \sum t_{c,dl} < t_{c,ml} \tag{3.3}$$

Figure 3.15b shows the same situation when only two mixing lines are utilized. Because the sum of the cycle times of the different dosings is less than the cycle time of the mixing line, the waiting time increases which results in less utilization of the dosing installation and thereby a lower output. The other extreme is also possible: when the sum of the cycle times of the dosings is bigger than the cycle time of the mixing lines, waiting times will be seen in the mixing lines. The lead time of the mixing line ($t_{ld,ml}$) will then increase. This is a missed opportunity because one of the products

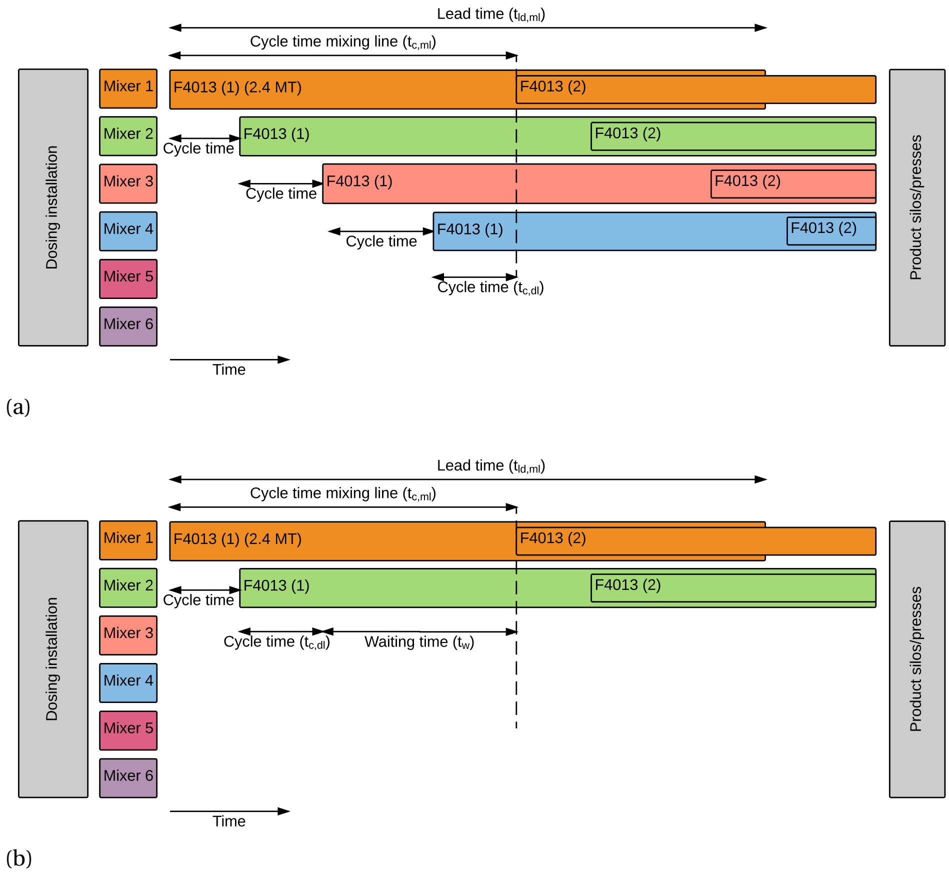


Figure 3.15: (a) Cycle and lead times with 4 parallel operating mixing lines (b) Cycle and lead times with 2 parallel operating mixing lines

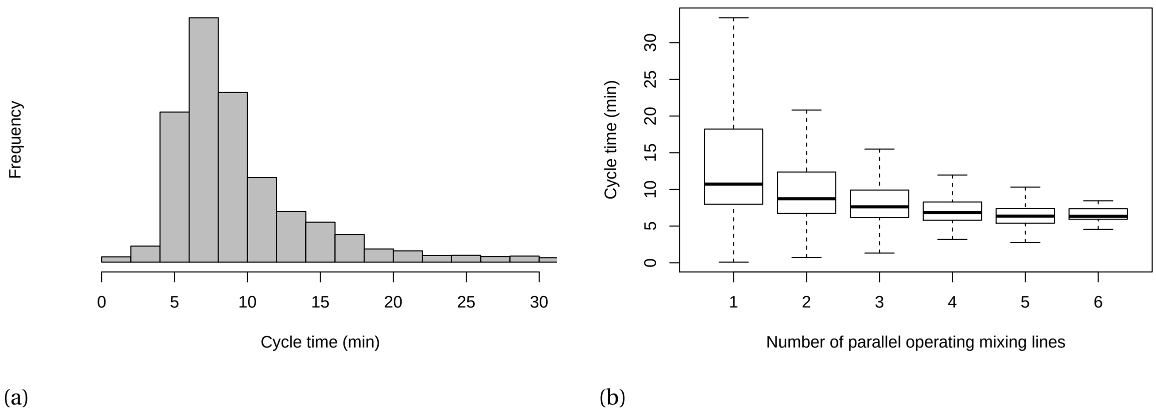
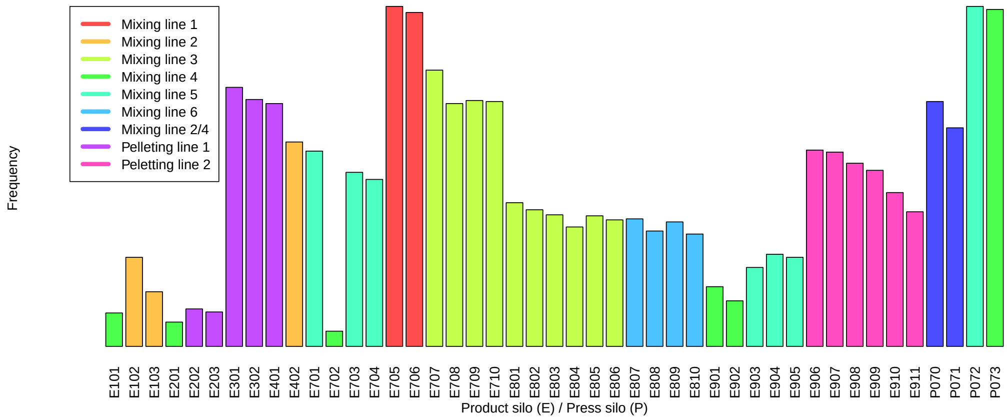


Figure 3.16: (a) Histogram of cycle times $t_{c,dl}$ plus waiting times t_w (b) The same times as a function of parallel operating mixing lines

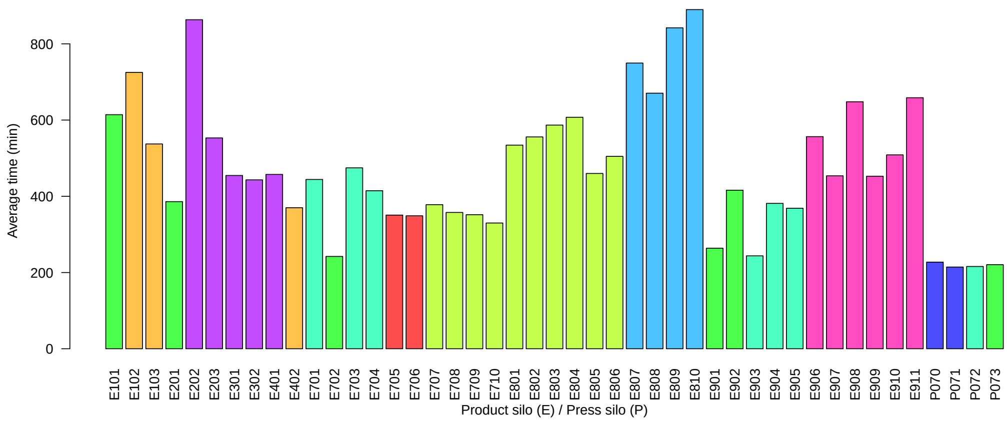
produced on one of these mixing lines could also be produced at times of less parallel production and thereby increase output at that particular time. The mean cycle time is currently 10.26 minutes (The median from the observations is 8.15 minutes). The cycle time is distributed as visualized in figure 3.16a. In figure 3.16b it is clearly visible that the variation in cycle time decreases with increasing parallel operating mixing lines. This makes sense because the waiting times are included in the cycle times which causes the variation. The lead time has little correlation with the cycle time. An equilibrium needs to be found to generate the ideal output and this equilibrium is not found at an average of 2.55 parallel mixing lines.

After mixing, the batches are blown to a storage zone consisting of 34 silos. This step in the process is performed using two compressors. When only one mixing line is operated, only one compressor is used because there is only one blowpipe to be operated. As shown earlier, the dosing step is not the bottleneck when only one mixing line is operated. The mixing step has a constant cycle time for all products, almost every product needs the same mixing time, which is the longest step in the mixing line. However, variation in the output of one mixing line is still observed. The main cause can be found in the discharge of the material via the blowpipes (figure 2.5). Materials with very fine ingredients are transported at a lower rate (MT/h) than materials with rougher (and in general lighter) ingredients.

The product and press silos are not available to all mixing lines. 30 of the silos are directly connected to the packaging lines (Product silos). The 4 other silos are connected to the 2 pelleting lines (Press silos). Between the pelleting lines and packaging lines there are another 11 silos. The exact layout is given in figure F.1. The frequency of usage for all silos is visualized in figure 3.17. As can be seen, the silos are not evenly utilized. Mixing line 1 and 3 produce 40% of all the products (see table 2.1), however, mixing line 1 has only two product silos while mixing line 3 has ten product silos. The utilization of the two product silo of mixing line 1 is much higher than the silos of mixing line 3. However, mixing line 3 produces more than twice as much (28% vs. 12% of the total tonnage). Apart from the amount of product silos the two mixing lines are identical. This example illustrates how the number and utilization of product silos affect the opportunity for the parallel operation of mixing lines. This is due to the fact that there is much capacity variation and the buffer captures these variations between the preceding and subsequent production step. If the buffer space was equally divided, both lines would produce 20% of the total tonnage. This would increase parallel production and thereby the productivity. Another interesting point about the storage zones is the time a product run remains in the buffer. On average, a product run will remain in the product or press silos for around 475 minutes. Figure 3.18 shows the distribution of the times spent by the products in the silo. The lower the time spent in a silo, the more opportunity for silo usage (and thereby parallel operating mixing lines) there is. A decrease in Work In Progress (WIP) can make the system more flexible and give the opportunity for productivity improvements, however, not all routes have the same amount of silos and receive the same amount of orders. Some routes are therefore more critical than others.



(a)



(b)

Figure 3.17: Frequencies (a) and average times (b) of product and press silo usage

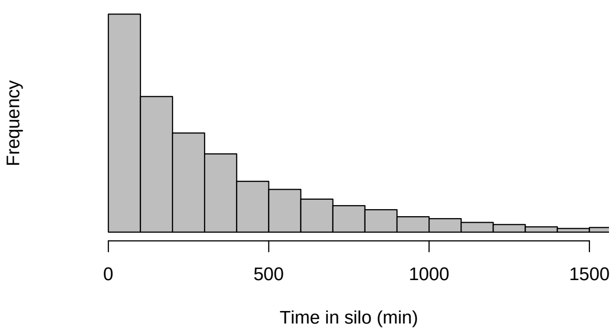


Figure 3.18: Distribution of time spend in product and press silos

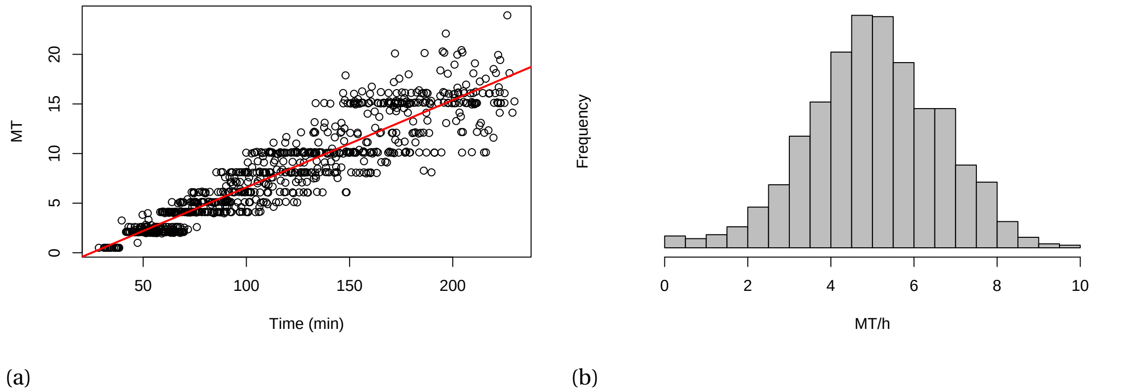


Figure 3.19: (a) Pelleting time as a function of pelleting weight (b) Distribution of the capacities of the pelleting presses

Pelleting is performed on two parallel presses. These presses each have an average capacity of 5 MT/h. The pelleting speed is depending on the type of material being pelleted as can be seen in figure 3.19. The setup time for all products is 30 minutes, this is the time necessary to empty the press and the bucket elevator used to transport the material to the top of the subsequent product silos. Furthermore, a die change (products are pressed in 2 and 2.5 mm diameter pellets) takes 150 minutes. Die changes occur on average 3.66 times a week. As can be seen in table 2.1 28% of the total tonnage is pelleted, this target can be easily met when only one product is made and demand is constant. However, the number of product types to be pelleted daily increases the production time significantly and demand varies over time. Besides, pelleted products are complete feeds which have very high-quality standards which translates in exclusion of other mixing lines in the preceding step. These jobs can not be grouped because there are only two silos preceding each press. To be able to mix the complete feeds for the pressing lines, the other mixing lines need to be stopped to rule out contamination risks. As a consequence of the number of buffers before pelleting, this needs to be done several times a day.

Packaging occurs on six parallel lines. For a more detailed description of the packaging lines, see paragraph 2.2.3. The data generated on the packaging lines is not sufficient because the release time indicated by the operator is manually inserted. Parts of setup times and coffee breaks after registration are also registered in the database of Promas. However, using the data for the bigger orders the steady state capacity can be estimated, this data is less prone to variations before and after the operations. Furthermore, the mean setup time for the packaging lines is estimated using the experience of the operators at 20 minutes. Distributions of the steady-state capacity of the packaging lines are given in figure 3.20.

According to the Theory of Constraints [6], the bottleneck (constraint) within the production process determines the overall capacity of the process. To improve the capacity of the process, this bottleneck should be identified, exploited, subordinated (synchronized with the other processes)

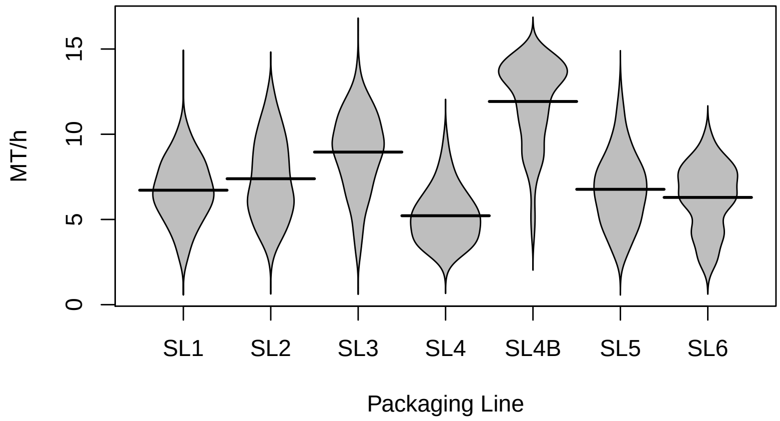


Figure 3.20: Capacities of packaging lines

Table 3.1: Total throughputs as a function of number of routes (mixing lines) used

	1 Route	2 Routes	3 Routes	4 Routes	5 Routes	6 Routes
With pelleting (MT/h)	5.0	10.1	N.A.	N.A.	N.A.	N.A.
Without pelleting (MT/h)	11.8	14.8	17.0	19.1	21.0	21.6

and at last elevated. Then, the process is repeated for the next bottleneck in the process. The production process at Cargill contains many routes, but the average capacities already tell something about the constraining process in various situations. The constraint can be easily visualized using a method introduced by the global technical director of Cargill Premix & Nutrition: Paulo Piero. This method uses a visualization of all the average capacities of the subsequent process steps in a diagram. The lowest point in this graph is the constraint, which determines the maximum capacity. An overview of the average capacity per individual route per situation is given in figure 3.21. Take in mind that if multiple routes are occupied, the throughput per route might be low, but the total throughput is multiplied by the number of routes used, making it a high number. Furthermore, it is assumed that every route uses a different packaging station. In reality, this is not always the case, which results in decreasing total packaging capacity. When one route is used, it has the potential of using all packaging stations, which is visible in the high packaging capacity. Take into account that there is a lot of variation in production capacities due to material and product type Total throughputs are given in table 3.1. Further investigations of bottlenecks within every route is performed in paragraph 5.2. The following conclusions can be drawn from the graphs:

Dosing — On average, dosing becomes a bottleneck when the number of parallel operating mixing lines is more than 4.

Mixing — Mixing is a bottleneck when the number of parallel routes used is on average, less than 4. This is only the case for nonpelleted products.

Product silos — The number of buffers can be low, which results in downtime for individual mixing lines. This is due to the fact that silos are occupied from the first batch entering

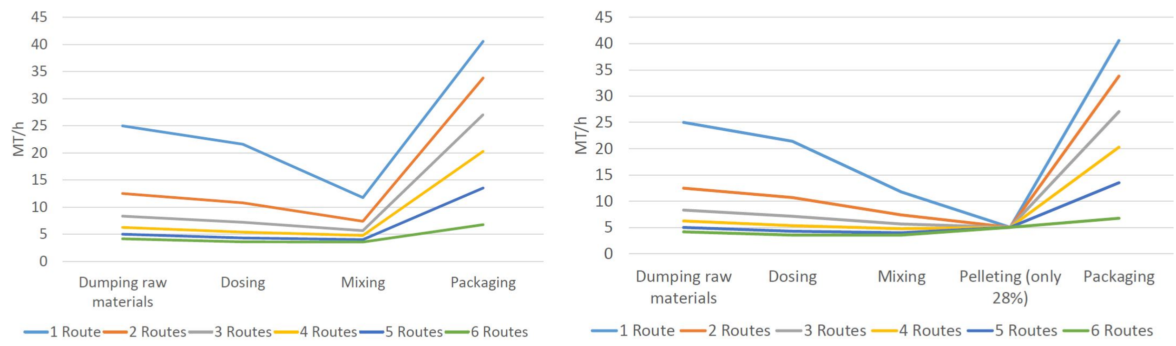


Figure 3.21: Overview of average capacity per individual route without pelleting (a) and with pelleting (b), the different graphs represent the numbers of routes (mixing lines) used

the silo until the last grain exits the silo for packaging (see figure 5.2). Besides, silos are used as buffers to capture differences in capacities between the preceding and subsequent production step. These capacities vary significantly, which results in blockage due to limited buffer size.

Pelleting Pelleting is a special case, it is a bottleneck for up to four parallel used routes, but since only 28% of the products needs to be pelleted production can be forestalled using the preceding silos while producing nonpelleted products. Pelleting is most efficient when produced with more than 5 parallel used routes. In reality, complete feeds are pelleted which are contamination sensitive and mostly do not allow other routes to be used.

Packaging In theory, there is enough packaging capacity to never let it the packaging step a bottleneck. However, not all lines are utilized evenly. Therefore they can not always operate parallel which decreases the capacity available. If for example, the production for a particular day is only destined for 2 (average) packaging lines, this will become a bottleneck when production increases above 14 MT/h.

The main contributor to a lower capacity is the uneven utilization of the mixing and packaging lines. If they would be evenly utilized these working stations could potentially be working parallel around the clock, and the dosing installation would be the bottleneck of the process. Since this bottleneck is then 100% utilized, no further logistical optimization would increase the capacity of the factory.

3.5.3. Quality check, storage and release of finished products

The output zone is the zone where finished products are temporarily stored or directly transferred towards the customer or Neele-Vat. Samples are taken from every product batch before releasing the products to a customer. From these samples, thirty samples are drawn and tested every month. Some products are fed to animals which are very sensitive to fluctuations in nutrients (e.g. rescue milk, a product used to increase growth in pigs born at a low weight). These products are handled with a 'positive release' procedure. This means that all samples from the product run are analyzed and only with positive results, the product is released. These procedures are the second filter function of the system. If the products are discarded, the batch is disposed of as waste. There is no such thing as add-the-missing. The event will trigger the FSQR department to look for the cause of the disturbance (feedback control loop). If the cause is found, a feed forward control loop will be applied in the form of a new standard like using a different type of equipment for a certain ingredient.

3.6. Functions of 'Use'

Within this function, resources are used to realize the transformation from raw materials to customer specific animal nutrition. The Delft System Approach represents the resources as a flow through the system. The resources are bought / hired, educated / tuned and maintained until the resources are no longer suitable for the transformation. The resources then get fired, retire, promote, or get disposed of as waste. This process is involved in many functions which are outside the system boundaries. However, some functions are inside the boundaries. Equipment maintenance is very important because it prevents unexpected distortions in the system. Maintenance is an important determinant of the system' availability. Besides, personnel must be motivated to increase their productivity and that of the equipment they operate.

3.7. Conclusions

To increase the productivity of the production system at Cargill Premix & Nutrition Rotterdam, the focus should be on the transformation function of the system. The other functions mainly influence the effectiveness of the production system while the productivity of the system is mainly determined by the capacities, routing and input of transformation process. Variations in capacity of the different production steps within the transformation process are large and there are many variables determining these variations. The only clear variable determining capacity has been found in the dosing and mixing step. The number of parallel operating mixing lines mainly determine the capacity in that process. The number of parallel operating mixing lines is limited by up- and downstream processes, contamination rules and an uneven utilization of the mixing lines, packaging lines and product silos which results in an average of 2.55 parallel operating mixing lines. Looking at average capacities, there is a potential of a 48% productivity improvement. In that case, the dosing and mixing step is the bottleneck of the system.

4

Research goal

This chapter describes the problem and states the research question. Next, based on the findings of chapter 2 and 3 several solution paths and other subjects for investigation are proposed.

4.1. Problem statement

Due to an increasing focus on the West European market (instead of a worldwide market), the factory of Cargill Premix & Nutrition in Rotterdam is producing a more diverse and concentrated product portfolio with smaller order sizes. This has a negative impact on the productivity of the factory, resulting in late deliveries, unsatisfied customers and declining sales. Besides, daily production quantities are varying a lot. It is not clear what determines the variation in production quantity. These developments gave reason to study what determines the productivity of the plant and how this can be improved.

