The design and optimisation of powder handling

A case study at Nestlé

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TUDelft

The design and optimisation of powder handling

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by

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Cover: Man working on silos (Modified) [49]

TU Delft

Preface

This thesis was written as the final research of the master Mechanical Engineering for the track Multi-Machine Engineering at Delft University of Technology. The report was written at Nestlé Nunspeet, a infant formula factory in the Netherlands. The research aims to find the best option for future powder handling at the factory through generating various concepts and optimisng them through Gurobi.

The past months have been a great journey, allowing me to learn a lot both professionally and personally. As with any project, there are ups and downs. It was difficult to find a suitable subject at my start at Nestlé due to the fast changing environment of the factory. However, all the colleagues I had there have been incredibly helpful and I want to thank them for their input, feedback and help I have gotten. I specifically want to thank Jose Neves for his continuous guidance, his flexibility and helpful discussions.

I also want to thank Mark Duinkerken for his feedback, discussions and comments that made me critically re-evaluate my work. I also would like to thank Prof. Dr. ir. Dingena Schott for her feedback during the progress meetings. Together with Mark she showed me that a good research also needs to be presented correctly and needs a clear story.

Finally I want to thank my girlfriend, friends, family and roommates for their support and interest during my master thesis.

A. P. Schipper
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Summary

This research explores several concepts for better powder handling in a future situation at Nestlé Nunspeet. The factory produces infant formula, to be used around the world. Currently Nestlé handles its goods via forklifts in its warehouse, but in the future this will be done via automatic guided vehicles (AGVs). Besides the implmentation of AGVs, Nestlé will ramp up its production in the coming years.

The introduction of AGVs and the growing amount of goods that it will handle, due to the growth of production, will cause problems in the warehouse. First of all, more storage area will be needed as the stock will grow due to the increased production. As the factory is reaching its limits of growth within the allocated land, it cannot increase its warehouse size and needs to look into more efficient ways of storing its goods. Second, the AGVs will have trouble handling certain goods: powders in bigbags placed on pallets. Bigbags might sag a little or lean over to one side and this could cause faulty handling by AGVs.

Therefore the goal of this research is to come up with alternative ways of handling the bigbags, while also reducing the storage space for them. The main research question is the following: *What is the optimal solution for powder handling for Nestlé in 2026?* This will be answered in the following steps. First the situation in the warehouse has to be analysed thoroughly. After concepts will be generated that could solve the problems. As the implementation of these concepts would be in the future, these have to be modeled to compare them. Therefore a literature study has been done to find suitable modeling options for each of the concepts. Models have been built for each concept, based on the findings in the literature. These models have been verified and validated, before being put into practise for the case at Nestlé.

Four concepts have been identified as satisfactory design alternatives and these are:

1. Storing the bigbags in a rented warehouse, transporting them to the factory when needed and using a bigbag reshaper to make the bigbags suitable for the AGVs.
2. Having the powders arrive in bulk, storing them in silos and transporting them pneumatically to production.
3. Having the powders arrive on bigbags, making them suitable for AGV handling with a bigbag reshaper, moving the powders to a tipping station, transporting them pneumatically to silos, storing the powders in silos and transporting them pneumatically to production.
4. Having some of the powders delivered in bulk, storing them in silos and transporting them pneumatically. Storing the other powders in a rented warehouse, transporting them to the factory when needed and using a bigbag reshaper to make the bigbags suitable for AGVs.

When examining the literature relevant for the concepts, the following was found. The rented warehouse model can be seen as a simplified multi item two stage lot sizing problem and has been discussed in literature. The model for the silo storage can be seen as a multi-period variable sized bin packing problem with conflicts and item fragmentation, with some extra constraints. This version of the bin packing problem has not been discussed in literature before and thus shows a scientific gap.

The models have been created based on the system analysis and the literature findings, taking the Nestlé specific constraints into consideration. The KPIs for the models are the investment costs, the operating costs, the amount of pallet storage needed, the amount of area needed and the amount of trucks arriving at the Nestlé facility. When verifying the models, these behaved as intended. During validation the models behaved as they should, except for a few situations. However, this is acceptable as these situations will not happen with the case study at Nestlé.

The results of the case study show that the option of storing pallets in the rented warehouse is the cheapest option and thus the best option for 2026. Implementing silos in any way is not feasible as these take up too much space. When looking at the combination of using silos and the rented warehouse,

the option of storing lactose (one of the powders) in silos and the other materials in the warehouse becomes suitable. This is because it is a solution that is feasible and has very low operating costs. The costs of implementing it would be higher than only using the rented warehouse, but the operating costs would be lower, making it the cheapest option after 8 years.