The average Overall Equipment Efficiency of the production system used at Cargill Premix & Nutrition is 70%. The production system has a nominal average output of 21.4 MT/hour (table 2.1) but the average operational output of the system now 15.87 MT/hour. The root cause of this low average utilization is caused by a demand for a great variety of products (concentration, the number of ingredients and packaging methods). The main variable determining the hourly output of the first process step in the system is the parallel operation of the mixing lines (figure 3.14). Mixing lines can not always be used to produce the products demanded, which results in partial downtime (figure 3.13a). As shown in chapter 2 and 3 the causes for this partial downtime can be found in four categories:

1. Blockage by upstream processes like late dumping of raw materials. This results in the inability of producing certain products at certain times. This problem is known and is now solved by adding an extra operator who his only job is dumping raw materials before they run out. Dumping the raw materials will therefore not be in the scope of this study.

2. Uneven utilization of mixing lines and packaging lines. The demanded volumes of the product portfolio do not result in evenly utilized mixing and packaging lines (table 2.1). This means that the mixing and packaging lines are, by definition, unable to produce parallel at all times.
3. Contamination rules to prevent the production of products across mixing lines. Some products can only be made when no other product is dosed on the scales. In practice this means that these products are produced exclusively (with some exceptions), meaning that the other mixing lines are not operating.
4. Blockage by downstream processes like pelleting and packaging the product. The number of silos between these processes is limited and variation in production capacity between and within processes prevent constant production on all mixing lines.

The goal of this research is to determine how the productivity of the system can be increased when the adjustments as proposed in the problem statement are implemented. The research question is therefore stated as:

> Can the input, control and layout of the production system of Cargill CPN be adjusted in a cost efficient manner such that the productivity is increased by 10%?

Sub-questions to be answered are:

1. How can the control of the system be adjusted such that the productivity increases?
2. How can the layout of the system be adjusted such that the productivity of the system increases?
3. How do adjustments in the input affect the productivity of the system?

4.2. Solution paths

The analysis of chapter 3 resulted in the subproblems stated above. By studying literature, logic thinking, brainstorming with the production experts at Cargill and interviewing KSE (the company behind process automation in this particular industry)[3], various solution paths have been determined. Many solution paths have been neglected because they did not focus on a constraining subprocess of the system or did not seem to be feasible financially, however, some solution paths have been studied in more detail:

Control There are two decisions points in the process: the choice of which order to mix and the choice of which order to package. Adjusting the sequencing rules at these decision points might have a positive effect on the overall throughput.

Input Coccidiostats are used in some of the products produced on mixing line 2. Outsourcing these products to another factory of Cargill would make mixing line 2 and 4 equal. Mixing line 4 now produces many contamination-sensitive products. These products can then be made on at least two production lines. This will also equalize the production on mixing lines 2 and 4 since they will have the same capabilities.

Layout Connecting the silos of mixing line 3 to mixing line 1. This would allow both mixing lines to produce the same product portfolio. This would result in an equal flow through mixing line 1 and 3 resulting in a more equalized production over these mixing lines.

Besides, Cargill Premix & Nutrition wants to know how a further decline in order sizes and increase in order quantity affects the productivity of the plant. These two developments are likely and might influence the results of the previously proposed solution routes.

5

System modelling

This chapter describes the process of choosing and applying a model to determine the impact of the solution paths proposed in chapter 4. First, an attempt is made to describe the system in a mathematical form using an LP formulation and queueing theory. Next, a Discrete Event Model is proposed and used to determine the effects of the solution paths proposed.

5.1. Choice of model

According to Law (2007) methodologies used to study alterations to a system can be categorized as shown in figure 5.1. The first decision to make is whether a model should at all be designed to ana-

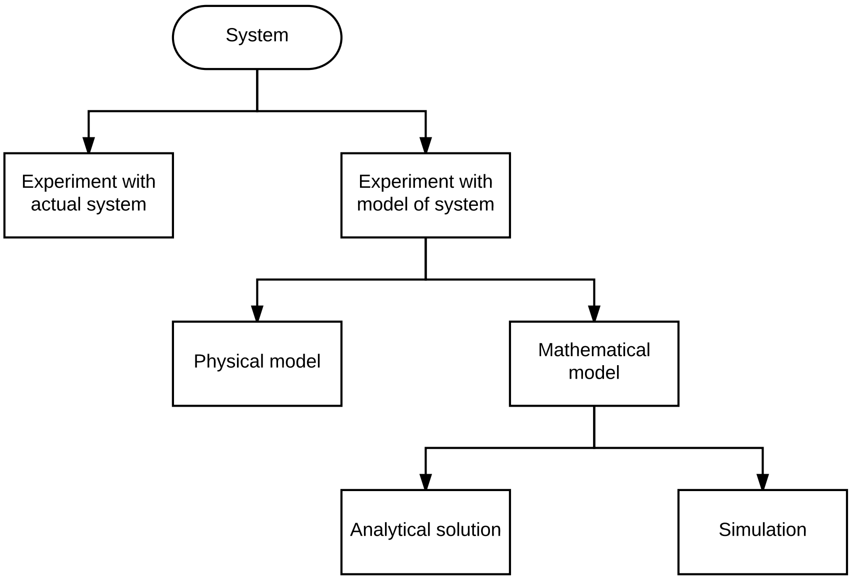


Figure 5.1: Methodologies to study hypothetical alterations to a system, source: [8]

lyze alterations to a system. If alterations to a system can be cost effectively performed to the actual system, it is desirable to do so because it gives the most reliable outcome, namely: reality. When using a model, there is always the question of whether the model really represents reality. However, for this particular problem, a physical or informational adjustment to the system at Cargill is costly, irreversible, and it can have a big impact on the performance of the system. Therefore, the proposed alteration must first be argued using a model of the system. Models can also be made as a physical model, a method especially used when the system is very scalable (for example: an experiment where production is represented using Lego stones) or used in many similar situations (for example: trying a different layout in one of a franchise fast food restaurant's many branches). Except for educational purposes, physical models are rarely used in operations research [8]. For the system under study it is probably not cost effective to study alterations to the system using a physical model. The factory is a unique factory with a unique layout and scaling the facility to a smaller and thereby more cost effective physical model is not a simple job. There is a lot of interdependency in the system and variability in production times is mostly caused by human decisions and equipment and material properties. A valid mathematical model might be able to describe the system under study. A mathematical model represents reality in terms of quantitative and logical relationships and can be manipulated to see how the model reacts. However, the question is, how this mathematical model can be used to determine a solution to this particular problem. If the model is simple enough, an analytical exact solution can be found. If no analytical solution can be found due to high complexity and/or stochastic variables, a simulation model can be used to get an idea of the effects of the alterations proposed. First, a mathematical model of the system is proposed in paragraph 5.2.

5.2. Mathematical model of the system

This section is focussed on trying to analyze the system using mathematical formulations of the operations. The production process at hand falls under the category of a flow shop. A flow shop is defined as a system where a product undergoes a series of transformations in a fixed sequence. It is allowed to skip a step, but not to return to a previous step, all machines can only be visited by a job once. However, this production process consists of multiple parallel machines per stage. The corresponding type of flow shop is usually referred to as a Hybrid (or parallel/multiprocessor) Flow Shop (HFS) [10]. Production scheduling on an HFS production line is a complex combinatorial problem and in most cases NP-hard (non-deterministic polynomial-time hard)[10].

The production process consists of 5 stages: mixing, buffering, pelleting, buffering and packaging. The times a job spends in these stages is visually represented in figure 5.2. In this figure, p_i^t is the processing time of job i at stage t, lt_i^t the lead time of the first batch of job j (which can consist of multiple batches) and wt_i^t the potential waiting time. The waiting time is only introduced when the subsequent process is not started when the first batch of an order falls into the silo. As can be seen, the buffer time starts after the lead time of the first batch through the mixing stage and ends when the successive stage is completed (which means that all material has exited the silo). Apart

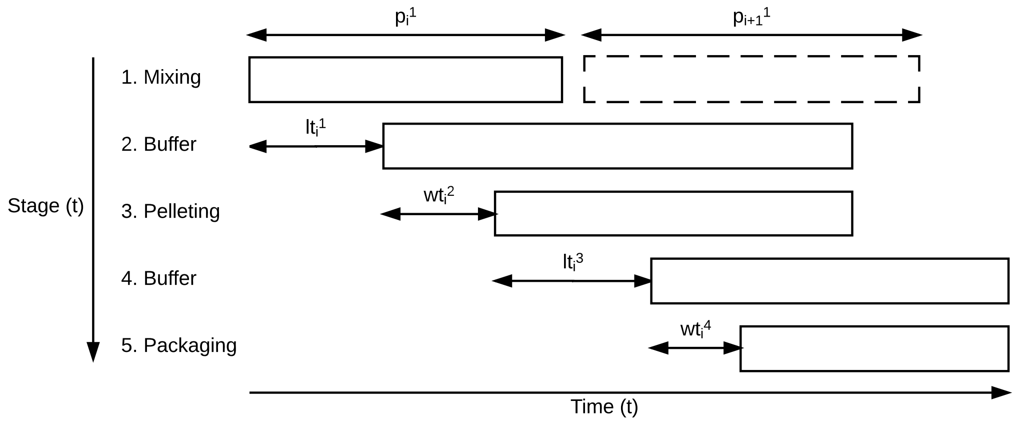


Figure 5.2: Visualization of the stages and processing times

from a few exceptions the parallel lines are unrelated. This means that a particular job can only be performed at a particular line. This is not the case for mixing line 1 and 3 because these lines have identical properties. Jobs on packaging on lines SL1, SL2 and SL3 can also be interchanged if there is a physical connection from the mixing line to these packaging lines. Other feasible constraints found for the linear model are limited intermediate storage (the silos), sequence dependent setup times (flushings between products) and dummy jobs on other machines in the mixing stage to model a contamination sensitive job. The real system introduces more constraints. The processing time of a job in the first stage (mixing) is depending nonlinearly on the amount of jobs performed parallel to it (figure 3.16b). Because this is a nonlinear relation it is impossible to use the LP formulation for the HFS problem, which assumes constant or linearly related processing times. Besides, all processes at hand are non-deterministic, a lot of variabilities is introduced to processing and arrival rates due to human decisions and errors in the process. An LP formulation of the system does not take these important stochastic effects into account [7].

However, using queuing theory, it is possible to analytically calculate the expected stability of the queues and the expected throughput per route. Distributions of processing times and inter-arrival times are estimated in paragraph 5.3.2. The inter-arrival time is gamma distributed and the production capacity of the pelleting lines and packaging lines are normal and Weibull distributed, respectively. Every route through the system can be described using G/G/1 model. After extensive literature research, no analytical study on this type of model has not been found, so the expected sojourn time can not be calculated and therefore Little's Law cannot be used. However, using the expected means of these distributions something can be said about the machine utilization, queue stability and the average throughput. First, the mean arrival rate (λ_k) for each number of parallel operating mixing lines is determined:

$$\lambda_k = \frac{\beta_k k}{\alpha_k} \tag{5.1}$$

Table 5.1: Mean arrival rates (λ_k) in batches per hour per mixing line as a function of parallel operating mixing lines.

$k=1$	$k=2$	$k=3$	$k=4$	$k=5$	$k=6$
4.90	3.08	2.36	1.99	1.67	1.50

Table 5.2: Mean service times ($\mu_{s,l}$) per batch in minutes of all the mixingline - packaging/pelletingline combinations (some are not feasible in reality)

	Mixer 1	Mixer 2	Mixer 3	Mixer 4	Mixer 5	Mixer 6
SL1	22.6	23.7	22.5	22.9	22.3	19.0
SL2	19.2	20.1	19.1	19.4	18.9	16.2
SL3	16.0	16.8	15.9	16.2	15.8	13.5
SL4	28.2	29.5	28.0	28.5	27.7	23.7
SL5	22.3	23.3	22.1	22.5	21.9	18.7
SL6	24.4	25.6	24.3	24.7	24.0	20.5
Press	29.5	30.9	29.3	29.8	29.0	24.8

Where α_k is the shape and β_k the rate of the gamma distribution with k parallel operating mixing lines. These parameters can be found in table 5.5. The expected inter arrival time is divided by k because the queueing model is used for a single line and the expected arrival rate is calculated for k parallel operating lines. The outcome is given in table 5.1. Next, the expected mean service time (μ_s) for the different packaging lines is calculated:

$$\mu_s^c = \frac{\beta_m}{\alpha_m}\Gamma(\alpha^{-1}) \qquad \forall \qquad s = 1,2,3,5,6 \tag{5.2}$$

$$\mu_s^c = \exp\left(\mu_{ln} + \frac{\sigma_{ln}^2}{2}\right) \qquad \forall \qquad s = 4 \tag{5.3}$$

$$\mu_{s,l} = \frac{W_l}{\mu_s^c} \tag{5.4}$$

Where μ_s^c is the expected mean capacity of packaging line s, μ_{ln} the mean and σ_{ln} the standard deviation of the log normal distribution for packaging line 4, W_k the mean batch size of mixing line l and μ_m the expected mean service time. For the pelleting line, the expected mean capacity (μ_p^c) and the expected mean service time (μ_p) is equal to:

$$\mu_p^c = \mu \tag{5.5}$$

$$\mu_{p,l} = \frac{W_l}{\mu_p^c} \tag{5.6}$$

All the service times are given in table 5.2. The machine utilization ρ is equal to the arrival rate multiplied by the service time:

$$\rho_{k,s/p,l} = \lambda_k \mu_{s/p,l} \tag{5.7}$$

The queueing system is stable only if the machine is utilized under 100%. This means for a stable queue the following must count:

$$\rho_{k,s/p,l} < 1 \tag{5.8}$$

The machine utilization factor ρ is calculated for all routes with respect to the number of parallel operating mixing lines. After pelleting, the arrival rate for the downstream process of packaging is changed to $\lambda_{p,l} = 1/\mu_{p,l}$ and is now independent of the number of parallel operating mixing lines. This can be assumed because the utilization of the presses is larger than 1 under most circumstances found in practice. The utilization is calculated using:

$$\rho_{p,s,l} = \lambda_{p,l}\mu_{s,l} \tag{5.9}$$

The results of the study are given in table 5.3. As can be seen, in many occasions queues are being built up in front of the packaging and pelleting lines. Only three packaging lines can operate simultaneously which means that with more than 3 parallel operating mixing lines, streams will be combined, which increases the arrival rate for one of the packaging stations by a factor 2. This results in a machine utilization exceeding 1 for many routes, a queue will build up which will prevent the extra mixing line from operating. An increase in the number of packaging personnel is not always increasing the productivity since the packaging lines are not equally utilized as can be seen in table 5.4. Besides, contamination rules prevent packaging lines from operating parallel. If every mixing line and every packaging/pellet station had an equal workload, the factory would be able to produce with six parallel operating mixing lines constantly: every workstation would have a utilization smaller than 1 which leaves the arrival rate of the mixing lines the constraint, which would result in an average daily production of 518 MT. Another observation is that for every route the constraint is occurring at the upcoming workstations at different arrival rates. A mixing line has many destinations, making it possible to switch from an unstable queue to a stable queue. However, when looking at the overall picture the utilization of the machines should be lower than 1. To get an indication of the overall utilization, the product stream percentage ($Q_{s/p,l}$) is multiplied by the corresponding utilization:

$$\rho_{weighted} = \sum Q_{s/p,l}\rho_{k,s/p,l} \qquad \forall \qquad k = 1,2,3,4,5,6 \tag{5.10}$$

As can be seen in table 5.3 the amount of servers (packaging lines) available should be at least 3 if the average number of parallel operating lines is bigger than 2. This way, the arrival rate of (on average) 3 parallel operating mixing lines does not cause over utilization of the workstations ahead.

It can be concluded that queueing theory is helpful to determine the queue stability and average expected throughput of a single line. However, limited buffer size, set-up times, shared routes and stochastic variables are not taken into account. Since these subjects certainly affect the productivity of the system, it cannot be used to determine the average productivity.

Table 5.3: Utilization as a function of parallel operating mixing lines, for route specifications see table 5.4.

Route	% MT	$\rho_{1,s/p,l}$	$\rho_{2,s/p,l}$	$\rho_{3,s/p,l}$	$\rho_{4,s/p,l}$	$\rho_{5,s/p,l}$	$\rho_{6,s/p,l}$	$\rho_{p,s,l}$
1	2.10%	1.31	0.82	0.63	0.53	0.45	0.4	
2a	2.90%	1.99	1.26	0.96	0.81	0.68	0.61	
2b	6.70%							
3	9.20%	2.52	1.59	1.21	1.02	0.86	0.77	0.54
4a	2.00%	2.52	1.59	1.21	1.02	0.86	0.77	0.96
4b	0.00%	2.52	1.59	1.21	1.02	0.86	0.77	
5	0.00%	2.52	1.59	1.21	1.02	0.86	0.77	0.76
6	0.00%	1.9	1.2	0.92	0.77	0.65	0.58	
7a	0.10%	2.09	1.31	1	0.85	0.71	0.64	
7b	0.50%							
8	9.10%	1.3	0.82	0.63	0.53	0.44	0.4	
9	7.20%	1.81	1.14	0.87	0.73	0.62	0.55	
10a	4.10%	1.98	1.25	0.95	0.8	0.68	0.61	
10b	7.40%							
11	4.50%	2.43	1.53	1.17	0.99	0.83	0.74	0.54
12a	3.30%	2.43	1.53	1.17	0.99	0.83	0.74	0.96
12b	1.00%	2.43	1.53	1.17	0.99	0.83	0.74	
13	7.10%	2.43	1.53	1.17	0.99	0.83	0.74	0.76
14	0.00%	2.43	1.53	1.17	0.99	0.83	0.74	0.65
15a	0.00%	2.43	1.53	1.17	0.99	0.83	0.74	0.96
15b	0.00%	2.43	1.53	1.17	0.99	0.83	0.74	
16	0.00%	2.43	1.53	1.17	0.99	0.83	0.74	0.76
17	0.50%	2.33	1.47	1.12	0.95	0.8	0.71	
18	0.50%	1.84	1.16	0.89	0.75	0.63	0.56	
19a	4.20%	2.02	1.27	0.97	0.82	0.69	0.62	
19b	2.20%							
20	2.00%	2.37	1.49	1.14	0.96	0.81	0.72	0.65
21a	3.70%	2.37	1.49	1.14	0.96	0.81	0.72	0.96
21b	4.10%	2.37	1.49	1.14	0.96	0.81	0.72	
22	2.10%	2.37	1.49	1.14	0.96	0.81	0.72	0.76
23	0.00%	2.26	1.43	1.09	0.92	0.77	0.69	
24	3.00%	1.79	1.13	0.86	0.73	0.61	0.55	
25a	1.10%	1.96	1.23	0.94	0.8	0.67	0.6	
25b	3.50%							
26	4.80%	1.1	0.69	0.53	0.45	0.38	0.34	
27	1.00%	1.68	1.06	0.81	0.68	0.57	0.51	
	$\rho_{weighted}$	1.62	1.02	0.78	0.66	0.55	0.49	

5.3. Simulation model of the system

As an analytical solution to the problem at hand can not be found due to the complexity and variability of the system, a simulation model is used to imitate the behavior of the system and see how the output measures of performance react to changing the input of the model. Simulation models can be distinguished in the following groups [8]:

Determenistic vs. stochastic: A static simulation model does not contain any probabilistic components. However, a stochastic simulation model can contain stochastic variables which differ every time the variable called. This is done by pulling a random number from a predefined distribution. After many iterations, the variable its values will be distributed exactly as the predefined distribution. However, it is very important that the random number is completely random. A random number is generated using alterations on a seed value. The alterations (the random number stream) on a particular seed value are always the same, this should be taken into account when replicating an experiment multiple times.

Static vs. dynamic: A static model consists of a state of a system at a particular time. These models can only be used if time plays no role in the behavior of the system. Dynamic systems simulate how a system evolves over time.

Continuous vs. discrete: Continuous models describe the system in terms of continuous relations. These continuous relations can, for example, be described in differential equations. Discrete models describe the states of a system using state variables which change instantaneously at separate points in time. These points in time define when an event occurs.

Since the system at hand has many probabilistic components and evolves over time, the model should have a stochastic, dynamic character. The choice between continuous and discrete is more complicated. The elements transformed into the system are a continuous flow of material. However, these continuous flows are grouped into small batches which finish a certain production step at discrete points in time. So: the level of detail determines the character of the model. In this case, the behavior of the batches in the system define the overall output and the process time of the individual process steps are defined by the continuous flow characteristics of the material. The process time of the individual process steps do have a big impact on the overall output of the system, but the alterations proposed are not affecting the process times. Clearly, a discrete model is better suited for this particular system. Therefore, discrete simulation is used to model the system and analyze the alterations proposed.

5.3.1. Simulation goal

The goal of the simulation model is the determination of the effects of changes in the product streams and physical routing in the system. The system performance is measured in tons produced per day. A few scenarios are investigated:

1. Trying different control strategies at the decision points in the system
2. Releasing the restriction of mixing line 2 incurred by producing Coccidiostats
3. Connecting silos of mixing line 3 to mixing line 1
4. A sensitivity analysis of a variation in the product streams
5. A sensitivity analysis of a variation in order sizes

5.3.2. Input

The input of the simulation model consists distributions of order properties, estimated parameters for the distributions of working station capacities and settings for the experiments which the simulation model should perform. Theoretical distributions are used in this simulation study because there are not enough data points to simulate enough replications.

Order generation

The orders are generated according to the distribution of the product portfolio of 9 months (Sep '15 - May '16). The reason for looking at just these months is the fact that the latest developments (focus on West Europe with declining order sizes) have ended in the time before this period, and the product portfolio has been rather stable since then. To cover unforeseen changes in the product portfolio, a sensitivity analysis regarding order size and order quantity per production route is performed. The product portfolio is retrieved using R from the data generated by Promas. There are 27 routes through the factory. Every route has its own historical amount of orders. The distribution of the number of orders over all routes is determined. Besides, the distribution of the number of batches per order for every mixer is determined. The average number of orders per route can be calculated using:

$$O_r = \frac{M_r}{\bar{m}_r} \tag{5.11}$$

Where O_r is the number of orders on route r, M_r the tonnage and $\bar{m}_r$ the average weight per order. From these numbers, the order frequency can be calculated. It is assumed that order size is mainly determined by the mixer it is produced. The mixing lines are dedicated to particular product types which are produced in particular quantities. From these distributions orders are generated using a random number stream. This way, an order stream is generated as the input of the simulation. The distribution of order sizes and average batch sizes are given in appendix D. Orders are picked by the simulation model from a limited number of orders. This limited number of orders is called the order horizon. Orders are known two days in advance and the average daily number of order is 34. Therefore the number of available order to choose from is 68.

Parameter estimation

The capacities of the system are drawn from a theoretical distribution to be able to model what could have happened in future configurations instead of simulating historical data on an altered system. Besides, the data is insufficient (170 days) to make all simulation runs necessary (496 days).

Table 5.4: Distribution of orders per route (SL4B is the destination for the bulk orders)

Route	Mixline	Pelletline	Packageline	% MT	% Orders
1	Mixer1		SL1	2.1%	2.3%
2a	Mixer1		SL4	2.9%	3.1%
2b	Mixer1		SL4B	6.7%	7.2%
3	Mixer2	Press1	SL3	2.0%	0.8%
4a	Mixer2	Press1	SL4	0.0%	0.0%
4b	Mixer2	Press1	SL4B	0.1%	0.0%
5	Mixer2	Press1	SL5	0.5%	0.2%
6	Mixer2		SL3	9.2%	3.9%
7a	Mixer2		SL4	0.0%	0.0%
7b	Mixer2		SL4B	0.0%	0.0%
8	Mixer3		SL1	9.1%	11.1%
9	Mixer3		SL3	7.2%	8.8%
10a	Mixer3		SL4	4.1%	5.0%
10b	Mixer3		SL4B	7.4%	8.9%
11	Mixer4	Press1	SL3	7.1%	6.2%
12a	Mixer4	Press1	SL4	0.0%	0.0%
12b	Mixer4	Press1	SL4B	0.5%	0.5%
13	Mixer4	Press1	SL5	4.2%	3.7%
14	Mixer4	Press2	SL2	3.3%	2.8%
15a	Mixer4	Press2	SL4	0.0%	0.0%
15b	Mixer4	Press2	SL4B	0.5%	0.5%
16	Mixer4	Press2	SL5	2.2%	1.9%
17	Mixer4		SL2	4.5%	3.9%
18	Mixer4		SL3	1.0%	0.9%
19a	Mixer4		SL4	0.0%	0.0%
19b	Mixer4		SL4B	0.0%	0.0%
20	Mixer5	Press2	SL2	3.7%	3.8%
21a	Mixer5	Press2	SL4	0.0%	0.0%
21b	Mixer5	Press2	SL4B	1.1%	1.2%
22	Mixer5	Press2	SL5	3.5%	3.5%
23	Mixer5		SL2	2.0%	2.0%
24	Mixer5		SL3	4.1%	4.1%
25a	Mixer5		SL4	2.1%	2.1%
25b	Mixer5		SL4B	3.0%	3.1%
26	Mixer6		SL1	4.8%	7.0%
27	Mixer6		SL6	1.0%	1.4%

The parameters of these distributions are estimated using historical data. First, a standard distribution must be chosen to fit the historical data. To be able to identify which type of distribution comes closest to the distribution of the historical data, a histogram of the historical data is made and the summary statistics calculated. Based on the shape of the histogram and the summary statistics a hypothetical theoretical distribution can be chosen. Especially important are the estimators of the skewness ($\hat{v}$) and the coefficient of variation ($\widehat{cv}$):

$$\widehat{cv}(n) = \frac{\sqrt{S^2(n)}}{\bar{X}(n)} \tag{5.12}$$

$$\hat{v}(n) = \sum_{i=1}^{n} \frac{[X_i - \bar{X}(n)]^3}{[S^2(n)]^{3/2}} \tag{5.13}$$

Where $\bar{X}$ is the estimated mean, S the estimated standard deviation, X_i a data point and n the number of samples. The skewness is an indicator for the symmetry of the distribution and the coefficient of variation is an indicator of the exponential distribution ($cv = 1$) and an indicator whether a lognormal, Weibull or gamma should be used for a positively skewed distribution.

Every distribution has two shape parameters. These parameters are determined using maximum-likelihood estimators (MLEs). For every distribution, a MLE has a different algebraic form. However, the general approach consists of defining a likelihood function:

$$L(\theta) = p_\theta(X_1)p_\theta(X_2)...p_\theta(X_n) \tag{5.14}$$

Where θ is the parameter to be estimated, $p_\theta(x)$ the probability mass function of the hypothesized distribution and $X_1, X_2...X_n$ the data point. Then $L(\theta)$ is the joint probability mass function. Now, as $L(\theta)$ is maximized by varying the parameter θ, the best estimation of this parameter can be found. The maximization formula is different for every distribution, this will not be described in detail.

Now that the parameters are determined, the fit of the theoretical distribution should be analyzed using a goodness-of-fit test. This is done visually using a Q-Q plot, a P-P plot and histograms of the (cumulative) distribution and analytically using a chi-square test. The Quantile-Quantile plot plots data points from the theoretical distribution against observed data points. The Probability-Probability plot does the same for the theoretical and observed probabilities. Both plots indicate a good fit if the intersections of these points form a straight, 45-degree line. The histograms of the (cumulative) theoretical and observed distributions plot the distributions on top of each other. An example is given in figure 5.3.

A chi square test is a numerical indicator of the goodness of the fit. To perform the chi square test, the data is sorted and grouped into $j = 1,2,3...k$ bins. Then the expected proportion p_j of data points (N_j) in these bins is calculated using the actual distribution. Next, the test statistic is described as follows:

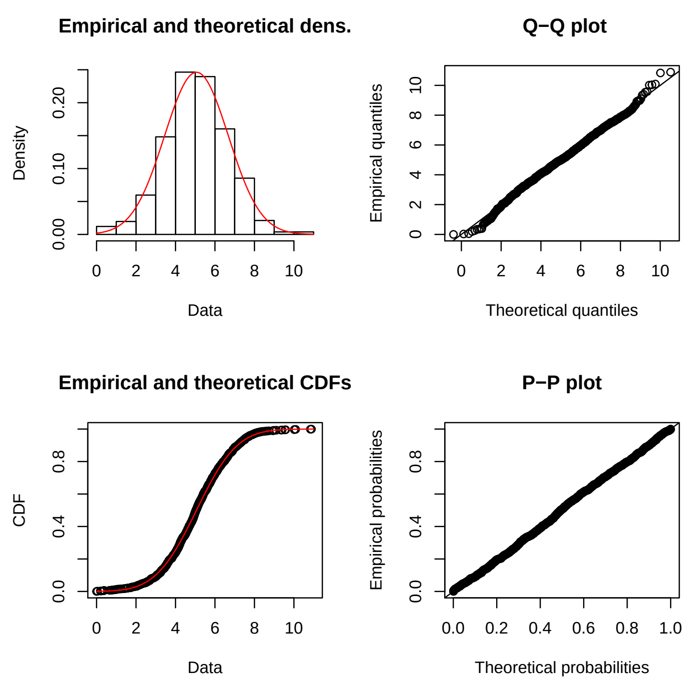


Figure 5.3: Q-Q plot, P-P plot and a (cumulative) histogram of the fitted distribution for the pelleting capacities

$$\chi^2 = \sum_{j=1}^{k} \frac{(N_j - np_j)^2}{np_j} \tag{5.15}$$

Where n is the number of data points. The smaller χ^2, the smaller the differences between the expected and observed proportion of data points for each bin, the better the fit. The hypothesis that the distribution represents the data (H_0) is rejected when $\chi^2 > \chi^2_{k-1,1-\alpha}$, where α is the probability of rejecting the hypothesis while it is true, a value of 0.7 is used in this case. The critical value $\chi^2_{k-1,1-\alpha}$ can be found using a table. This procedure was performed for the variables shown in table 5.5. The inter arrival time represents the time between two batches exiting any of the six mixers as a function of the number of parallel operating mixers. The Q-Q, P-P and (cumulative) histogram plots can be found in appendix C.

Experiment plan

The following experiments will be performed:

Experiment 1	Replicating the current situation
Experiment 2	Input: releasing the restriction of mixing line 2 incurred by producing Coccidiostats. The order distribution between mixing line 2 and 4 will be equalized since they can now produce the same products. Besides, contamination-sensitive products can now be produced on two lines which increase parallel production.
Experiment 3	Layout: connecting silos of mixing line 3 to mixing line 1. A relatively small physical adjustment will make it possible to share the silos which are now dedicated to mixing line 3. This routing will be added to the SiloRoute table. The order distribution

Table 5.5: Distributions and parameter estimations of stochastic variables

		P1	P2	χ^2	k	$\chi^2_{k-1,1-\alpha}$	Rejected?
Int.arrival.1 [h]	Gamma	4.23	20.71	16.95	25	20.87	No
Int.arrival.2 [h]	Gamma	4.78	29.49	27.23	33	28.31	No
Int.arrival.3 [h]	Gamma	4.84	34.24	16.34	33	28.31	No
Int.arrival.4 [h]	Gamma	5.58	44.42	14.45	26	21.79	No
Int.arrival.5 [h]	Gamma	7.08	59.23	7.54	14	10.82	No
Int.arrival.6 [h]	Gamma	13.69	122.99	0.99	3	1.42	No
Pellet [MT/h]	Normal	5.06	1.62	10.21	28	23.65	No
SL1 [kg/h]	Weibull	4.04	7261.65	17.45	22	18.10	No
SL2 [kg/h]	Weibull	3.50	8632.34	8.73	13	9.93	No
SL3 [kg/h]	Weibull	4.94	10137.42	14.16	18	14.44	No
SL4 [kg/h]	LogNormal	5012.01	1.39	16.13	20	16.27	No
SL5 [kg/h]	Weibull	3.34	7461.75	11.15	17	13.53	No
SL6 [kg/h]	Weibull	4.21	6718.56	4.95	9	6.39	No

between mixing line 1 and 3 will be recalculated based on the routing difference.

Experiment 4 Layout and input: combination of experiment 2 and 3.

Experiment 5 Input: A sensitivity analysis of a variation in the product streams with the current operations. The percentage of Metric Tons as stated in table 5.4 will be changed with 5% increase to see how the system reacts to hypothetical changes in sales for every route.

Experiment 6 Input: A sensitivity analysis of a further decline in average order sizes. The order sizes are varied between an average of 1 - 30 batches to see how this influences the productivity of the system. This experiment is performed in combination with experiment 1 to 4.

Using the following adjustments in control of the system:

(a) Earliest Due Date (EDD) for production order sequencing and First Come First Serve (FCFS) for packaging order sequencing. Orders are sequenced according to the sequence of arrival (if possible) at both decision points.

(b) Critical Path Priority (CPP) for packaging order sequencing and EDD for production order sequencing. Packaging orders blocking the most production orders will be packaged first.

(c) Increasing the number of packaging operators if necessary.

The experiment settings can be found in appendices B, D and E. The order quantities and number of batches per order are equalized by shifting tonnages between routes in such a way that an equilibrium per equivalent route is found. Experiment six is performed using a percentage decline in order sizes with the set point being the orders per batch distribution for experiment 1 as described in appendix D.

Number of replications

To be sure the estimated mean result represents the true result with a certain relative error, the number of replications (days in this case) must be determined [8]. The number of replications can be increased such that the confidence interval of the true mean is small enough. This must be done because the variation in results gives a distorted view of the true mean if estimated using too little replications. The confidence interval can be calculated using the student t distribution:

$$\bar{X} \pm t_{n-1,1-\alpha/2}\sqrt{\frac{s_X^2}{n}} \tag{5.16}$$

Where $\bar{X}$ is the estimated mean and s_X^2 the estimated standard variance of the data set and n the number of replications. The equation can be rewritten to:

$$\frac{t_{n-1,1-\alpha/2}\sqrt{\frac{s_X^2}{n}}}{\bar{X}} = \gamma \tag{5.17}$$

Where γ is the half-width of the confidence interval relative to the estimated mean. The relative error of the estimated mean can be defined as β. This relative error is normally set at 0.1. Now the number of replications is increased until:

$$\gamma < \beta \tag{5.18}$$

This results in a minimal number of replications (simulation days) of 496 days. This is a big number since the variation in daily output is large.

Warm up period

The model starts empty. In reality, there are always occupied silos in the system. To account for this difference, a warm up period is introduced. Results of this warm up period are neglected since they do not represent reality. The results of the model stabilize after 10 days (replications). To make sure enough time has passed for the system to warm up, a warm up period of 15 days is introduced.

Availability

The availability of the workstations is limited by a number of reasons which are all modeled in the simulation model:

1. The availability of the mixing lines is limited due to technical errors, maintenance activities and logistical failures. The downtime is determined at 8,94 % of the operational time (see figure 3.8 for reasons for this downtime). A negative exponential distribution is used to determine the inter failure times.
2. Batches with destination SL4B (Bulk) can only be processed from 7:00 AM - 17:00 PM since bulk cars are only loaded during day time and batches with destination SL4 (BB) can only be processed from 18:00 PM - 6:00 AM.
3. A press die must be, on average, changed 1.83 times a week. A die change takes 150 minutes to complete. A negative exponential distribution is used to determine the interchange times.

Number of packaging operators

The number of packaging operators is an input variable of the system since in reality, an extra person can be hired if necessary. However, this will increase the costs of operation.

5.3.3. Output

The output of the system consists of the following parameters:

- Daily output Q_{av}
- Standard deviation of daily output $S_{Q_{av}}$
- Overall Equipment Efficiency OEE
- Average parallel production on mixing lines p
- Daily output of resources $Q_{s,av}$
- Utilization of resources u_s
- Average time spent in silos t_b
- Utilization of packaging operators u_{op}

The Overall Equipment Efficiency using:

$$OEE = Availability \times Performance \times Quality \tag{5.19}$$

The availability of the system is an input parameter as described in paragraph 5.3.2. The performance of the system is calculated as:

$$Performance = \frac{Actual\ output}{Nominal\ output} \tag{5.20}$$

The nominal output only takes into account the available time. The quality of the end product is not a relevant parameter for the simulation model and is therefore neglected. The combination of resource and silo utilization will give insight in which resource makes is the bottleneck in the process and how silo space can be used best.

The utilization of the resources is calculated using:

$$Utilization = \frac{Time\ used}{Time\ available} \tag{5.21}$$

5.3.4. Model assumptions

To reduce the complexity of the model, assumptions are made:

- There is a lot of human decision making involved in the real system and these decisions vary for every individual operator. This variation in decision making is assumed to be randomly distributed.
- Product properties, operator efficiency, time of the day, equipment condition, humidity and temperature are the most important variables determining production capacity. Because there is not enough information on the relation between these variables and the production capacity, the values for production capacities are randomly drawn from the distributions as described in paragraph 5.3.2.
- The capacities of the system are drawn from a theoretical distribution to be able to model what could have happened in future configurations instead of simulating historical data on

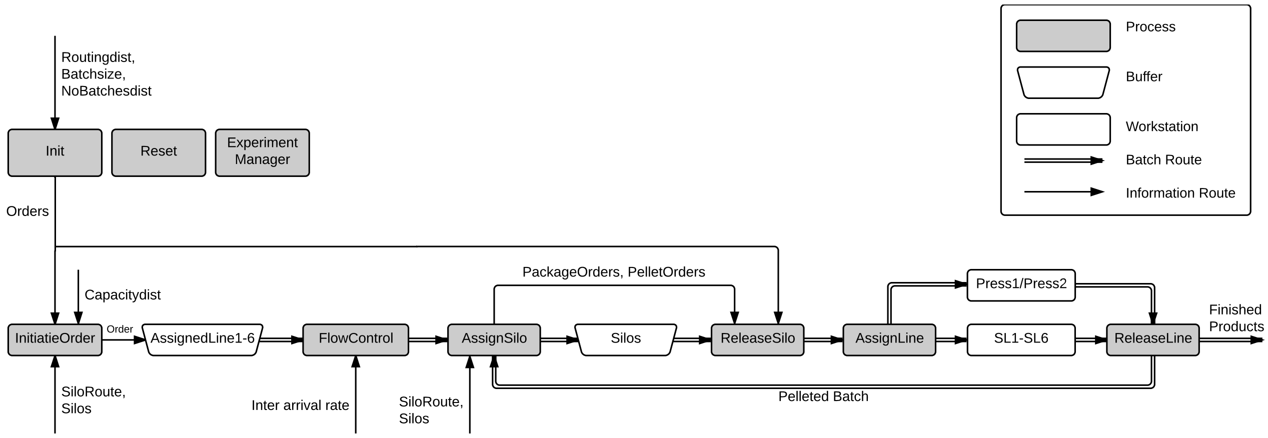


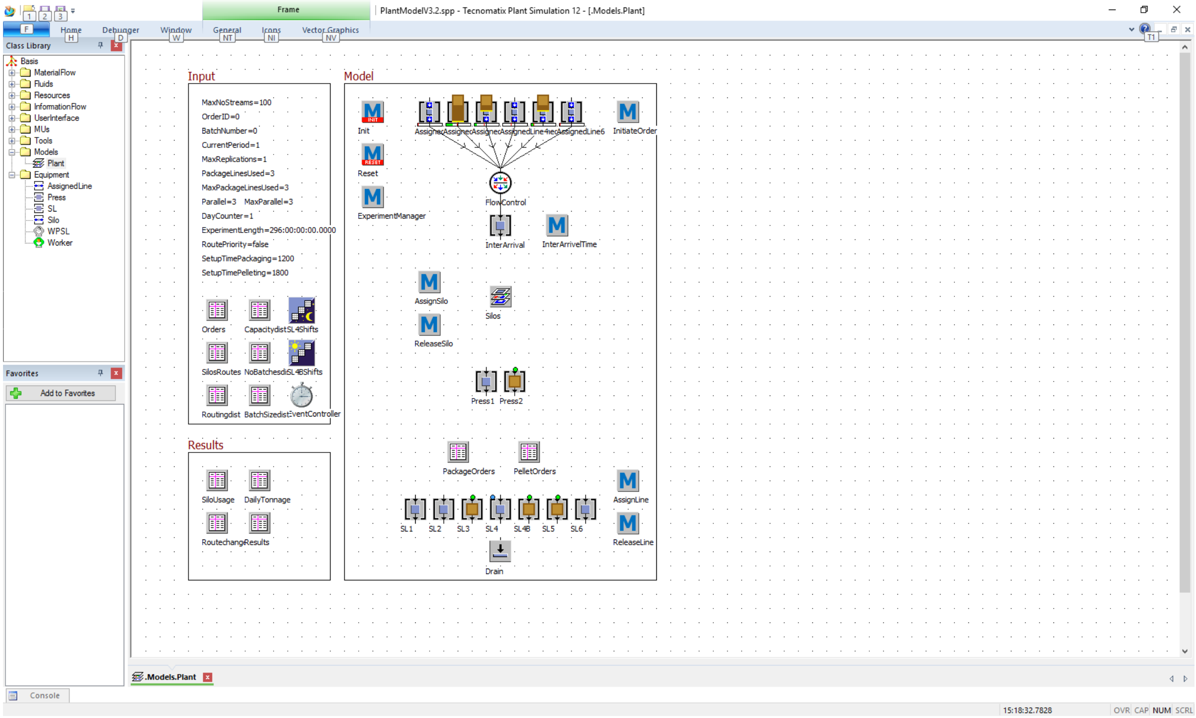
Figure 5.4: Layout of simulation model

an altered system. Besides, the data is insufficient (170 days) to make all simulation runs necessary (496 days).

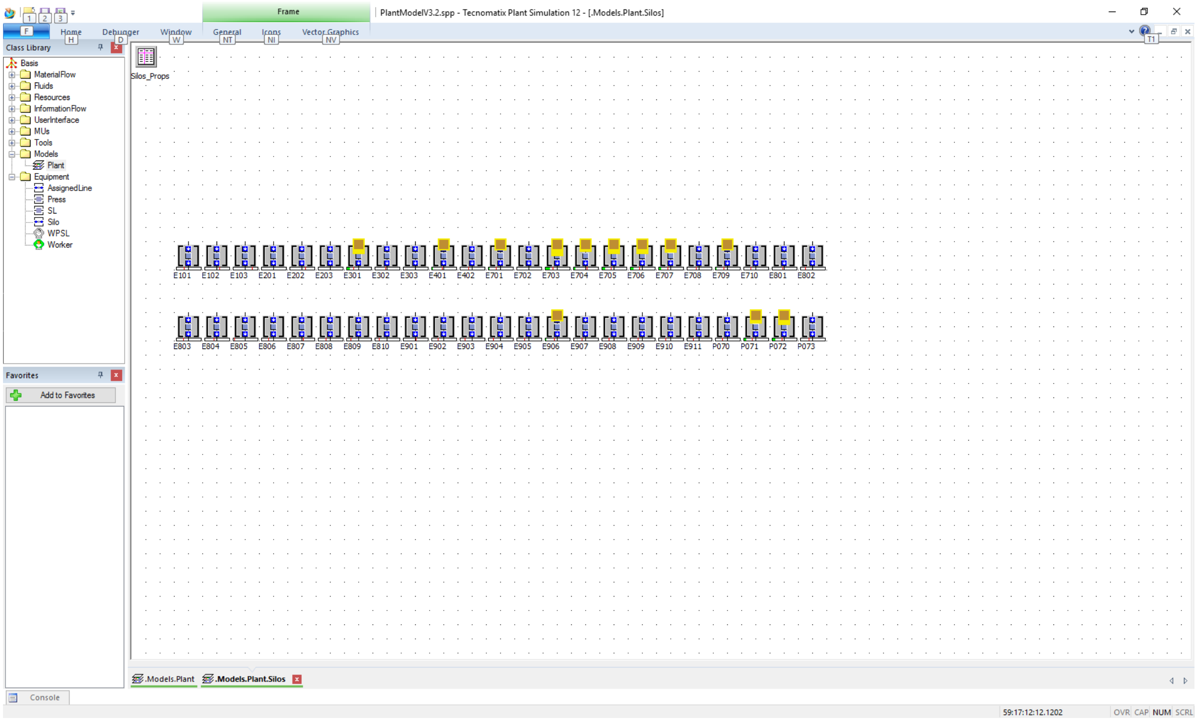
- The distributions of production capacities, order size and route are based on data of 9 months (Sep '15 - May '16). It is assumed that the relative growth of the product portfolio will occur equally in all product segments. If there are only changes in a particular (property of a) segment this will have an effect on the inter-arrival times and capacity distributions which are not taken into account in the model.
- Common Random Numbers (CRN) are used for all experiments to make sure the alternative configurations are analyzed under the same conditions. CRN is a technique where the same random number stream is used for different experiments. This results in the same order list and processing times for every experiment. This way only the differences between scenarios is less likely to occur due to variation alone.
- Products are dedicated to mixing, packaging and pelleting lines. In reality, some products can be made on multiple lines, which makes it possible to switch between lines until the last moment. This has not been incorporated in the model since the decision making process is hard to replicate and this would add another uncertainty in the model. This only affects the total portion of orders on a route, decisions about which order to make first on a particular mixing line are still included in the model.