The limitations of this study are mostly focused on the data availability. Although the data has been validated, having one extra truck arrive on a certain day, might still impact the amount of silos needed. Furthermore the filling strategy might be different than has been modelled. The recommendations of this research are to research the optimal size of the bulk trucks, to look into having even bigger silo sizes and to reduce the inventory. Also a heuristic solution algorithm could be made for the variant of the bin packing problem relevant for Nestlé. Future research would also focus most on data quality and detailed calculations on the needed equipment. Finally the bulk truck sizes could also be optimised per powder, to have the smallest amount of silos.

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Nomenclature

Abbreviations

Abbreviation	Definition
AGV	Automated Guided Vehicle
AHP	Analytic Hierarchy Process
BBP	Bin Packing Problem
BPPC	Bin Packing Problem with Conflicts
BPPC-IF	Bin Packing Problem with Conflicts and Item Fragmentation
BPPIF	Bin Packing Problem with Item Fragmentation
KPI	Key Performance Indicator
3PL	Third Party Logistics Supplier
CATWOE	Customers Actors Transformation Worldview Owners Environment
CI	Consistency Index
CR	Consistency Ratio
CSPM	Combined Silo Pallet Model
DBPP	Dynamic Bin Packing Problem
EOQ	Economic Order Quantity
FDBPP	Fully Dynamic Bin Packing Problem
GSSP	Generalised Segregated Storage Problem
MD	Maltodextrin
MPVSBPPC-IF	Multi Period Variable sized Bin Packing Problem with Conflicts and Item Fragmentation
NP	Nondeterministic Polynomial time
OG	Optimality Gap
OW	Owned Warehouse
PMM	Pallet Movement Model
RCI	Random Consistency Index
RW	Rented Warehouse
SAP	Systems Applications and Products in Data Processing
SITAP	Single Instant Tank Allocation Problem
SM	Silo Model
SPM	Silo Pallet Model
SSP	Segregated Storage Problem
TAP	Tank Allocation Problem
VCSBPP	Variable Cost and Size Bin Packing Problem
VSBPP	Variable sized Bin Packing Problem
VSBPPC-IF	Variable Sized Bin Packing Problem with Conflicts and Item Fragmentation
VSBPP-IF	Variable Sized Bin Packing Problem with Item Fragmentation

1

Introduction and Research Definition

1.1. Background and business context

Companies are constantly changing the way they operate to stay competitive and to accommodate demand. The introduction of new products, innovations and regulations drive these changes and how they are implemented. These changes in operations bring a lot of possibilities, but also problems that have to be solved in order to implement them.

Nestlé is one of such companies trying to constantly innovate and improve their processes. Within the Netherlands, Nestlé produces different types of infant formula. It does so on two locations, of which the factory in Nunspeet is the biggest. This factory is focused on innovating and delivering high quality products.

As this factory is a food processing factory, besides the standard safety rules also extra hygienic regulations are present. Compared to most other food companies, the regulations are even more strict as infants are at higher risk than adults to get dhealth problems from poorly handled products. Nestlé is well known for its high quality infant formula and strives to maintain this position while innovating.

1.2. Problem Description

Nestlé is planning to increase the production in 2026 by doubling the output of one production line while its warehouse is reaching its maximum capacity. Next to this, the warehouse management is planning to implement automated guided vehicles (AGVs) as well.

Currently the process within the facility is the following: trucks deliver pallets with bulk materials, such as milk powder and sugars, to the warehouse. These are unloaded by forklifts and then stored within a racking system within the warehouse. Once the bulk material is needed by production, it is retrieved from the warehouse and brought to a drop off location where it is inserted in the production line.

One of the problems of using AGVs is that these cannot handle big bags with bulk powders due to the instability of these big bags. These big bags with powders make up about 10 percent of all the stored items. As the warehouse capacity will not be sufficient in 2026 and the AGVs will have trouble handling the powders in bigbags, Nestlé is looking for a solution to both handle the powders safely and reduce its necessary storage space.

Possible solutions for these problems could be changing the way the powder is handled at the factory. This can be done by having the powders arrive in bulk, store them in silos and transport them via pipes for example. Or by modifying the pallet on which the bigbag is placed, such that it can be handled by AGVs. This pallet could be stored in an extra warehouse somewhere else. The best option has to be found.