5.3.5. Process description

The simulation model is written in Plant Simulation [4], a modeling package which works object oriented and is focussed on simulating production facilities. The model consists of processes and elements as explained in the following paragraph. A visual representation of the information and batch flow through the simulation model is given in figure 5.4. The interface is represented in figure 6.1. As can be seen, all elements are derived from different classes which are represented in the left pane. This way the common settings for all elements stay inherited while only the differences are translated into the settings.



(a)



(b)

Figure 5.5: (a) Overview of the model with all processes and workstations (b) Overview of silos in model (The yellow squares represent the batches)

Element attributes

```
Batch
    Route : integer
    OrderID    : integer
    BatchID : integer
    Batchsize : real
    NoBatches : integer
    Mixline : string
    Pelletline : string
    Packageline : string
    PelletingTime : real
    PackagingTime : real
    SiloIndex : integer
    SiloIndexP : integer
    MaxParallel : integer

AssignedLine
    NewBatch : Batch (element)

SL1−SL6
    Processtime : Batch.PackagingTime (real)
    DownTime : Real

Press1/Press2
    Processtime : Batch.PelletingTime (real)
    FailureRate : Real
```

Brief explanation of processes and elements

Batch	This element represents an individual batch, the only Moving Unit in the system
Init	This process initializes all settings before an experiment
Reset	This process resets the model after an experiment
ExperimentManager	This process sets settings for an experiment
InitiateOrder	This process initiates orders
AssignedLine1-6	These elements represent the output of the mixing lines
FlowControl	This process picks the batches from the mixing lines
AssignSilo	This process assigns batches to the right silo
Silos (46)	These elements represent the product silos
ReleaseSilo	This process opens a silo for the subsequent process
AssignLine	This process moves the batch to a subsequent process
Press1/Press2	These elements represent the pelleting lines
SL1-SL6	These elements represent the packaging lines
ReleaseLine	This process deletes the finished batches

Detailed explanation of processes and elements

Batch — This element represents a batch and has attributes as stated before. A batch moves through the system where it travels through various workstations and buffers.

Init — Init is executed at the start of an experiment. It resets all global variables and generates a random order list using the routing distribution (appendix B), average batch sizes and the distribution of the number of batches per order (appendix D).

Reset — This process executed at the end of an experiment. All moving elements are deleted and results are written away.

ExperimentManager — The experiment manager is used to initialize and reset the different experiments and replications within experiments.

InitiateOrder — This process picks an order from the available orders of the order list. The number of orders to choose from is limited and all orders must be executed to go through the list generated by Init. Orders are executed when the silos on the route for this particular order are free. Priority lies in the order with the earliest delivery date. If the route is free, the order is executed and the batches are generated in the queue. AssignedLine1-6. Silos on the route are assigned and declared occupied. The service and setup times for the package- and pellet line are drawn from the distributions (see table 5.5) and assigned to the batches.

AssignedLine1-6 — These 6 queues hold the batches until they are cyclically picked by the FlowControl process.

FlowControl — This process picks the batches from the occupied AssignedLines. This happens by picking one batch from each line in a sequential manner. This way, the actual process is replicated. The arrival rate is depending on the number of occupied AssignedLines (Number of parallel operating mixing lines).

AssignSilo — Batches are moved to the silo assigned by InitiateOrder. An order for the subsequent process steps (Packaging or Pelleting) is generated.

Silos (46) — This is a cluster of queues where batches are stored until the next process step. For the possible origins and destination for every silo see appendix B.

ReleaseSilo — This process is used to open the silos and let the batches flow into the process they are waiting for. The process goes through the package or pellet orders which are prioritized using different rules. When a package or pellet order is found for which the subsequent process is available, the silo is opened. Only one silo can be opened for one subsequent process.

AssignLine — Batches are moved to the package- and pellet lines using this process.

Press1/Press2 — According to the service time defined in the attribute of the batch, the batches are processed on the pelleting lines. Afterward, the batches are declared pelleted and go through the process of entering a silo again.

SL1-SL6 — According to the service time defined in the attribute of the batch, the batches are processed on the packaging lines. There are only three operators on the packaging department, so no more than three packaging lines (excluding SL4B (Bulk)) can be used simultaneously in the initial situation.

ReleaseLine In this process the batches are moved to a pelleting line or the exit of the model, results are written away to tables and packaging lines, pelleting lines and silos are released for the next order when the last batch has exited the line.

PDL

```
Init
    Clear all tables
    Set variables to initial value
     Create Silos
    Generate orders
    Assign route variables to order table

Reset
    Delete all moving elements

InitiateOrder
    while OrderID < Orderhorizon
        if mixline free and silos on route free then
            Declare order performed
            Declare silos on route occupied
            Draw random service times for package and pelletlines
            Exit while loop
        else
            Add order to waiting list for route
            Go to next order

    for number of Batches in order loop
        Create Batch
        Assign  variables to Batch
        if first Batch then
            Add setup time to service time
         Move Batch to AssignedLine

FlowControl
    Move Batch from AssignedLine to AssignSilo
    Check number of parallel operating mixing lines
    Draw random inter arrival time

    Wait until simtime + inter arrival time
        Repeat FlowControl

AssignSilo
    if Batch is first batch and pelleted is true then
```

```
        Register package order
    elseif Batch is first batch and pelleted is false then
        Register pellet order

    Move Batch to Silos

ReleaseSilo
    Sort package orders on priority

    while operators and package orders are available loop
        Pick first package order
        if packageline available then
            Open silo
            Declare packageline occupied
            Exit while loop

    Sort pellet orders on priority

    while pelletline is free and pellet orders are available loop
        Pick first pellet order
        if pelletline available then
            Open silo
            Declare pelletline occupied
            Exit while loop

AssignLine
    if Batch is not pelleted then
        Move Batch to pelletline
    else
        Move Batch to packageline

ReleaseLine
    if all Batches for order are processed then
        Declare silo available
        Declare pelletline or packageline available

    if pelleted is true then
        Register tonnage
        Move from packageline to Exit
    else
        Pelleted is true
        Move from Pelletline to AssignSilo
```

5.3.6. Verification

Verification is the process of ensuring that the model design (the conceptual model as described in chapter 3) has been transformed into a computer model with sufficient accuracy [9]. The question asked should be: is this model built in the right way?

Analytical verification

In paragraph 5.2 the mean throughput and stability of the queues between the process steps are determined. By product streams over these particular steps in the process, the simulation outcome can be compared to the outcomes of the analytical approach. Verification experiments:

1. Assign 100% of all orders with 30 batches per order to a particular route. Since all routes would be over utilized, a growing queue should be observed. The average output rate should be equal to the service rate of the package or pellet line with the highest service time.
2. Do the same experiment with six parallel operating routes such that all utilization rates are smaller than 1. The output rate should be equal to the arrival rate and stable queues should be observed.

The results are given in table 5.6. The first experiment was executed on route 1 and 23. Both experiments showed queue build up and an output rate slightly lower than the service rate of the constraint. The second experiment is performed on route 1, 6, 10a, 17, 22 and 27 which also showed no queue built up and an output rate slightly lower than the arrival rate of three parallel operating mixing lines. It is notable that the output rate is always slightly lower than the rate of the constraining process. This is due to the fact that the number of silos between the process steps is sometimes not enough to account for the variation in the capacity of the preceding and subsequent process step. If that is the case, a route gets blocked for some time. This results in the constraint not being utilized for 100%, which results in a lower average output. This can be particularly seen in the second experiment since there are six routes which can cause blockage.

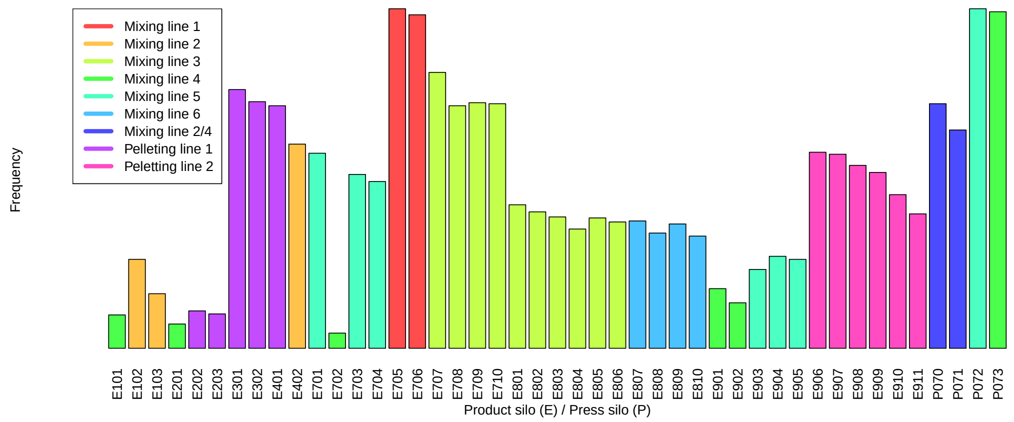
The analytically calculated daily throughput of the second experiment is the maximal achievable throughput since the mean throughput will never exceed the mean arrival rate of six parallel producing mixing lines. However, this only accounts for the product portfolio as produced for the last nine months.

Verification by tracing

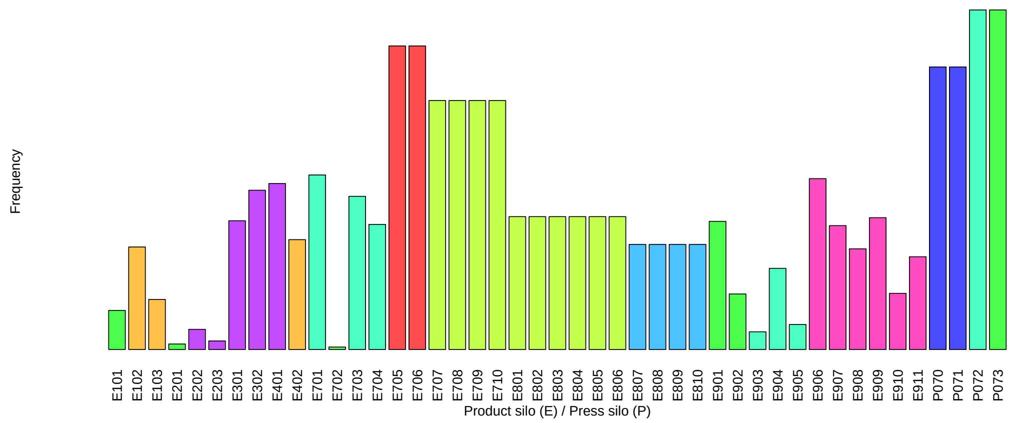
By tracing an element one can see what process steps the element goes through. This allows the user to check whether the element goes through the correct processes. This function has been used during programming the simulation model and during the verification of the total model. No illogical steps were found when tracing the model.

5.3.7. Validation

Validation is the process of ensuring that the model is sufficiently accurate for the purpose at hand. Or: is this the right model for the purpose at hand? Validation can be broken down in two subsec-



(a)



(b)

Figure 5.6: (a) Frequency of silo usage in the real system (b) Frequency of silo usage in the simulated system

tions, black and white box validation [9]. Black box validation validates the model by only comparing the in- and output of the model with that of the real system. White box validation validates the model by looking at the in- and output of parts of the model and the logic behind the model. The logic behind the model can be verified using paragraph 5.3.5.

Since the model is a simplified version of reality (see paragraph 5.3.4) absolute results of the simulation model may be used as an indication for validity but not as a hard proof of validity (which is true in general, since it might be sheer luck that absolute results coincide). To validate, it is better to look at relative results by using a sensitivity analysis and a theoretical, logical explanations for the observed results (as in paragraph 6.2).

Validation of absolute results can be performed by comparing two data sets (the output of the real system and the output of the model) using a student's t-test to see if the sets differ significantly.

Table 5.6: Results of analytical verification

Experiment	Analytical result (MT/day)	Simulation result (MT/day)
1a: Route 1	158.400	156.621
1b: Route 23	225.033	224.393
2: All Routes	518.400	514.823

Table 5.7: Black box validation of the output of the system

Variable	$\bar{X}_{sim}$	$\bar{X}_{real}$	$s^2_{X_{sim}}$	$s^2_{X_{real}}$	n	Low. B.	Up. B.
MT/24h	344.17	350.04	51.37	53.55	496	-1.92	10.2

The independent two sample t-test assumes equal true variance and equal sample size. The confidence interval of the true mean can be calculated using:

$$\bar{X}_1 - \bar{X}_2 \pm t_{2n-2,1-\alpha/2}\sqrt{\frac{s^2_{X_1} + s^2_{X_2}}{n}} \tag{5.22}$$

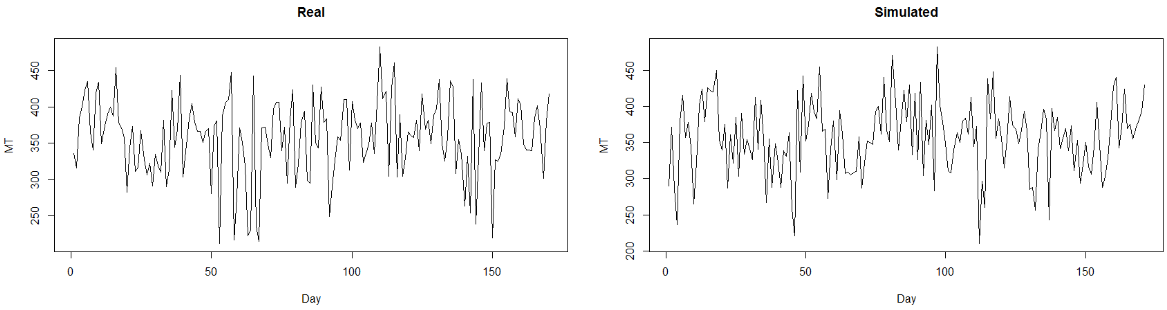
Where $\bar{X}_1$ is the estimated mean and $s^2_{X_1}$ the estimated standard variance of the data set and n the number of samples in a sample. The critical value of $t_{2n-2,1-\alpha/2}$ can be found in a table by choosing the chance of not rejecting the hypothesis that the means do not differ significantly α and the degrees of freedom $2n-2$. If 0 falls in the confidence interval, the true difference between the estimated means is insignificant.

White box validation

The silos are the core of the simulation model. The white box validation especially focusses on the results gained from the time spent in the silos and the usage frequency of the silos as can be found figure 3.17. The average time spent in the simulated silos is 410 minutes. This is 90 minutes shorter than the average of the real system. This is due to a difference in the prioritization of the packaging orders. It is assumed that a First Come First serve strategy is used in the factory. However, in reality this is not true for all cases. Operators vary in the strategy they apply. The frequency of silo usage shows similar patterns as can be seen in figure 5.6. The usage frequency of the silos after pelleting are lower, this is due to the fact that pelleted materials have lower densities and are often stored in multiple silos, in the simulation model the number of silos locked is based on the average density of the material.

Black box validation

A black box validation validates the output of the model only in a particular configuration. It does not guarantee valid outcomes for changes to the system. The input of experiment 1 as described in paragraph 5.3.2 should result in the output as described in chapter 3. Also, the tonnage of all the lines in the system should be divided as described in 2.1. A sample of the output of the real and simulated system are given in figure 5.7. As can be seen, variation and absolute values show a similar pattern. A difference can be seen in the trend through time. The real system is more stable on the long run than the simulated system. This due to the fact that the real system is emptied and closed down in the weekends. This 'resets' all relations over time. The simulated system assumes constant



(a) (b)

Figure 5.7: (a) Output of the real system (b) Output of the simulated system

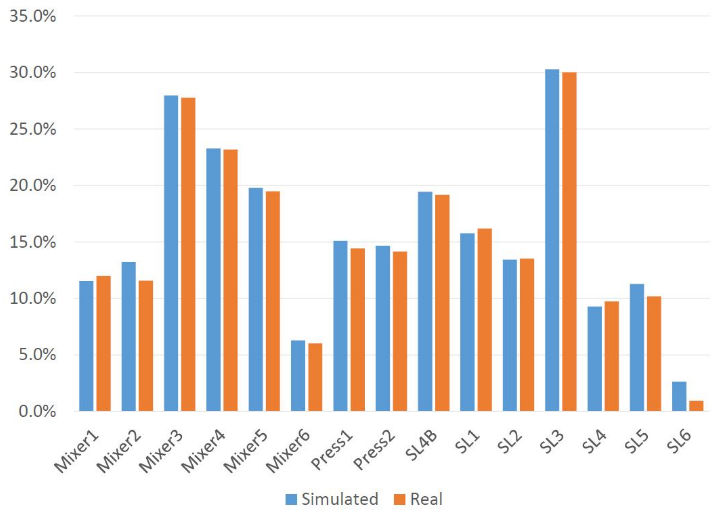


Figure 5.8: Daily average production per line

production through time which results in a more related pattern. The result of the two sample t-test for the average daily output can be found in table 5.7. The average daily output and variation in output are similar which only confirms that the model results are not in the wrong direction. The simulated and real percentages of daily average production per line is compared in figure 5.8. As can be seen, the distribution of production in MT over the lines used is similar.

5.4. Conclusions

A mathematical model of the system cannot be used to calculate the effects of the solution paths due to the complex, stochastic character of the system. Since an analytical solution cannot be found, a Discrete Event Simulation model is used to simulate the behaviour of the system under different circumstances. Verification and validation showed that the model gave decent results from which conclusions about relative improvement of the output of the system can be drawn.

6 Results

This chapter summarizes the results of the various experiments. Experiment 1 to 4 are addressed first. These experiments are measures to see how the productivity of the factory with the current product portfolio can be improved. Experiment 5 and 6 focus on how changes in the product portfolio in both size and route affect the productivity of the plant.

6.1. Experiments 1, 2, 3 and 4

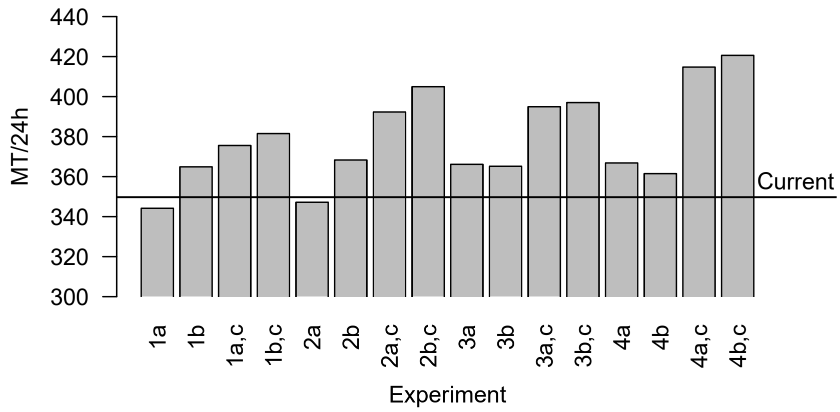
The numerical results of these experiments can be found in appendix G. Experiment 1, 2, 3, and 4 simulate the following alterations:

1. Current situation
2. Releasing the restriction incurred by Coccidiostats
3. Combining silos between mixing line 1 and 3
4. A combination of experiment 2 and 3

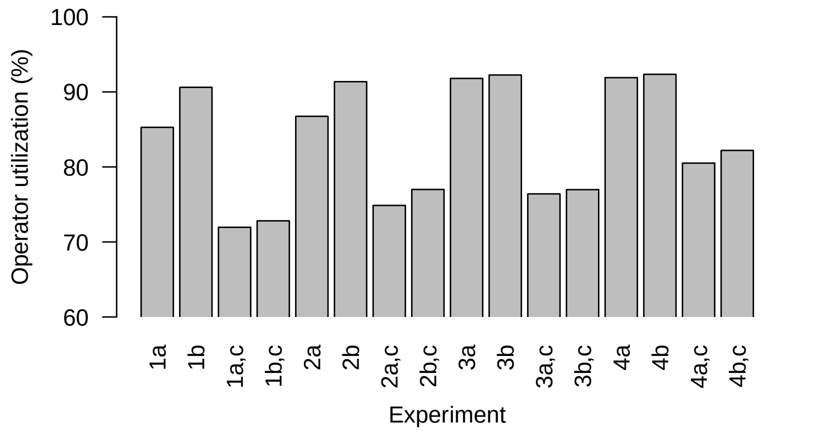
The experiments are performed using the following control alterations:

(a) First Come First Serve
(b) Critical Path Priority
(c) 4 instead of 3 packaging operators

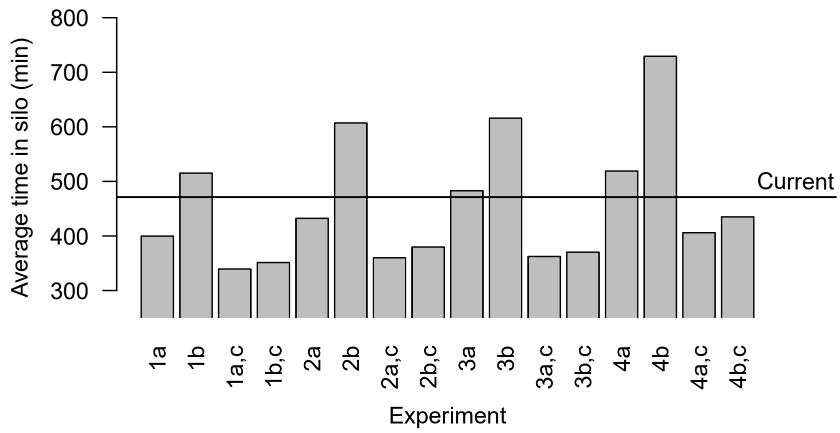
The most important results are graphically represented in figure 6.1. All numerical results can be found in appendix G. The results of experiment 1 show that the current sequence strategy does not completely rely on the First Come First Serve sequencing because the daily output is higher and the average time spent in silo is larger in reality. However, there is still room for improvement by implementing Critical Path Priority. Productivity can increase with 4.3% without an extra packaging operator and with 9.1% with an extra packaging operator. Extra operators increase the productivity slightly, but the operator utilization decreases to 72% which means that on average, one operator is



(a) Average MT/24h



(b) Average operator utilization



(c) Average time in silo

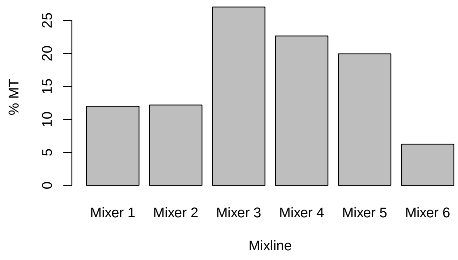
Figure 6.1: Results of experiments 1, 2, 3 and 4

standing by. It should be investigated whether the extra costs weigh up against the benefits.