1.3. Preliminary literature study

The problem of determining where to store which item and in which silo has a lot of similarities with problems occurring elsewhere. For example the segregated storage problem for liquid transport ships, where different types of oil cannot be stored in the same compartment of the container while the ship is constantly filling and emptying its compartments, as has been done by Hvattum [32]. Another very similar problem is the warehouse sizing problem, where companies have to determine the size of a new warehouse with seasonal demand with the possibility of a spillover for the least costs, as has been done by Hung [31].

In these studies the problem has been written down mathematically, has then been modeled and solved. Such as where Basnet [6] minimises the amount of warehouses needed for items which might or might not be compatible, when the warehouse sizes are already predetermined. The corresponding mathematical model is very similar to the knapsack problem and a variation on it: the bin-packing problem (BBP). Still Basnet only optimises for fixed warehouse sizes and does not consider the option of changing demand.

A model could be developed that determines the amount of silos and their corresponding sizes; it would determine how much of each material will be stored in every silo; and what silo will be used for production. Determining which batch will be ordered from which supplier could be done, but this is out of scope due to the fact that procurement is done globally and this process can be influenced little. This model then would check the feasibility of implementing silos and how many are needed in the specified operation environment. This can then be compared to renting extra warehouse space and buying special pallets, to see if the solution would be a good fit.

When comparing this to the literature, the model that is most similar to the silo storage is the one presented by Ekici [20] where a model is presented for bins of variable sizes where some items cannot be mixed and where items can be divided over multiple bins. This problem is called the variable sized bin packing problem with conflicts and item fragmentation (VSBPPC-IF), but it still does not describe the multi-period supply and demand faced at the food manufacturing company as well as the unknown sizes of the silos beforehand. This thus presents the research gap, to the best of the students knowledge.

1.4. Research objective and research questions

The goal of the research is to find and evaluate options of handling the powders in 2026 at Nestlé. This will be done by developing concepts and by modelling these to see how these would perform in 2026. The models would determine what infrastructure would be needed, what the storage strategy would be and what the costs would be.

The main research question is thus:

What is the optimal solution for powder handling for Nestlé in 2026?

With the corresponding sub-questions:

1. How are the powders currently handled within the food processing factory?
2. What changes will happen within the factory and what problems will arise regarding powder handling?
3. What are the design alternatives?
4. How to evaluate the the performance of the conceptual designs?
5. How to model and solve the conceptual designs?
6. Are the developed models an accurate representation of the design alternatives?
7. Case study: can the design alternatives be implemented in a food processing environment?

1.5. Research Methodology

This research will be done in such a way that it starts with clearly defining the problem and collecting data on the current situation at the food processing factory. Therefore interviews will be held with experts and with personnel in order to clearly understand the the limitations of the factory and the regulations it has to follow. Besides this, data will be extracted regarding the amount of incoming and outgoing material, as well as the weekly storage throughout the year and the related batch numbers. This will answer the first sub-question and help prepare for the case study.

After that different concepts will be generated and compared with each other. For the best concepts models will be created. Next a literature study will be done to compare the concepts with already available literature to find relations with other industries and research that has already been done by others. When this has been done, a model or simulation can be developed to solve the problem found at Nestlé. Before the models will be used, these have to be tested and verified. Once this has been done, the models will be implemented on the data delivered by the food processing company.

1.6. Outline of thesis

After the subject is introduced and the research objective has been presented in chapter 1. The problem will be defined further in chapter 2, explaining the processes and constraints that follow from the factory.

In chapter 3 concepts will be generated and a selection will me made of the most promising concepts to be modeled. Chapter 4 will look into the concepts in more detail to determine any considerations and constraints for the models. In chapter 5 a literature study will be done on similar problems that have already been modeled and solved by others. Chapter 6 will define a new model, filling in the gap that has been presented by literature. Chapter 7 will focus on the developed models verification and performance. In chapter 8 the model will be applied to the case presented at the food processing factory. Finally conclusions and recommendations will be presented in chapters 9 and 10.

1.7. Scientific contribution

As powder handling in factories is nothing new, this is not where the research gap is. To the best of the students knowledge and after doing a literature study, no research has been done before on the modelling of powder storage in silos for a specific case. This case is the following: the demand and supply of the powders is known, different powders cannot be stored at the same time in the same silo, the silos can have different sizes and all have a different cost and the powders can be stored in multiple silos.

This case can be modelled as the multi-period variable sized bin packing problem with conflicts and item fragmentation and has not been studied before. Therefore this variant of the bin packing problem will be the scientific contribution.

2
System Analysis

This chapter will focus on the system analysis of the situation within the food processing factory. It will therefore try to answer the following sub-questions:

- *How are the powders currently handled within the food processing factory?*
- *What changes will happen within the factory and what problems will arise regarding powder handling?*

As the food processing factory is in the process to change its material handling in the warehouse, two scenarios will be described: the current situation and the to-be situation.

The current situation will give a clear overview of the current flows within the factory as well as the corresponding data. The to-be situation is when the new production line has been built and the AGVs have been implemented. In this situation the problem of not enough space and poor handling by AGVs will become a reality. Analysing both scenarios will give a good idea of the flows within the factory and the problems that will have to be solved. This will give a better understanding of the operations within the food processing factory as well as help formulate the problem.

2.1. General factory processes

The food processing factory of Nestlé in Nunspeet produces infant formula in powder form. The factory produces multiple types of infant formula on different production lines. In general the factory works in the following way: raw materials enter the factory via the warehouse or in bulk. The bulk materials are liquid and are loaded into tanks immediately. The other raw materials include powders that are either packaged in smaller 25 kg bags or bigbags, vitamins and oildrums. Besides the raw materials, packaging materials also enter the factory via the warehouse. These include cans, boxes and other items.

The raw materials are brought to special drop off points, depending on the production line and the material. Meanwhile, the packaging materials are brought to the packaging lines. All of this is currently done via forklifts. The raw materials are combined and undergo certain processes within the factory, where the finished product that comes out is infant formula in powder form. This powder is then packaged in one of the packaging lines, before it enters the warehouse again. Finally the finished products are transported to a third party warehouse, before being shipped worldwide.

Besides this short description, a blackbox model of the system will be made and a CATWOE analysis will be done. The blackbox model helps with understanding the information flows of the system (the factory in this case) and defining the relevant requirements and KPI's of the system. The CATWOE analysis gives relevant insights of the stakeholders who will either use or have an impact on the system.

2.1.1. Blackbox model

According to Zhang [75], a blackbox model is simply the functional relationships between the system inputs and the outputs. In this case, the blackbox model will give the relationships between the inputs and outputs, while also taking the requirements and performance of the factory into account as can be seen in figure 2.1.

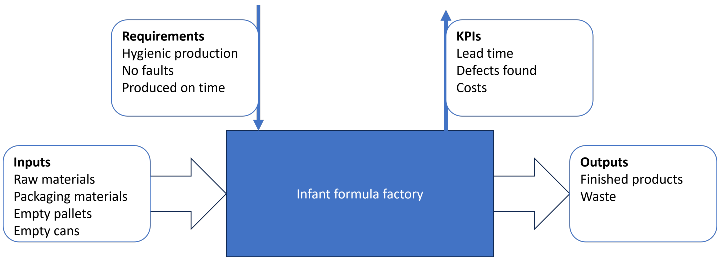


Figure 2.1: Blackbox model of the factory

In the blackbox model a couple of things can be seen. These include the inputs, the outputs, the requirements and the KPI's. For the factory raw materials, packaging materials, empty pallets and empty cans enter it. These are then turned into finished goods and waste, that leave the factory. The requirements for the factory are that the products are made hygienically, there are no faults in the products and that these are produced on time. The KPIs of the factory include the lead time, the amount of defects found and the costs.

2.1.2. CATWOE analysis

The CATWOE analysis is a technique to get the perspective on the relevant stakeholders for a project or for a change. CATWOE stands for the first letters of the following words: customers, actors, transformation, worldview, owners and environment.

Customers: The customers are the customers of Nestlé: parents who have infant children
Actors: The actors are the engineers and operators of Nestlé. However the third party logistics supplier and the material suppliers will also play a role in the factory.
Transformation: The transformation is the production of infant formula.
Worldview: The safe and healthy infant formula of Nestlé contribute to the development of healthy infants.
Owners: Nestlé is the owner of this transformation.
Environment: The environment includes suppliers, the local municipality, neighbours of Nestlé Nunspeet and regulatory bodies such as national governments and european lawmakers.