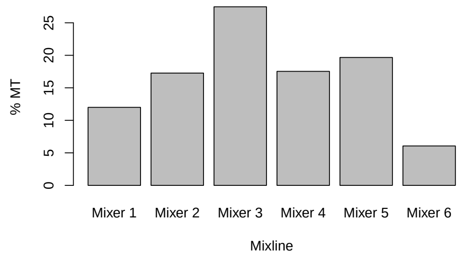
Experiment 2 shows the same results when three packaging operators are deployed. However, there is much potential for productivity as can be seen when an extra packaging operator is deployed. The extra parallel production due to more evenly utilized mixing lines (figure 6.2b and parallel production of contamination-sensitive products on mixing line 2 and 4 have a positive effect on the average productivity of the plant. Productivity increases with 15.5%. Both experiment 1 and 2 show a decline in average time in silo when an extra operator is deployed, which makes sense.

Experiment 3 results in a different pattern due to a decrease in critical paths. Mixing line 1 was a critical path due to the low amount of silos, and now shares the silos of mixing line 3. This also adds another route from mixing line 1 to packaging line SL3 which makes it possible to equalize the utilization of packaging line SL1 and SL3 (figure 6.3c). The production is now equally divided over mixing line 1 and 3 as can be seen in figure 6.2c. The control strategy has little effect on the productivity and only results in a longer average time in silo. This shows that the Critical Path Priority sequencing rule should only be applied when critical paths exist. Again, we see that an average operator utilization of > 90% is a bottleneck. When adding a fourth packaging the productivity can increase up to 13.4%.

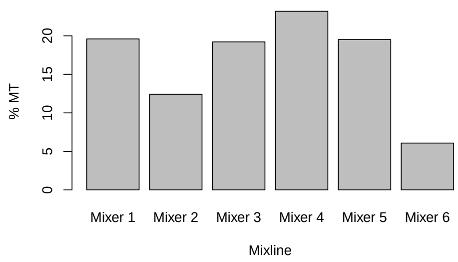
Experiment 4 shows the best of both worlds. Again, an extra packaging operator is necessary to release the potential increase in productivity with 20.3%. The combination of experiment 2 and 3 gives a equalized utilization of the mixing lines and a more equalized utilization of the packaging lines. However, as can be seen in figure 6.2d, there is much potential when looking at equalizing the utilization of the packaging lines. Operator utilization is now 82% which is close to the average of the current situation.



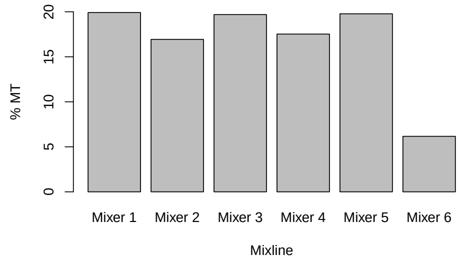
(a) Percentage MT per mixer for experiment 1



(b) Percentage MT per mixer for experiment 2

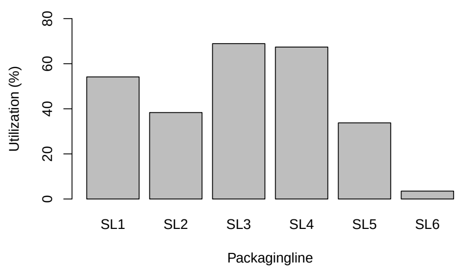


(c) Percentage MT per mixer for experiment 3

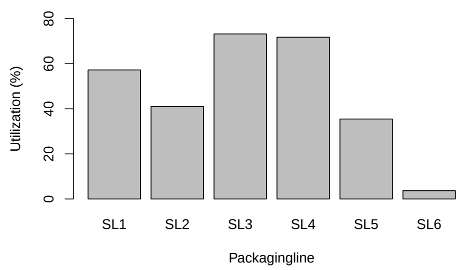


(d) Percentage MT per mixer for experiment 4

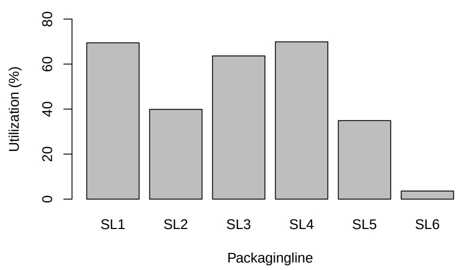
Figure 6.2: Production ratio per mixing line for experiments 1 to 4



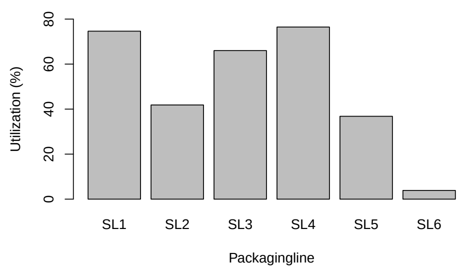
(a) Package line utilization for experiment 1



(b) Package line utilization for experiment 2



(c) Package line utilization for experiment 3



(d) Package line utilization for experiment 4

Figure 6.3: Utilization of packaging lines for experiments 1 to 4

6.2. Experiments 5 and 6

Experiment 5 is performed using the overall settings (if not changed) of experiment 1a. Experiment 6 is performed using the settings of experiment 1a,c because the sensitivity analysis must show the productivity as a function of order size and not of the number of packaging operators. The experiments consist of the following study:

5. Sensitivity analysis of increase of production orders per route
6. Sensitivity analysis of average order size

The results of experiment 5 are visualized in figure 6.4. Clearly, increasing order quantities on some routes have a very negative impact on the overall productivity. The routes with the most neg-

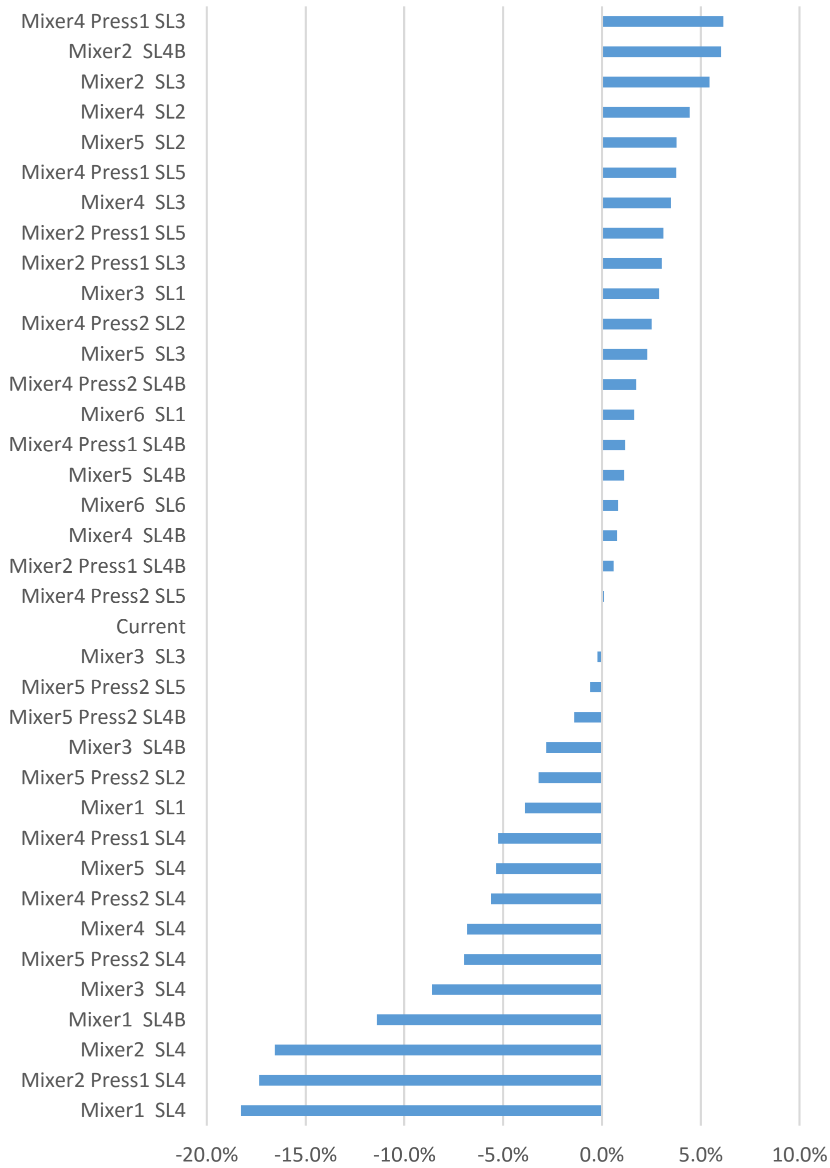


Figure 6.4: Results of the sensitivity analysis for productiviy with a 5% increase in orders for every route

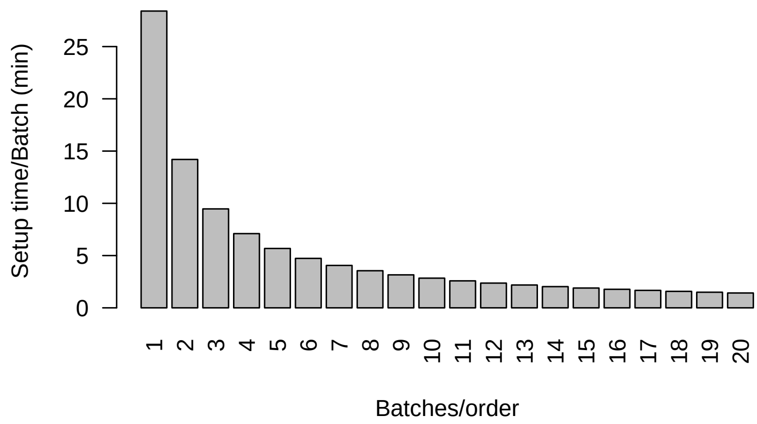


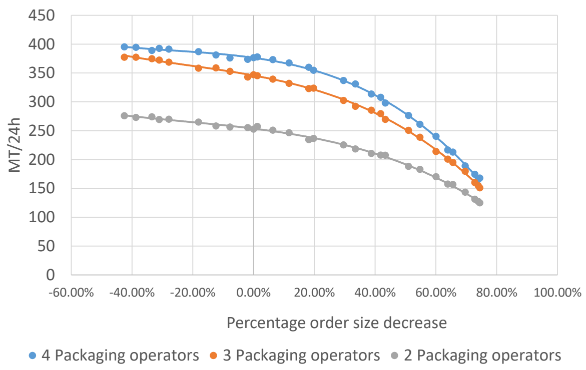
Figure 6.5: Set-up time per batch as a function of batches per order

ative impact on productivity are dominated by mixing line 1 and the packaging line SL4/SL4B. This makes sense because mixing line 1 has limited silo space and the SL4/SL4B packaging lines are only part of the day available which results in a lot of intermediate storage which blocks the mixing lines. Orders on mixing line 2, 4 and 5 and packaging line 1, 2, 3 and 5 have a positive impact on the overall productivity.

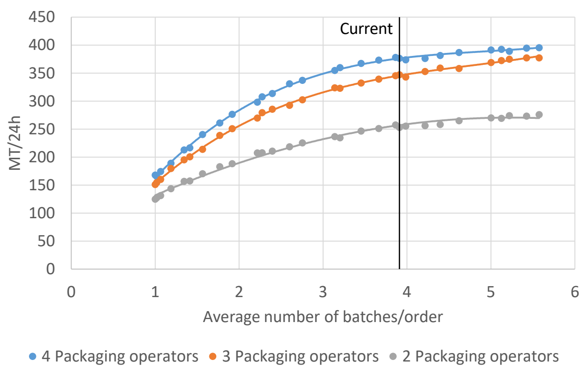
Figure 6.6 shows the results of experiment 6. A decline in average order size clearly influences the productivity of the plant. The analysis shows that with decreasing order size the productivity decline is increasing. This is due to fact that the set-up time per batch increases reciprocally with decreasing order sizes. A simple calculation shows how the set-up time per batch ($t_{set,MT}$) increases with the number of batches per order (Q_{order}):

$$t_{set,MT} = \frac{t_{set}}{Q_{order}} \tag{6.1}$$

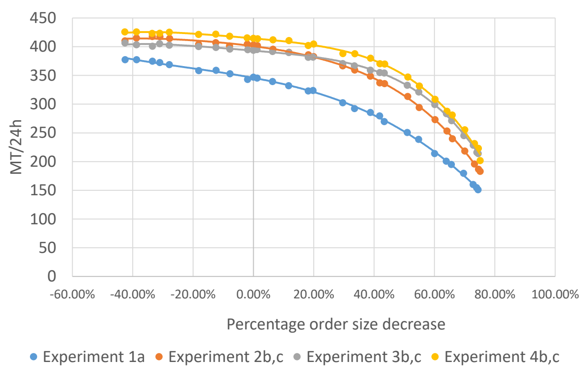
Where t_set represents the average set-up time per order ($t_{set} = 0.28*50+0.72*20$ minutes). The effect of a varying order size on set-up time per batch is visualized in figure 6.5. When looking at the variation in numbers of packaging operators, it is interesting to see that the difference between three or four packaging operators is small, especially when looking at the extreme order sizes. Big orders utilize the silos very well, which increases the buffer capacity. This results in a system less sensitive to variation in production capacities and less peak demand for packaging capacity. Therefore an extra packaging operator initially used to help out at peak times has less impact on the average production capacity. On the other hand, small order sizes result in a very inefficient usage of silo capacity. Silo capacity becomes a bottleneck because variation in production capacities can not be captured. The number of packaging operators is in this case less important for the overall average production capacity because the packaging capacity is not the constraining process. When only 2 operators are working, the packaging capacity is clearly the bottleneck. Production capacity plum-



(a)



(b)



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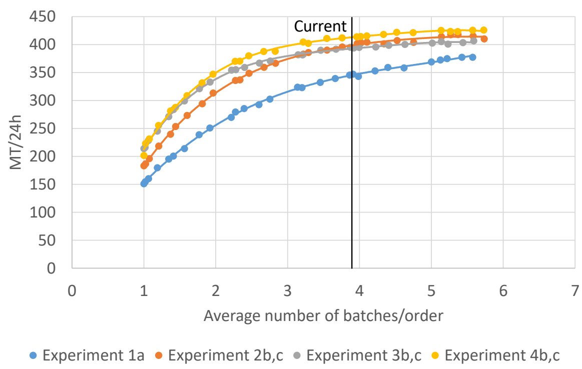

(d)

Figure 6.6: Production capacity as a function of order size, number of packaging operators and experiment

mets for one-third. This makes sense since the operator utilization is already quite high (85%) when three operators are utilized.

Figure 6.6c and 6.6d show similar patterns. However, the productivity decreases slower with decreasing order size. There is much more room for order sizes to decrease while maintaining an acceptable productivity. This can be explained by the fact that silos are more equally, and therefore more efficiently utilized. Experiment 2 has a more equalized usage of the silos after mixing line 2 and 4 since the production over these lines is equalized. The same can be stated about experiment 3 since silo space is now better divided between mixing line 1 and 3.

7

Implementation

This chapter focusses on the practical implementation of the solution routes. This includes costs and other implications for the rest of the system.

7.1. Critical Path Priority

The Critical Path Priority rule should be implemented using the following steps:

1. Show the operators what the benefits and consequences of sequencing packaging orders are, create the need for the change.
2. Teach them what the best method is and what the decision parameters should be. Learn them how the change can be realized.
3. To sustain the change in sequencing, the packaging orders should be automatically ordered on basis of the number of orders waiting for that particular order to be finished. This can be done by changing the daily Excel file containing the production orders (as described in paragraph 3.3). In this Excel file, the route should be determined for each job. The number of jobs waiting per route should be counted. This information can then be used to sequence the packaging jobs.

Besides, the communication between production and packaging can be improved by having monitors installed at each packaging line, showing the packaging jobs for that particular packaging line in the right sequence. This reduces communication errors and decreases the set-up times of the packaging lines since the packaging operators do not need to walk to the operator room to get a sticker. Set-up times become an increasingly important determinant of production capacity because of declining order sizes (figure 6.5. The changes in information flow with respect to figure 3.9 are visualized in figure 7.1. Costs for this implementation is minimal, while it can increase the average productivity by 4.3%.

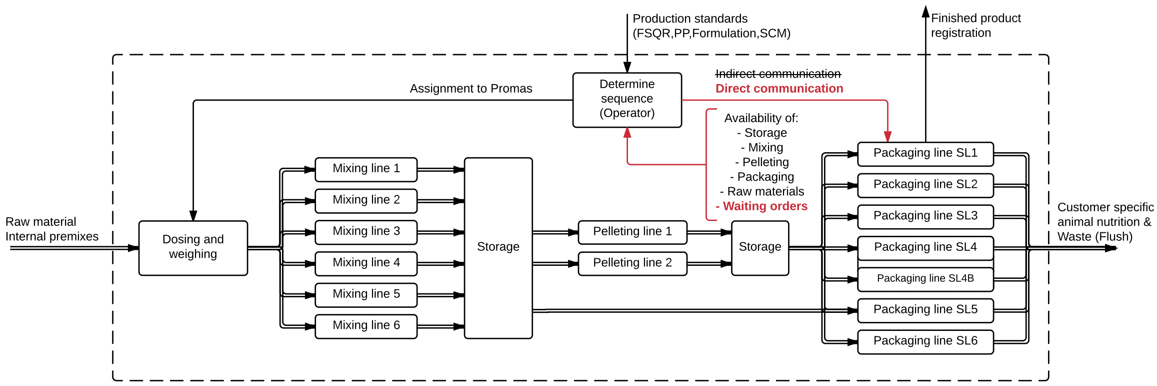

Figure 7.1: Feed forward loop changed by implementing Critical Path Priority and direct communication

7.2. Increasing the number of packaging operators

At Cargill Premix & Nutrition, operators are normally hired full time, there are only a few people working on a part-time basis. Therefore, the costs for an extra operator is calculated based on a full-time contract. It is assumed that an operator costs €19,- / hour. This means that for every production day (24h) the costs increase by €456,- and yearly by €106.704,-. It depends on the margin gained by this extra production capacity whether this is a decision worth making. However, when the other changes are executed, they will only increase the productivity if the extra packaging operators are hired. Therefore, these costs must be taken into account when calculating the costs of these changes. An alternative could be to only hire operators for a one or two shifts instead of all three shifts.

7.3. Outsourcing products containing Coccodiostats

Historically, only 1200 MT of the products produced per year contains Coccidiostats. This is 1.4% of the total production. However, the fact that the plant is capable of producing these products gives the sales personnel access to tenders they would otherwise not be capable of participating in. These tenders mostly contain a small ratio of products containing Coccidiostats, but disability to provide these will exclude them from participation. Therefore, outsourcing this part of a tender or order to another factory is the only solution. Cargill owns a factory in France which is focussed on producing products containing Coccidiostats. A study to the possibility of outsourcing these products is being performed. If possible, extra logistical costs will be made since products containing Coccidiostats for customers in the northern part of Europe are now produced in Rotterdam

Table 7.1: Costs of the different solution paths

Solution path	Fixed costs	Variable costs (€/year)	Prod. impr.
1. Critical Path Priority	Minimal	None	4.30%
2. Outsourcing Coccodiostats	None	€106.704,- + Log. costs	15.50%
3. Connecting silos	€130.000,-	€106.704,-	13.40%
4. Combination exp. 1-3	€130.000,-	€106.704,- + Log. costs	20.30%

7.4. Connecting silos of mixer 1 and 3

Six of the silos of mixing line 1 and mixing line 3 are very close to each other and can be connected without much alterations to the system. Figure 7.2 shows the current setup of the connection between mixing line 1 and 3 and the silos E705 - E710. The connection between mixing line 1 and E707 - E710 can be realized by adding downpipes and two-way valves in the same way mixing line 3 is connected to these silos. This adjustment must also be integrated into the production automation software, Promas. A quotation for these adjustments is requested and the realization costs came down to €30.000,-. According to the model, this particular step would increase the productivity by 5.6% instead of 13.4%. Connecting the E801 - E806 series is more complicated since the horizontal distance between the exit of mixing line 1 and these silos is too far to let the material be transported in a downpipe. A drag chain or blowpipe can be used to transport the material. The price of this adjustment is quoted at €100.000,-. To summarize, all variable and fixed costs per solution path have been stated in table 7.1.

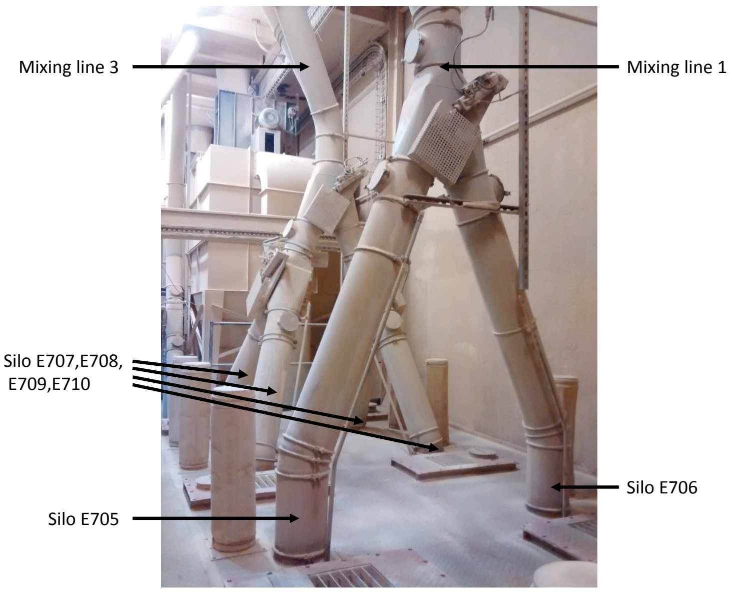

Figure 7.2: Connections between mixing line 1 and 3 and product silos E705-E710

8

Conclusions and recommendations

This chapter will answer the research question and sub-questions posed in chapter 4. Next, recommendations will be given.

8.1. Conclusions

The plant Cargill Premix & Nutrition is facing declining productivity due to decreasing order sizes and increasing product complexity. On the other hand, the strategy of Cargill is to increase production in the plant in Rotterdam. To be able to cope with this increased demand, the productivity must increase. The research question was therefore stated as:

> Can the input, control and layout of the production system of Cargill Premix & Nutrition be adjusted in a cost efficient manner such that the productivity is increased by 10%?

The answer to this question is: yes, this is possible. To prove this, several adjustments to the input, control and layout of the system at Cargill Premix & Nutrition are proposed using the Delft System Approach, knowledge of production experts at Cargill and KSE and similar cases found in literature. To demonstrate the effects of these adjustments, a model is made by the aid of Discrete Event Simulation. This model is verified and validated using white and black box validation techniques to make sure the relative outcomes are credible. The answers to the sub-questions will further explain the changes proposed:

> How can the control of the system be adjusted such that the productivity increases?

There are two decision points during the production process: the decision of:

1. Which order to start producing
2. Which order to start packaging

The first decision is made based on the Earliest Due Date (EDD), contamination rules and the availability of resources (raw materials and machines). The second decision is mostly based on the first sequence, the First Come First Serve (FCFS) strategy. If a route is used for a lot of orders at a certain time (if the route is critical), this route should be prioritized such that it will not form a bottleneck in the system. The alteration proposed is the Critical Path Priority, which means that the silo which blocks the most production orders will be packaged first. If this method is applied the average productivity improves by 4.3%.

> How can the layout of the system be adjusted such that the productivity of the system increases?

During the analysis, the number of silos between production steps per route is identified as a bottleneck for production. Since there is a lot of variability in production capacities and only a limited number of packaging lines can be used simultaneously, buffer capacity between the production steps is important. Mixing line 1 is only connected to only 2 product silos which constraints the production capacity of this particular line. Connecting mixing line 1 to the silos of mixing line 3 relieves this constraint. Since similar products are produced by mixing line 1 and 3, the production load can now be equalized which raises the average productivity by 13.4%. A condition for this solution is the deployment of an extra packaging operator. This increases the packaging capacity, which would otherwise become the bottleneck process. Since the most critical route is relieved, the Critical Route Priority rule shows little improvement in the new situation.

> How do adjustments of the input affect the productivity of the system?

This question has been extensively researched. First, a deliberate change in input to obtain production capacity improvement is analyzed. after that market changes of order per route and order size are investigated. A small part of the products is produced using Coccidiostats, traces of this material may not be found in many other products. Therefore the mixing line used to produce these products can only be used for a few products. Outsourcing the products containing Coccidiostats to a different Cargill factory releases this restriction and thereby gives room to equalize production between mixing lines. Besides, contamination-sensitive products can now be made simultaneously on multiple mixing lines. This adjustment improves the average productivity by 15.50 %. Again, a condition for this improvement is the deployment of an extra packaging operator.

Besides this deliberate change, an analysis to (unforeseen) changes in the product portfolio has been analyzed by performing the following two experiments:

- Sensitivity analysis of increase of production orders per route
- Sensitivity analysis of average order size

In the first experiment, the productivity increase (or decrease) as a consequence of an increase in orders for a particular route shows whether (a working station on a) route is a bottleneck. The analysis showed decreases in productivity when an increasing number of orders is produced on either mixing line 1 and/or packaging line SL4(B). Mixing line 1 has few intermediate product silos which act as a buffer for variation in production capacities. SL4(B) is partly available for big bags and partly available for bulk, silo space is needed for products to wait to be packaged. This blocks other routes which results in productivity decrease.

The second experiment showed that the productivity decline increases with decreasing order sizes. This makes sense since the set-up time per batch decreases reciprocally with the number of batches per order. It must be taken into account that a further decline in order sizes can be problematic since the productivity decline experienced is rather small in comparison to what it would be if the same order decline is experienced once more. However, the proposed alterations give much room for further decline of order sizes. In case the current demand in MT will stay stable and all alterations are implemented, there is room for the average order size to decline with another 40% while maintaining enough capacity.

8.2. Recommendations

Recommendations for further research proposed:

- The production of a product can occur on 27 routes. Research to whether this complexity really adds to the productivity of the facility might give reason for decreasing the number of routes of the facility such that the production capacity is more predictable and the sales and operation planning can be better coordinated.
- Research to the reduction of production capacity variation can give a more deterministic production system as well. Production capacities within the factory vary a lot, which results in an unpredictable productivity and it demands a lot of the buffers between production steps. A suggestion for this research can be the monitoring of production capacities and ask the operators for an explanation of the variation. The cause for the variation can then be taken away or reduced.
- The product portfolio of Cargill Premix & Nutrition is very diverse. Research to whether it is possible to combine types of products and thereby decrease the product diversity would result in combinable production orders. As a consequence, less set-up time is required and silo space will be more efficiently used which increases the productivity.
- Research to whether the current production planning is sufficient and optimal should be performed to see whether the current production order sequencing results in the highest productivity. A planning tool or simple algorithm could help with finding best practices for the operators.

A

Research paper

Improving the production logistics at Cargill Premix & Nutrition

L.M.C. van der Spek[1], prof. dr. ir. G. Lodewijks, dr. ir. H.P.M. Veeke

***Abstract*— Cargill Premix & Nutrition Rotterdam is experiencing declining order sizes due to a demand shift to the West European market. This results in a declining productivity of the plant in Rotterdam. Together with a future increase in demand, a production capacity deficit is foreseen. To be able to handle this deficit, the productivity of the plant is supposed to increase. Using the Delft System Approach, expert knowledge, literature and interviews with KSE several solution paths for increasing the productivity are proposed. Using Discrete Event Simulation the system is modelled and the solution paths analyzed. The analysis shows that productivity can be improved by up to 20.3% with relatively small capital and operational investments. This result shows that the plant can handle the future increase in demand.**

Keywords: Discrete Event Simulation, Delft Systems Approach, Cargill, feed milling, production logistics

Fig. 1. The plant in Rotterdam

I. INTRODUCTION

Cargill Premix & Nutrition (CPN) develops, manufactures and sells customized animal nutrition products and services for customers primarily focused on pork, poultry and ruminants. CPN Rotterdam manufactures roughly three types of products: premixes, concentrates and specialties (milk replacers, piglet feeds). These products are delivered to farmers, feed millers and traders in small bags on pallets, big bags or by bulk truck. Daily, an average of 350 MT of animal feed is produced and packaged in the facility. This is done by dosing batches (average 2.4 MT) of ingredients in 1 of the 6 paddle mixers after which the products can be pelletized on one of the 2 presses. At last, they are packaged on one of the 6 packaging lines. Between these steps, products are temporarily stored in silos. The plant is experiencing a declining productivity due to a shift in market from big export orders to small local (West European) orders. Small orders result in less efficient silo usage and setup times are more prevalent. To be able to handle a foreseen increase in production demand, the following research question is posed:

> Can the input, control and layout of the production system of Cargill Premix & Nutrition be adjusted in a cost efficient manner such that the productivity is increased by 10%?

This research only focusses on the effects of adjustments in control, input and layout of the current production system in Rotterdam.

II. METHODS

1) Delft System Approach [1]: The Delft System Approach is a combination of soft and hard systems analysis and is a fundamental approach for analyzing an industrial system. It logically and systematically combines quantitative and qualitative system modeling. Using the CATWOE method the root definition of the system is posed and then the

A. Peeters, Operations manager Cargill Premix & Nutrition, Rotterdam, the Netherlands, alexander_peeters@cargill.com

[1] Faculty of Mechanical Engineering, Delft University of Technology, Delft, the Netherlands, l.m.c.vanderspek@student.tudelft.nl

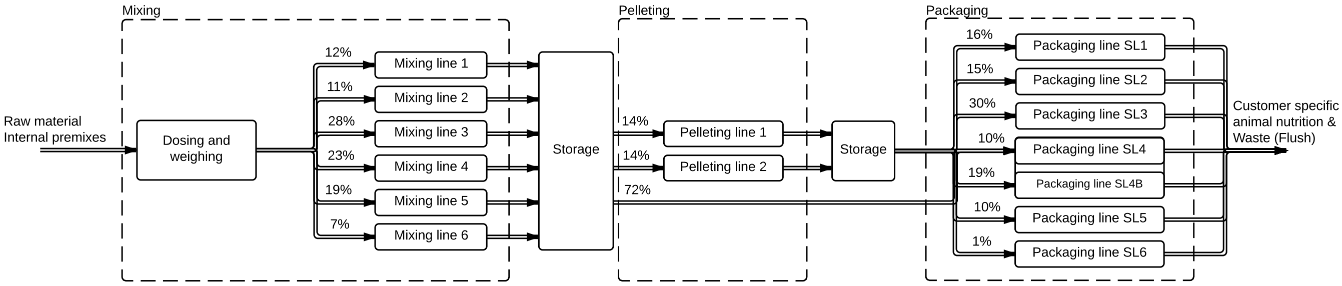

Fig. 2. Mixing, pelleting and packaging lines, the percentages represent the ratio in production volume for that line

system is described in more detail using the black box approach. This way the system is functionally described with enough detail whilst not letting go of the overall picture.

2) Data analysis: To quantify the functions defined using the Delft System Approach, production order data from the automation software (KSE Promas) is used. Since production has been stable for the past nine months, data from these months is used. From this data arrival rates and (variables determining) function capacities are quantified. Besides, the order size and order quantities of the product flow through the 27 routes of the system are found.

3) Theory of Constraints [4]: According to the Theory of Constraints, the bottleneck (constraint) within the production process determines the overall capacity of the process. To improve the capacity of the process, this bottleneck should be identified, exploited, subordinated (synchronized with the other processes) and at last elevated. Then, the process is repeated for the next bottleneck in the process. The theory of constraints is applied using the average production capacities of the system.

4) Queueing theory [5]: Using queueing theory, queue built up and utilization of workstation for each of the 27 routes through the system are determined. Using this method nominal throughput and constraining workstations are identified.

5) Discrete Event Simulation [2]: Discrete Event Simulation models describe the states of a system using state variables which change instantaneously at separate points in time. These points in time define when an event occurs. This results in a calendar of events, which the model goes through. Stochastic variables are introduced to simulate variation in orders, capacities and arrival rates. The model is made using Siemens Plant Simulation [3].

6) OFAT sensitivity analysis [2]: An OFAT (One-Factor-At-a-Time) sensitivity analysis determines the impact of a variable on the performance of a system by varying that particular variable while keeping the other input variables constant. Using this sensitivity analysis the impact of an increase of orders for a particular route and the impact of order size is analyzed.

III. RESULTS

Using the Delft System Approach, the scope is determined and the production process is broken down into three functions: mixing, pelleting and packaging. The functions are fulfilled using the production lines as depicted in figure 2. Dosing the batches of an order is performed sequentially, parallel to the orders dosed on other mixing lines. Since only one dosing installation is present, the mixing lines are served one by one. Between the production steps, a buffer zone in the form of 46 silos is present. The data analysis showed that there is significant variation in capacities of the mixing, pelleting and packaging lines. The number of parallel operating mixing lines is an important determinant for the capacity distribution of the mixing function (figure 3). The variation in the capacity of the other lines varies by material type, outside temperature, humidity, operator effectiveness and product complexity. Because there is no information on the relation between these variables, this variation is later modeled using a random number generator. Since the main variable determining overall output is the number of operating parallel mixing lines the focus of this research is on taking away reasons for unparallel operation. The reasons found using interviews with KSE

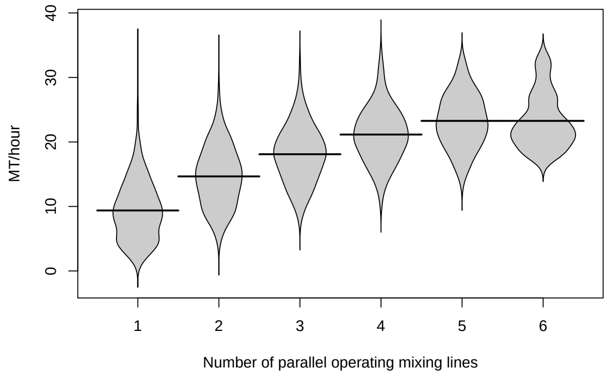

Fig. 3. Output of the system as a function of number of parallel operating mixing lines

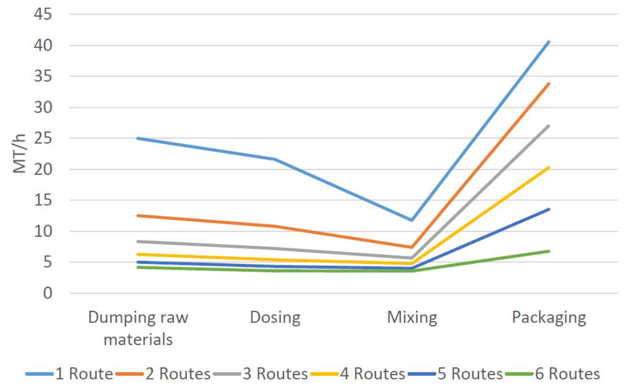

Fig. 4. (Potential) capacities as a function of parallel (but separate) routes used

(the automation software producer) and production experts were:

1) Blockage by upstream processes like late dumping of raw materials
2) Uneven utilization of mixing and packaging lines
3) Contamination rules to prevent production of products across mixing lines
4) Blockage by downstream processes like pelleting and packaging the product

Since the first reason can be relatively easy solved by hiring an extra, dedicated operator the focus of this research is on taking away the three other reasons. Using the theory of constraints and queueing theory the average capacity of the system and bottlenecks in the process are determined. This analysis does not take into account the variation in production capacities and limited buffer size between the production steps. The average output of the system can be different since the buffer size is sometimes not sufficient to cover the capacity variations. It is calculated that the potential average capacity of the system is 518 MT/24h when six separate production routes are used. The capacity profile when using four to six parallel routes is very flat, which indicates that negative production capacity fluctuations almost always result in a constraint for the overall process (figure 4). The current number of parallel routes used is 2.55. This results in an average production capacity of 350 MT/24h. By studying literature, logic thinking, brainstorming with the production experts at Cargill and interviewing KSE (the company behind process automation in this particular industry), various solution paths (experiments) have been determined:

1) Current situation
2) Outsourcing products containing Coccidiostats (a medicinal ingredient) to a different plant of Cargill
3) Connecting the silos of mixing line 3 to mixing line 1
4) A combination of the previous two solution paths

There can be unforeseen changes in the route and size of orders. To see the consequences of these unforeseen developments two sensitivity analysis are added to the experiment plan:

5) Sensitivity analysis of production orders per route
6) Sensitivity analysis of order size

The following adjustments in control of the system are used for experiment 1-4:

a) First Come First Serve (FCFS) sequencing for packaging orders
b) Critical Path Priority (CPP) sequencing for packaging orders
c) Increasing the number of packaging operators from 3 to 4

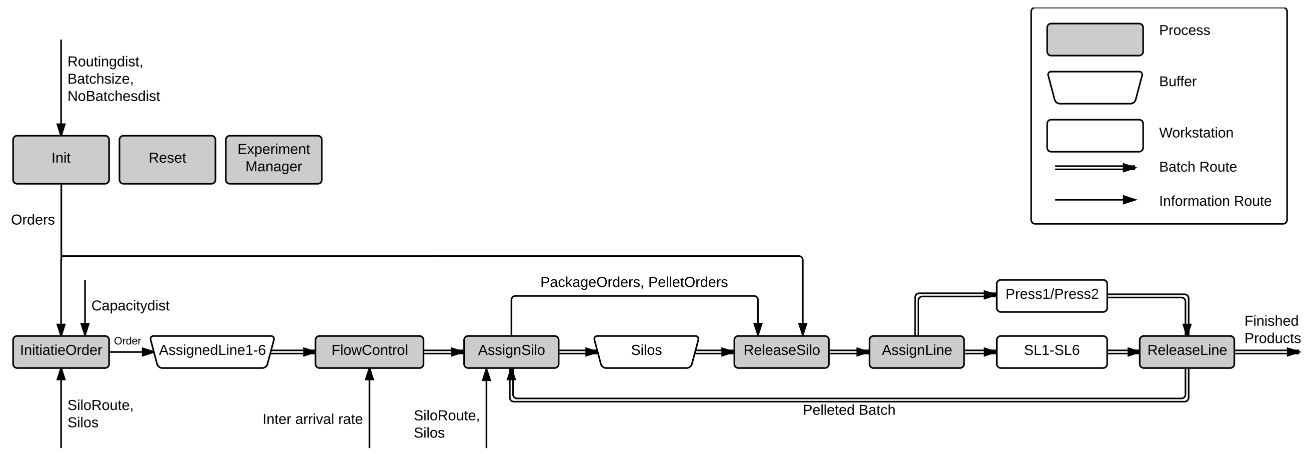

Fig. 5. Graphical layout of the simulation model

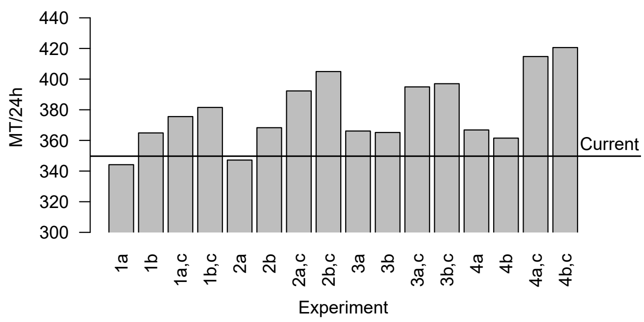

Fig. 6. Resulting average production capacity per experiment

To calculate the impact of these hypothetical changes a model of the production system is made. Because of the complex and stochastic character of the system Discrete Event Simulation is used to make a model in Siemens Plant Simulation [3]. The process logic, discrete distributions of order type and size, continuous distributions of capacities and the availability of lines are inserted in this model. The layout of the model is graphically represented in figure 5. A brief explanation of the processes and elements used:

- Batch: This element represents an individual batch
- Init: This process initializes all settings before an experiment
- Reset: This process resets the model after an experiment
- ExperimentManager: This process sets settings for an experiment
- InitiateOrder: This process initiates orders
- AssignedLine1-6: These elements represent the output of the mixing lines
- FlowControl: This process picks the batches from the mixing lines
- AssignSilo: This process assigns batches to the right silo
- Silos: These elements represent the product silos
- ReleaseSilo: This process opens a silo for the subsequent process
- AssignLine: This process moves the batch to a subsequent process
- Press1/Press2: These elements represent the pelleting lines
- SL1-SL6: These elements represent the packaging lines
- ReleaseLine: This process deletes the finished batches

The product flow is modeled on batch level. This means that an order consists of multiple batches which flow through the system individually, but only the batches of a particular order can flow into a silo reserved for this order. The model is verified and validated using the process logic and analytical and historical results.

The results of the experiments in average production capacity is given in figure 6. The

TABLE I

COSTS AND PRODUCTIVITY IMPROVEMENTS OF THE DIFFERENT SOLUTION PATHS

Solution path	Fixed costs	Variable costs (€/year)	Prod. impr.
Critical Path Priority	Minimal	None	4.30%
Outsourcing Coccodiostats	None	€106.704,- + Log. costs	15.50%
Connecting silos	€130.000,-	€106.704,-	13.40%
Combination	€130.000,-	€106.704,- + Log. costs	20.30%

costs and maximal achievable productivity improvements are given in table I. All proposed adjustments result in a production capacity improvement. As can be seen, an extra packaging operator is needed to get to the full potential capacity

The results of experiment 5 show a steep productivity decline if orders for either mixing line 4 and/or packaging line SL4 increase. An increase in orders for the SL1 - SL3 (small bags) results in a positive productivity.

The results of experiment 6 show that a decline in average order size clearly influences the productivity of the plant. The analysis shows that with decreasing order size the productivity decline is increasing. This is due to fact that the set-up time per batch increases reciprocally with decreasing order sizes. A visual representation of the results is given in figure 7. The proposed changes to the system give more room for order size decline. This is due to the fact that silos are more equally utilized in the new situation. The production capacity variations between production steps must be buffered by the silos. Smaller orders still occupy the complete silo. This reduces the effectiveness of silos resulting in more blocking of downstream routes. If silos are more equally utilized, there is more room for buffering.

IV. DISCUSSION

The productivity of the plant of Cargill Premix & Nutrition can be increased by 10% in a cost efficient manner. Moreover, the analysis shows an increase of 20.3% if the proposed adjustments are made in the control, input and layout of the system. Outsourcing products containing Coccidiostats can equalize the production on mixing line 2 and 4. Besides, sharing the silo space of mixing line 3 with that of mixing line 1 takes away the bottleneck of

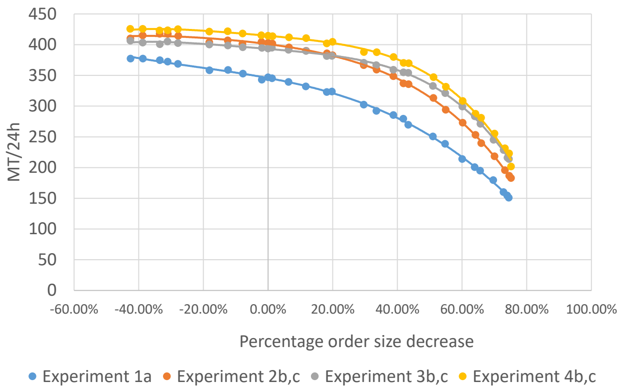

Fig. 7. Productivity as a function of order size decrease

mixing line 1. Both adjustments increase parallel production on the mixing lines, which, on its turn, increases productivity. Sequencing the packaging orders using Critical Path Priority utilizes critical (bottleneck) routes better, which also results in an increase in productivity. When the adjustments are implemented the plant in Rotterdam will be able to handle the increase in production demand even when the order sizes decrease by another 30%.

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B

Routes

Table B.1: All origin destination combinations including silos for experiment 1,2,5 and 6

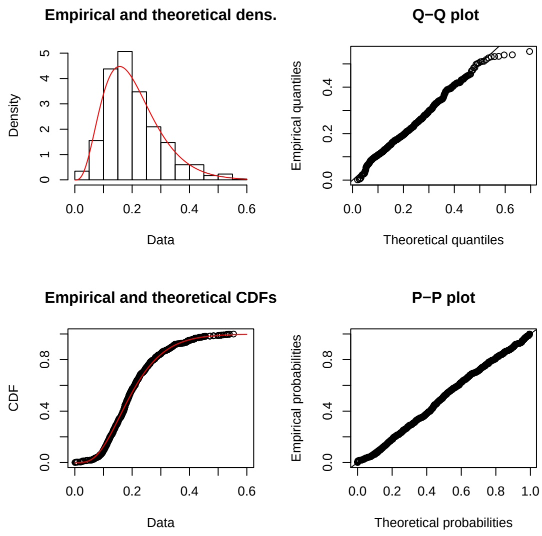
Origin	Silo	Dest	Origin	Silo	Dest	Origin	Silo	Dest
Mixer1	E705	SL1	Mixer4	P071	Press1	Press1	E302	SL4
Mixer1	E706	SL1	Mixer4	P073	Press2	Press1	E401	SL4
Mixer1	E705	SL4	Mixer4	E901	SL2	Press1	E402	SL4
Mixer1	E706	SL4	Mixer4	E902	SL2	Press1	E301	SL4B
Mixer1	E705	SL4B	Mixer4	E903	SL2	Press1	E302	SL4B
Mixer1	E706	SL4B	Mixer4	E101	SL3	Press1	E401	SL4B
Mixer2	P070	Press1	Mixer4	E201	SL3	Press1	E402	SL4B
Mixer2	P071	Press1	Mixer4	E702	SL3	Press1	E301	SL5
Mixer2	E102	SL3	Mixer4	E702	SL4	Press1	E302	SL5
Mixer2	E103	SL3	Mixer4	E702	SL4B	Press1	E401	SL5
Mixer2	E202	SL3	Mixer5	P072	Press2	Press1	E402	SL5
Mixer2	E203	SL3	Mixer5	E904	SL2	Press2	E906	SL2
Mixer2	E203	SL4	Mixer5	E905	SL2	Press2	E907	SL2
Mixer2	E202	SL4	Mixer5	E701	SL3	Press2	E908	SL2
Mixer2	E203	SL4B	Mixer5	E703	SL3	Press2	E909	SL2
Mixer2	E202	SL4B	Mixer5	E704	SL3	Press2	E910	SL2
Mixer3	E801	SL1	Mixer5	E701	SL4	Press2	E911	SL2
Mixer3	E802	SL1	Mixer5	E703	SL4	Press2	E906	SL4
Mixer3	E803	SL1	Mixer5	E704	SL4	Press2	E907	SL4
Mixer3	E804	SL1	Mixer5	E701	SL4B	Press2	E908	SL4
Mixer3	E805	SL1	Mixer5	E703	SL4B	Press2	E909	SL4
Mixer3	E806	SL1	Mixer5	E704	SL4B	Press2	E910	SL4
Mixer3	E707	SL3	Mixer6	E807	SL1	Press2	E911	SL4
Mixer3	E708	SL3	Mixer6	E808	SL1	Press2	E906	SL4B
Mixer3	E709	SL3	Mixer6	E809	SL1	Press2	E907	SL4B
Mixer3	E710	SL3	Mixer6	E810	SL1	Press2	E908	SL4B
Mixer3	E707	SL4	Mixer6	E807	SL6	Press2	E909	SL4B
Mixer3	E708	SL4	Mixer6	E808	SL6	Press2	E910	SL4B
Mixer3	E709	SL4	Mixer6	E809	SL6	Press2	E911	SL4B
Mixer3	E710	SL4	Mixer6	E810	SL6	Press2	E906	SL5
Mixer3	E707	SL4B	Press1	E301	SL3	Press2	E907	SL5
Mixer3	E708	SL4B	Press1	E302	SL3	Press2	E908	SL5
Mixer3	E709	SL4B	Press1	E401	SL3	Press2	E909	SL5
Mixer3	E710	SL4B	Press1	E402	SL3	Press2	E910	SL5
Mixer4	P070	Press1	Press1	E301	SL4	Press2	E911	SL5

Table B.2: All origin destination combinations including silos for experiment 3 and 4

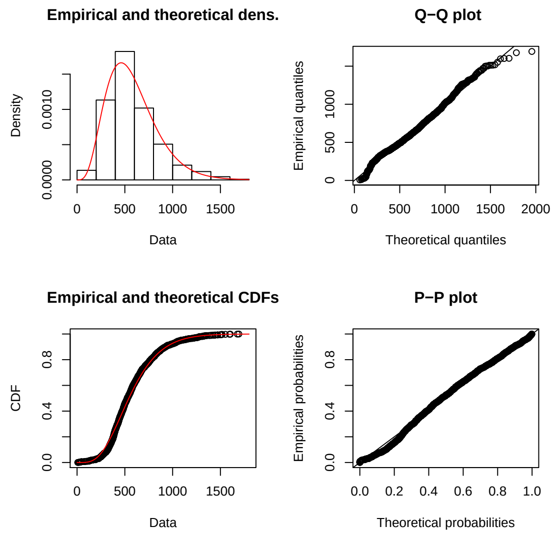
Origin	Silo	Dest	Origin	Silo	Dest	Origin	Silo	Dest
Mixer1	E705	SL1	Mixer3	E708	SL3	Mixer6	E808	SL6
Mixer1	E706	SL1	Mixer3	E709	SL3	Mixer6	E809	SL6
Mixer1	E707	SL3	Mixer3	E710	SL3	Mixer6	E810	SL6
Mixer1	E708	SL3	Mixer3	E705	SL4	Press1	E301	SL3
Mixer1	E709	SL3	Mixer3	E706	SL4	Press1	E302	SL3
Mixer1	E710	SL3	Mixer3	E707	SL4	Press1	E401	SL3
Mixer1	E705	SL4	Mixer3	E708	SL4	Press1	E402	SL3
Mixer1	E706	SL4	Mixer3	E709	SL4	Press1	E301	SL4
Mixer1	E707	SL4	Mixer3	E710	SL4	Press1	E302	SL4
Mixer1	E708	SL4	Mixer3	E705	SL4B	Press1	E401	SL4
Mixer1	E709	SL4	Mixer3	E706	SL4B	Press1	E402	SL4
Mixer1	E710	SL4	Mixer3	E707	SL4B	Press1	E301	SL4B
Mixer1	E705	SL4B	Mixer3	E708	SL4B	Press1	E302	SL4B
Mixer1	E706	SL4B	Mixer3	E709	SL4B	Press1	E401	SL4B
Mixer1	E707	SL4B	Mixer3	E710	SL4B	Press1	E402	SL4B
Mixer1	E708	SL4B	Mixer4	P070	Press1	Press1	E301	SL5
Mixer1	E709	SL4B	Mixer4	P071	Press1	Press1	E302	SL5
Mixer1	E710	SL4B	Mixer4	P073	Press2	Press1	E401	SL5
Mixer1	E801	SL1	Mixer4	E901	SL2	Press1	E402	SL5
Mixer1	E802	SL1	Mixer4	E902	SL2	Press2	E906	SL2
Mixer1	E803	SL1	Mixer4	E903	SL2	Press2	E907	SL2
Mixer1	E804	SL1	Mixer4	E101	SL3	Press2	E908	SL2
Mixer1	E805	SL1	Mixer4	E201	SL3	Press2	E909	SL2
Mixer1	E806	SL1	Mixer4	E702	SL3	Press2	E910	SL2
Mixer2	P070	Press1	Mixer4	E702	SL4	Press2	E911	SL2
Mixer2	P071	Press1	Mixer4	E702	SL4B	Press2	E906	SL4
Mixer2	E102	SL3	Mixer5	P072	Press2	Press2	E907	SL4
Mixer2	E103	SL3	Mixer5	E904	SL2	Press2	E908	SL4
Mixer2	E202	SL3	Mixer5	E905	SL2	Press2	E909	SL4
Mixer2	E203	SL3	Mixer5	E701	SL3	Press2	E910	SL4
Mixer2	E203	SL4	Mixer5	E703	SL3	Press2	E911	SL4
Mixer2	E202	SL4	Mixer5	E704	SL3	Press2	E906	SL4B
Mixer2	E203	SL4B	Mixer5	E701	SL4	Press2	E907	SL4B
Mixer2	E202	SL4B	Mixer5	E703	SL4	Press2	E908	SL4B
Mixer3	E705	SL1	Mixer5	E704	SL4	Press2	E909	SL4B
Mixer3	E706	SL1	Mixer5	E701	SL4B	Press2	E910	SL4B
Mixer3	E801	SL1	Mixer5	E703	SL4B	Press2	E911	SL4B
Mixer3	E802	SL1	Mixer5	E704	SL4B	Press2	E906	SL5
Mixer3	E803	SL1	Mixer6	E807	SL1	Press2	E907	SL5
Mixer3	E804	SL1	Mixer6	E808	SL1	Press2	E908	SL5
Mixer3	E805	SL1	Mixer6	E809	SL1	Press2	E909	SL5
Mixer3	E806	SL1	Mixer6	E810	SL1	Press2	E910	SL5
Mixer3	E707	SL3	Mixer6	E807	SL6	Press2	E911	SL5

C

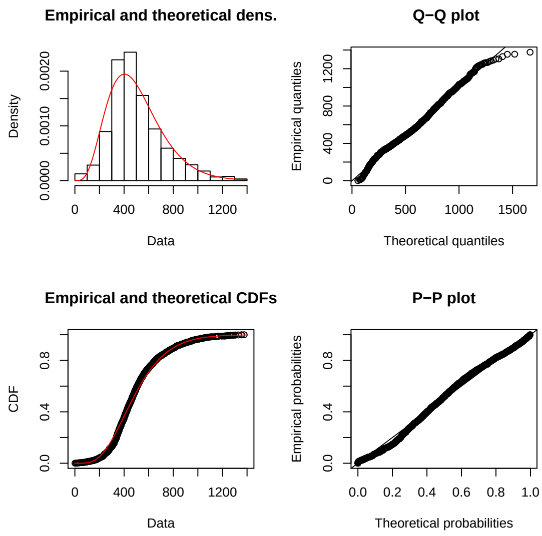
Fitted distributions



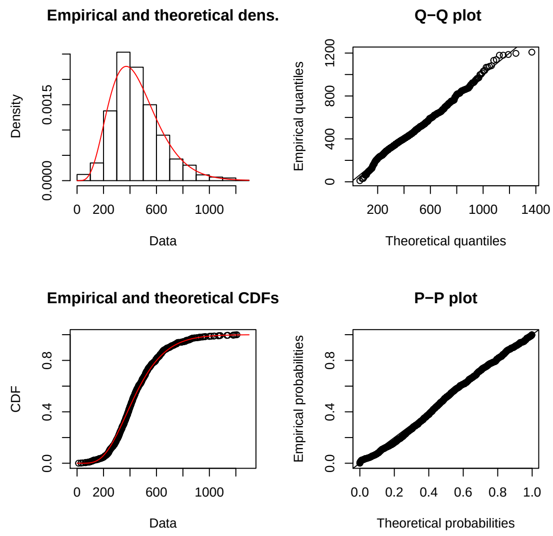
(a)



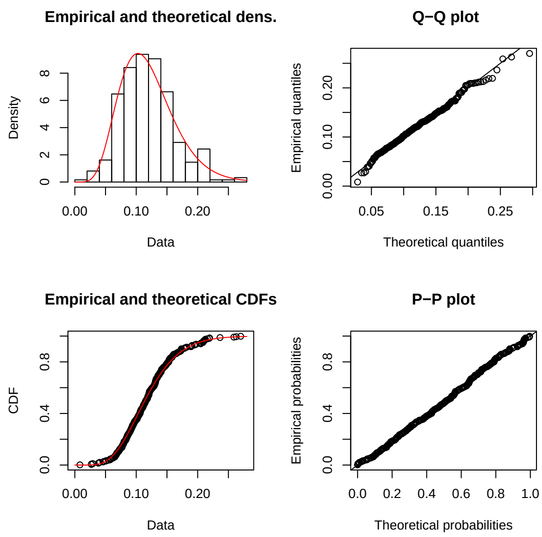
(b)



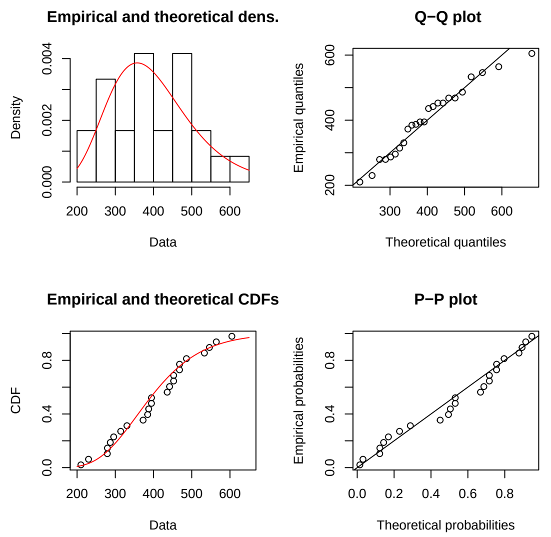
(c)



(d)



(e)



(f)

Figure C.1: Distributions of inter arrival time between batches as a function of mixing lines used

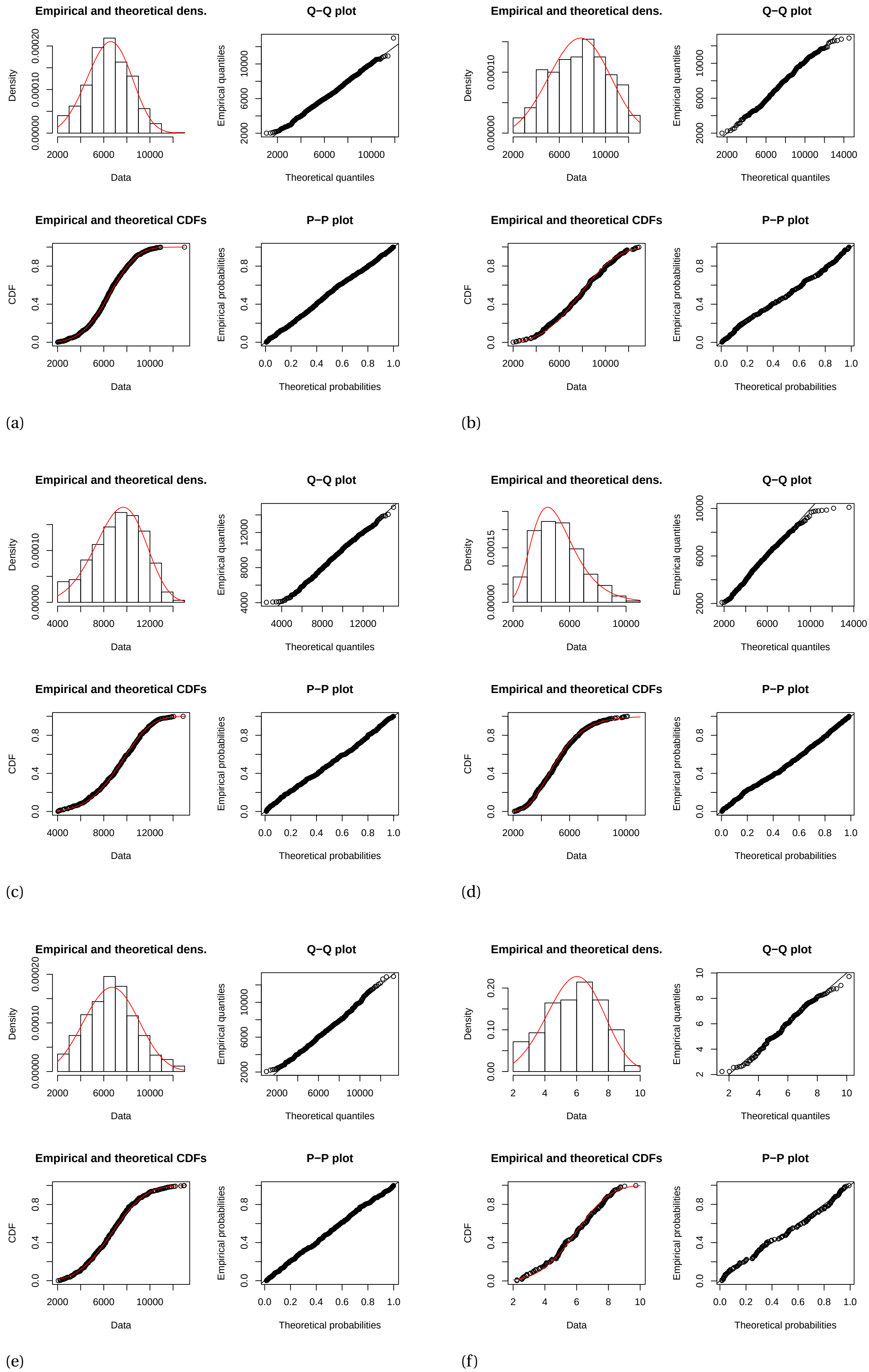


Figure C.2: Distributions of capacities of packaging lines

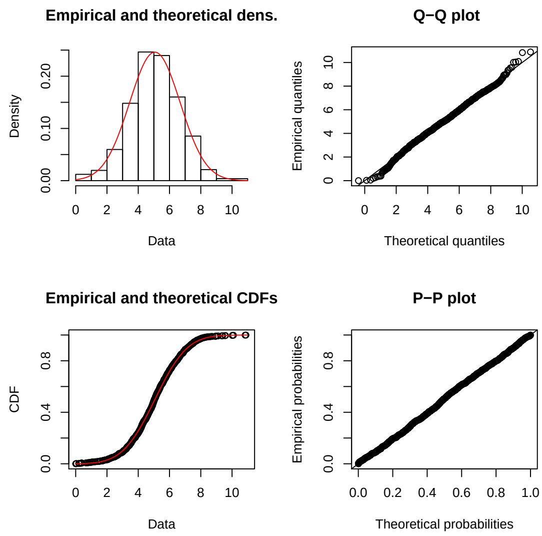


Figure C.3: Distribution of capacity of pressing lines

D

Batches per order

Table D.1: Frequency distribution of number of batches per order for experiment 1,5 and 6

Number of batches	Mixer 1	Mixer 2	Mixer 3	Mixer 4	Mixer 5	Mixer 6
1	21.3%	9.9%	32.8%	20.2%	26.0%	23.6%
2	24.2%	10.4%	26.0%	17.3%	22.6%	26.7%
3	15.2%	5.6%	12.2%	12.5%	13.6%	14.7%
4	11.8%	6.2%	9.3%	13.5%	10.4%	13.7%
5	8.6%	4.8%	4.9%	5.4%	3.8%	8.9%
6	3.2%	7.3%	3.1%	11.3%	5.5%	6.0%
7	4.6%	13.0%	1.5%	2.4%	1.5%	3.4%
8	3.1%	4.2%	2.8%	3.9%	3.7%	1.2%
9	5.1%	4.8%	2.2%	6.2%	2.8%	0.0%
10	1.8%	2.8%	1.7%	2.8%	6.2%	0.6%
11	0.4%	2.3%	0.5%	0.9%	0.3%	0.0%
12	0.5%	3.4%	0.9%	1.2%	1.7%	0.8%
13	0.0%	5.6%	0.3%	0.2%	0.7%	0.0%
14	0.1%	3.7%	0.2%	0.6%	0.4%	0.0%
15	0.1%	0.3%	0.3%	0.1%	0.0%	0.0%
16	0.0%	2.0%	0.2%	0.3%	0.2%	0.0%
17	0.0%	0.8%	0.2%	0.2%	0.1%	0.3%
18	0.0%	2.5%	0.1%	0.4%	0.5%	0.0%
19	0.0%	1.4%	0.2%	0.1%	0.0%	0.2%
20	0.0%	1.7%	0.2%	0.2%	0.1%	0.0%
21	0.0%	0.6%	0.0%	0.0%	0.0%	0.0%
22	0.0%	0.8%	0.2%	0.0%	0.0%	0.0%
23	0.0%	2.0%	0.0%	0.0%	0.0%	0.0%
24	0.0%	1.4%	0.0%	0.0%	0.0%	0.0%
25	0.0%	0.3%	0.0%	0.1%	0.1%	0.0%
26	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%
27	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%
28	0.0%	0.3%	0.0%	0.1%	0.0%	0.0%
29	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
30	0.0%	1.41%	0.0%	0.0%	0.0%	0.0%

Table D.2: Frequency distribution of number of batches per order for experiment 2

Number of batches	Mixer 1	Mixer 2	Mixer 3	Mixer 4	Mixer 5	Mixer 6
1	21.3%	16.7%	32.8%	16.7%	26.0%	23.6%
2	24.2%	15.0%	26.0%	15.0%	22.6%	26.7%
3	15.2%	10.2%	12.2%	10.2%	13.6%	14.7%
4	11.8%	11.1%	9.3%	11.1%	10.4%	13.7%
5	8.6%	5.2%	4.9%	5.2%	3.8%	8.9%
6	3.2%	10.0%	3.1%	10.0%	5.5%	6.0%
7	4.6%	5.9%	1.5%	5.9%	1.5%	3.4%
8	3.1%	4.0%	2.8%	4.0%	3.7%	1.2%
9	5.1%	5.8%	2.2%	5.8%	2.8%	0.0%
10	1.8%	2.8%	1.7%	2.8%	6.2%	0.6%
11	0.4%	1.4%	0.5%	1.4%	0.3%	0.0%
12	0.5%	2.0%	0.9%	2.0%	1.7%	0.8%
13	0.0%	2.0%	0.3%	2.0%	0.7%	0.0%
14	0.1%	1.6%	0.2%	1.6%	0.4%	0.0%
15	0.1%	0.1%	0.3%	0.1%	0.0%	0.0%
16	0.0%	0.8%	0.2%	0.8%	0.2%	0.0%
17	0.0%	0.4%	0.2%	0.4%	0.1%	0.3%
18	0.0%	1.1%	0.1%	1.1%	0.5%	0.0%
19	0.0%	0.6%	0.2%	0.6%	0.0%	0.2%
20	0.0%	0.7%	0.2%	0.7%	0.1%	0.0%
21	0.0%	0.2%	0.0%	0.2%	0.0%	0.0%
22	0.0%	0.3%	0.2%	0.3%	0.0%	0.0%
23	0.0%	0.7%	0.0%	0.7%	0.0%	0.0%
24	0.0%	0.5%	0.0%	0.5%	0.0%	0.0%
25	0.0%	0.1%	0.0%	0.1%	0.1%	0.0%
26	0.0%	0.1%	0.0%	0.1%	0.0%	0.0%
27	0.0%	0.1%	0.0%	0.1%	0.0%	0.0%
28	0.0%	0.1%	0.0%	0.1%	0.0%	0.0%
29	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
30	0.0%	0.5%	0.0%	0.5%	0.0%	0.0%

Table D.3: Frequency distribution of number of batches per order for experiment 3

Number of batches	Mixer 1	Mixer 2	Mixer 3	Mixer 4	Mixer 5	Mixer 6
1	29.4%	9.9%	29.4%	20.2%	26.0%	23.6%
2	25.5%	10.4%	25.5%	17.3%	22.6%	26.7%
3	13.1%	5.6%	13.1%	12.5%	13.6%	14.7%
4	10.1%	6.2%	10.1%	13.5%	10.4%	13.7%
5	6.0%	4.8%	6.0%	5.4%	3.8%	8.9%
6	3.2%	7.3%	3.2%	11.3%	5.5%	6.0%
7	2.4%	13.0%	2.4%	2.4%	1.5%	3.4%
8	2.9%	4.2%	2.9%	3.9%	3.7%	1.2%
9	3.0%	4.8%	3.0%	6.2%	2.8%	0.0%
10	1.7%	2.8%	1.7%	2.8%	6.2%	0.6%
11	0.5%	2.3%	0.5%	0.9%	0.3%	0.0%
12	0.8%	3.4%	0.8%	1.2%	1.7%	0.8%
13	0.2%	5.6%	0.2%	0.2%	0.7%	0.0%
14	0.2%	3.7%	0.2%	0.6%	0.4%	0.0%
15	0.3%	0.3%	0.3%	0.1%	0.0%	0.0%
16	0.1%	2.0%	0.1%	0.3%	0.2%	0.0%
17	0.2%	0.8%	0.2%	0.2%	0.1%	0.3%
18	0.1%	2.5%	0.1%	0.4%	0.5%	0.0%
19	0.1%	1.4%	0.1%	0.1%	0.0%	0.2%
20	0.1%	1.7%	0.1%	0.2%	0.1%	0.0%
21	0.0%	0.6%	0.0%	0.0%	0.0%	0.0%
22	0.1%	0.8%	0.1%	0.0%	0.0%	0.0%
23	0.0%	2.0%	0.0%	0.0%	0.0%	0.0%
24	0.0%	1.4%	0.0%	0.0%	0.0%	0.0%
25	0.0%	0.3%	0.0%	0.1%	0.1%	0.0%
26	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%
27	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%
28	0.0%	0.3%	0.0%	0.1%	0.0%	0.0%
29	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
30	0.0%	1.4%	0.0%	0.1%	0.0%	0.0%

Table D.4: Frequency distribution of number of batches per order for experiment 4

Number of batches	Mixer 1	Mixer 2	Mixer 3	Mixer 4	Mixer 5	Mixer 6
1	29.39%	16.73%	29.39%	16.73%	26.02%	23.62%
2	25.48%	15.02%	25.48%	15.02%	22.57%	26.69%
3	13.12%	10.24%	13.12%	10.24%	13.60%	14.72%
4	10.08%	11.07%	10.08%	11.07%	10.35%	13.65%
5	6.01%	5.20%	6.01%	5.20%	3.80%	8.90%
6	3.15%	9.97%	3.15%	9.97%	5.45%	5.98%
7	2.40%	5.89%	2.40%	5.89%	1.52%	3.37%
8	2.87%	4.00%	2.87%	4.00%	3.66%	1.23%
9	3.04%	5.75%	3.04%	5.75%	2.83%	0.00%
10	1.71%	2.79%	1.71%	2.79%	6.21%	0.61%
11	0.50%	1.35%	0.50%	1.35%	0.28%	0.00%
12	0.79%	1.96%	0.79%	1.96%	1.66%	0.77%
13	0.20%	2.02%	0.20%	2.02%	0.69%	0.00%
14	0.20%	1.64%	0.20%	1.64%	0.41%	0.00%
15	0.26%	0.14%	0.26%	0.14%	0.00%	0.00%
16	0.14%	0.84%	0.14%	0.84%	0.21%	0.00%
17	0.17%	0.42%	0.17%	0.42%	0.14%	0.31%
18	0.09%	1.12%	0.09%	1.12%	0.48%	0.00%
19	0.11%	0.56%	0.11%	0.56%	0.00%	0.15%
20	0.11%	0.70%	0.11%	0.70%	0.07%	0.00%
21	0.03%	0.19%	0.03%	0.19%	0.00%	0.00%
22	0.11%	0.28%	0.11%	0.28%	0.00%	0.00%
23	0.00%	0.66%	0.00%	0.66%	0.00%	0.00%
24	0.00%	0.47%	0.00%	0.47%	0.00%	0.00%
25	0.00%	0.14%	0.00%	0.14%	0.07%	0.00%
26	0.00%	0.09%	0.00%	0.09%	0.00%	0.00%
27	0.00%	0.09%	0.00%	0.09%	0.00%	0.00%
28	0.03%	0.14%	0.03%	0.14%	0.00%	0.00%
29	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
30	0.00%	0.52%	0.00%	0.52%	0.00%	0.00%

E
Orders per route

Table E.1: Distribution of orders per route for experiment 1

Route	Mixline	Pelletline	Packageline	% MT	% Orders
1	Mixer1		SL1	2.1%	2.3%
2a	Mixer1		SL4	2.9%	3.1%
2b	Mixer1		SL4B	6.7%	7.2%
3	Mixer2	Press1	SL3	2.0%	0.8%
4a	Mixer2	Press1	SL4	0.0%	0.0%
4b	Mixer2	Press1	SL4B	0.1%	0.0%
5	Mixer2	Press1	SL5	0.5%	0.2%
6	Mixer2		SL3	9.2%	3.9%
7a	Mixer2		SL4	0.0%	0.0%
7b	Mixer2		SL4B	0.0%	0.0%
8	Mixer3		SL1	9.1%	11.1%
9	Mixer3		SL3	7.2%	8.8%
10a	Mixer3		SL4	4.1%	5.0%
10b	Mixer3		SL4B	7.4%	8.9%
11	Mixer4	Press1	SL3	7.1%	6.2%
12a	Mixer4	Press1	SL4	0.0%	0.0%
12b	Mixer4	Press1	SL4B	0.5%	0.5%
13	Mixer4	Press1	SL5	4.2%	3.7%
14	Mixer4	Press2	SL2	3.3%	2.8%
15a	Mixer4	Press2	SL4	0.0%	0.0%
15b	Mixer4	Press2	SL4B	0.5%	0.5%
16	Mixer4	Press2	SL5	2.2%	1.9%
17	Mixer4		SL2	4.5%	3.9%
18	Mixer4		SL3	1.0%	0.9%
19a	Mixer4		SL4	0.0%	0.0%
19b	Mixer4		SL4B	0.0%	0.0%
20	Mixer5	Press2	SL2	3.7%	3.8%
21a	Mixer5	Press2	SL4	0.0%	0.0%
21b	Mixer5	Press2	SL4B	1.1%	1.2%
22	Mixer5	Press2	SL5	3.5%	3.5%
23	Mixer5		SL2	2.0%	2.0%
24	Mixer5		SL3	4.1%	4.1%
25a	Mixer5		SL4	2.1%	2.1%
25b	Mixer5		SL4B	3.0%	3.1%
26	Mixer6		SL1	4.8%	7.0%
27	Mixer6		SL6	1.0%	1.4%

Table E.2: Distribution of orders per route for experiment 2

Route	Mixline	Pelletline	Packageline	% MT	% Orders
1	Mixer1		SL1	2.1%	2.3%
2a	Mixer1		SL4	2.9%	3.2%
2b	Mixer1		SL4B	6.7%	7.4%
3	Mixer2	Press1	SL3	4.5%	2.9%
4a	Mixer2	Press1	SL4	0.0%	0.0%
4b	Mixer2	Press1	SL4B	0.1%	0.1%
5	Mixer2	Press1	SL5	3.5%	2.3%
6	Mixer2		SL3	9.5%	6.2%
7a	Mixer2		SL4	0.0%	0.0%
7b	Mixer2		SL4B	0.0%	0.0%
8	Mixer3		SL1	9.1%	11.4%
9	Mixer3		SL3	7.2%	9.0%
10a	Mixer3		SL4	4.1%	5.1%
10b	Mixer3		SL4B	7.4%	9.2%
11	Mixer4	Press1	SL3	4.6%	3.1%
12a	Mixer4	Press1	SL4	0.0%	0.0%
12b	Mixer4	Press1	SL4B	0.5%	0.4%
13	Mixer4	Press1	SL5	1.3%	0.9%
14	Mixer4	Press2	SL2	3.3%	2.2%
15a	Mixer4	Press2	SL4	0.0%	0.0%
15b	Mixer4	Press2	SL4B	0.5%	0.4%
16	Mixer4	Press2	SL5	2.2%	1.5%
17	Mixer4		SL2	4.5%	3.1%
18	Mixer4		SL3	0.7%	0.5%
19a	Mixer4		SL4	0.0%	0.0%
19b	Mixer4		SL4B	0.0%	0.0%
20	Mixer5	Press2	SL2	3.7%	3.9%
21a	Mixer5	Press2	SL4	0.0%	0.0%
21b	Mixer5	Press2	SL4B	1.1%	1.2%
22	Mixer5	Press2	SL5	3.5%	3.6%
23	Mixer5		SL2	2.0%	2.1%
24	Mixer5		SL3	4.1%	4.2%
25a	Mixer5		SL4	2.1%	2.1%
25b	Mixer5		SL4B	3.0%	3.2%
26	Mixer6		SL1	4.8%	7.2%
27	Mixer6		SL6	1.0%	1.5%

Table E.3: Distribution of orders per route for experiment 3

Route	Mixline	Pelletline	Packageline	% MT	% Orders
1	Mixer1		SL1	5.6%	6.5%
2	Mixer1		SL3	3.6%	4.2%
3a	Mixer1		SL4	3.5%	4.1%
3b	Mixer1		SL4B	7.0%	8.2%
4	Mixer2	Press1	SL3	2.0%	0.8%
5a	Mixer2	Press1	SL4	0.0%	0.0%
5b	Mixer2	Press1	SL4B	0.1%	0.0%
6	Mixer2	Press1	SL5	0.5%	0.2%
7	Mixer2		SL3	9.2%	3.9%
8a	Mixer2		SL4	0.0%	0.0%
8b	Mixer2		SL4B	0.0%	0.0%
9	Mixer3		SL1	5.6%	6.6%
10	Mixer3		SL3	3.6%	4.2%
11a	Mixer3		SL4	3.5%	4.1%
11b	Mixer3		SL4B	7.0%	8.2%
12	Mixer4	Press1	SL3	7.1%	6.2%
13a	Mixer4	Press1	SL4	0.0%	0.0%
13b	Mixer4	Press1	SL4B	0.5%	0.5%
14	Mixer4	Press1	SL5	4.2%	3.7%
15	Mixer4	Press2	SL2	3.3%	2.8%
16a	Mixer4	Press2	SL4	0.0%	0.0%
16b	Mixer4	Press2	SL4B	0.5%	0.5%
17	Mixer4	Press2	SL5	2.2%	1.9%
18	Mixer4		SL2	4.5%	4.0%
19	Mixer4		SL3	1.0%	0.9%
20a	Mixer4		SL4	0.0%	0.0%
20b	Mixer4		SL4B	0.0%	0.0%
21	Mixer5	Press2	SL2	3.7%	3.8%
22a	Mixer5	Press2	SL4	0.0%	0.0%
22b	Mixer5	Press2	SL4B	1.1%	1.2%
23	Mixer5	Press2	SL5	3.5%	3.5%
24	Mixer5		SL2	2.0%	2.0%
25	Mixer5		SL3	4.1%	4.1%
26a	Mixer5		SL4	2.1%	2.1%
26b	Mixer5		SL4B	3.0%	3.1%
27	Mixer6		SL1	4.8%	7.0%
28	Mixer6		SL6	1.0%	1.4%

Table E.4: Distribution of orders per route for experiment 4

Route	Mixline	Pelletline	Packageline	% MT	% Orders
1	Mixer1		SL1	5.6%	6.5%
2	Mixer1		SL3	3.6%	4.2%
3a	Mixer1		SL4	3.5%	4.1%
3b	Mixer1		SL4B	7.0%	8.2%
4	Mixer2	Press1	SL3	4.5%	2.9%
5a	Mixer2	Press1	SL4	0.0%	0.0%
5b	Mixer2	Press1	SL4B	0.1%	0.1%
6	Mixer2	Press1	SL5	3.5%	2.3%
7	Mixer2		SL3	9.5%	6.2%
8a	Mixer2		SL4	0.0%	0.0%
8b	Mixer2		SL4B	0.0%	0.0%
9	Mixer3		SL1	5.6%	6.6%
10	Mixer3		SL3	3.6%	4.2%
11a	Mixer3		SL4	3.5%	4.1%
11b	Mixer3		SL4B	7.0%	8.2%
12	Mixer4	Press1	SL3	4.6%	3.1%
13a	Mixer4	Press1	SL4	0.0%	0.0%
13b	Mixer4	Press1	SL4B	0.5%	0.4%
14	Mixer4	Press1	SL5	1.2%	0.8%
15	Mixer4	Press2	SL2	3.3%	2.2%
16a	Mixer4	Press2	SL4	0.0%	0.0%
16b	Mixer4	Press2	SL4B	0.5%	0.4%
17	Mixer4	Press2	SL5	2.2%	1.5%
18	Mixer4		SL2	4.5%	3.1%
19	Mixer4		SL3	0.7%	0.5%
20a	Mixer4		SL4	0.0%	0.0%
20b	Mixer4		SL4B	0.0%	0.0%
21	Mixer5	Press2	SL2	3.7%	3.9%
22a	Mixer5	Press2	SL4	0.0%	0.0%
22b	Mixer5	Press2	SL4B	1.1%	1.2%
23	Mixer5	Press2	SL5	3.5%	3.6%
24	Mixer5		SL2	2.0%	2.1%
25	Mixer5		SL3	4.1%	4.2%
26a	Mixer5		SL4	2.1%	2.2%
26b	Mixer5		SL4B	3.0%	3.2%
27	Mixer6		SL1	4.8%	7.2%
28	Mixer6		SL6	1.0%	1.5%

F

Route visualization

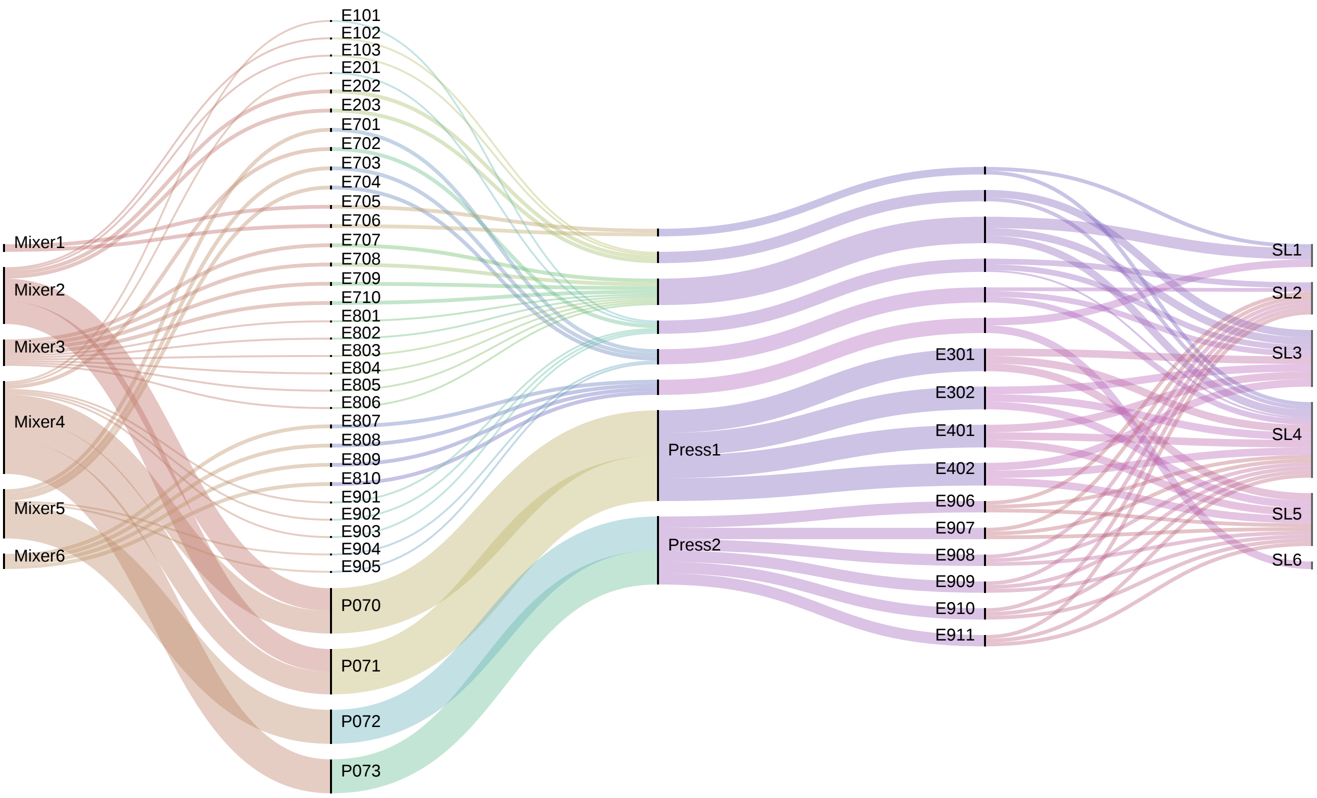


Figure F.1: Physcial routes through the factory

G

Results

Table G.1: Results of experiment 1 and 2

Experiment	1a	1b	1a,c	1b,c	2a	2b	2a,c	2b,c
Silo time (min)	400	515	339	351	432	607	360	380
Operator utilization	85%	91%	72%	73%	87%	91%	75%	77%
OEE	66%	70%	72%	74%	67%	71%	76%	78%
Parallel	2.39	2.55	2.69	2.77	2.44	2.61	2.86	3.02
SD Daily output	59.0	46.5	54.8	52.4	57.5	48.4	58.5	53.4
MT/24h	344	365	376	382	347	368	392	405
Mixer 1 (MT/24h)	41	44	45	47	41	44	47	49
Mixer 2 (MT/24h)	44	46	47	47	61	65	69	70
Mixer 3 (MT/24h)	95	101	103	105	96	102	108	112
Mixer 4 (MT/24h)	79	84	87	88	61	65	69	71
Mixer 5 (MT/24h)	70	74	76	77	69	73	78	80
Mixer 6 (MT/24h)	21	23	24	24	22	23	24	25
Press 1 (MT/24h)	49	52	54	54	51	54	58	58
Press 2 (MT/24h)	52	55	56	57	51	54	57	58
SL1 (MT/24h)	56	59	60	61	55	59	63	65
SL2 (MT/24h)	48	50	51	51	48	50	53	56
SL3 (MT/24h)	102	110	113	115	105	111	119	123
SL4 (MT/24h)	31	33	34	34	32	33	35	36
SL4B (MT/24h)	70	74	76	77	69	73	78	80
SL5 (MT/24h)	36	38	39	40	39	40	43	42
SL6 (MT/24h)	8	9	9	9	8	9	9	9
Press 1 utilization	54%	57%	59%	60%	54%	57%	60%	62%
Press 2 utilization	59%	62%	65%	65%	56%	60%	64%	66%
SL1 utilization	49%	52%	54%	54%	49%	53%	56%	57%
SL2 utilization	35%	37%	39%	38%	35%	36%	38%	41%
SL3 utilization	61%	65%	67%	69%	63%	66%	72%	73%
SL4 utilization	61%	65%	66%	67%	62%	65%	69%	72%
SL4B utilization	47%	49%	51%	52%	46%	49%	52%	54%
SL5 utilization	29%	32%	33%	34%	31%	32%	34%	35%
SL6 utilization	3%	3%	4%	4%	3%	3%	4%	4%

Table G.2: Results of experiment 3 and 4

Experiment	3a	3b	3a,c	3b,c	4a	4b	4a,c	4b,c
Silo time (min)	483	616	362	370	519	729	406	435
Operator utilization	92%	92%	76%	77%	92%	92%	81%	82%
OEE	71%	70%	76%	77%	71%	70%	80%	81%
Parallel	2.62	2.61	3.00	3.02	2.63	2.60	3.23	3.30
SD Daily output	46.2	46.4	50.6	47.3	51.4	49.7	56.1	52.6
MT/24h	366	365	395	397	367	361	415	421
Mixer 1 (MT/24h)	72	72	78	79	73	72	83	84
Mixer 2 (MT/24h)	49	48	50	50	64	63	71	71
Mixer 3 (MT/24h)	71	71	77	77	72	71	82	83
Mixer 4 (MT/24h)	86	85	93	93	64	63	74	74
Mixer 5 (MT/24h)	73	72	78	79	73	72	82	83
Mixer 6 (MT/24h)	22	23	24	24	23	23	25	26
Press 1 (MT/24h)	53	53	57	58	53	54	59	60
Press 2 (MT/24h)	55	55	59	59	54	54	61	61
SL1 (MT/24h)	73	73	78	79	74	73	83	85
SL2 (MT/24h)	49	50	53	54	50	50	57	57
SL3 (MT/24h)	100	99	107	107	99	98	110	112
SL4 (MT/24h)	32	32	35	35	33	33	38	39
SL4B (MT/24h)	71	71	78	78	70	69	80	81
SL5 (MT/24h)	39	38	41	41	41	39	44	44
SL6 (MT/24h)	9	9	9	9	8	9	9	9
Press 1 utilization	59%	59%	64%	64%	55%	55%	64%	64%
Press 2 utilization	63%	62%	66%	67%	60%	60%	68%	69%
SL1 utilization	64%	64%	69%	69%	65%	64%	73%	75%
SL2 utilization	36%	37%	40%	40%	37%	36%	41%	42%
SL3 utilization	59%	58%	63%	64%	59%	57%	66%	66%
SL4 utilization	64%	64%	69%	70%	65%	65%	75%	76%
SL4B utilization	48%	48%	52%	53%	48%	47%	54%	55%
SL5 utilization	32%	33%	35%	35%	31%	32%	36%	37%
SL6 utilization	3%	3%	4%	4%	3%	3%	4%	4%

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