2.2. Current situation

In the current situation there are no AGVs present in the warehouse of the company. All products and goods are moved on pallets by forklifts. In general raw materials arrive at the warehouse, are stored there and driven to production when needed. Currently there are about an average of 365 pallets of bigbags stored within the warehouse, which is about 10% of the total available spots within the warehouse.

All goods shipped to Nestlé arrive within the warehouse between 7:30 and 16:00 during weekdays. During these times trucks are allowed to drive within the Nestlé facility and can be unloaded. Furthermore warehouse personnel only works during these times. Nestlé produces goods 24/7, but these can also only leave the facility between 07:30 and 16:00. As Nestlé is always producing, goods always move from the warehouse to production. This is done mostly by the warehouse personnel, but sometimes also by production personnel.

Materials and production lines

The materials arriving in bigbags are eight different kinds of powders. The powders that are being handled at the food processing factory are milk powders, sugars and starches. These are predominantly maltodextrins with different properties. Some maltodextrins are almost exactly the same but have been processed in different hygienic environments and are therefore slightly different. These are the following:

1. Skimmed milk powder
2. Lactose
3. Glucose
4. Maltodextrin 12 - 1
5. Maltodextrin 12 - 2
6. Maltodextrin 11 - 1
7. Maltodextrin 11 - 2
8. Maltodextrin 17

There are two production lines within the factory where the powders are used. One of these is peptide-free, called EHP. The other production line is called Egron. The materials going to the peptide-free production line are: glucose, maltodextrin 12 - 1 & 12 - 2, as well as lactose. The other materials go to the Egron production line, however lactose is used by both production lines.

Before a material is used, the different production lines make a production planning of when to use which material. Since there are 2 production lines, 2 production plans are made. One of these is a yearly planning and for this line, production is known up till 12 months in the future. The other production line has a planning horizon of 3 weeks. The ordering of all materials is done by procurement, this department works on a global level. Procurement makes deals with multiple suppliers and makes the decision on which supplier will deliver at what time. This is usually based on prices and availability.

Storage and layout

The bigbags and powders are currently stored within the F-section of the warehouse. This part has been highlighted in figure 2.2 in yellow and given the number 3. This accounts to a total of 891 pallet storage locations, of which 453 are stored in the left part and 270 in the right part. Just beneath the green 'road', 168 pallet spots are available for bigbag storage. Depending on the amount of other raw materials stored, the bigbags are stored in 1 of 3 sections. Currently there is an average of 365 pallets of bigbags stored in the warehouse. An example of the stored bags can be seen in figure 2.3.

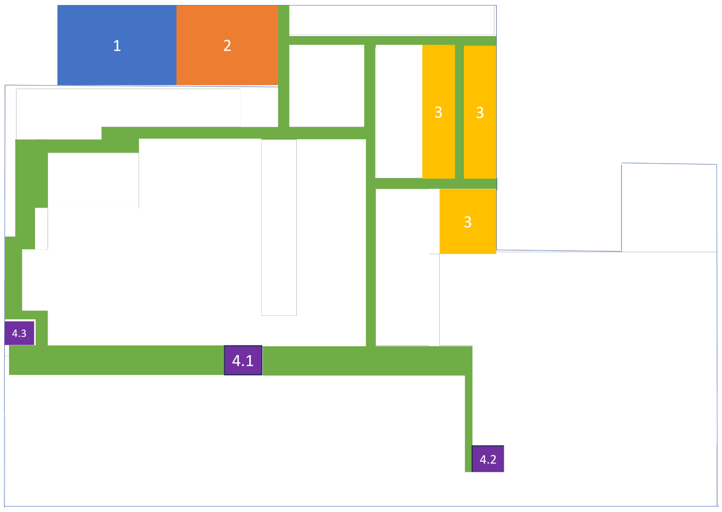


Figure 2.2: Current layout of the factory with pallet storage in area 3

Figure 2.3: Maltodextrin bigbags stored within the F-section of the warehouse

2.2.1. Powder handling process

This section will discuss the powder handling process as it is currently happening. It will give a swimlane diagram, show the routing of the trucks and what happens after drop-off.

Swimlane diagram

The swimlane diagram of the bigbags in the warehouse can be seen below in figure 2.4. Currently all materials are unloaded within the staging area, then scanned and checked before being moved to the warehouse. After this, the bigbag is can be put on a pallet changer and an airrinser or not, before being tipped by an operator. Note that there is some intermediate storage in the tipping room itself, since multiple bigbags can be stored there.

Figure 2.4: Current swimlane diagram of bigbags

Vehicle routing

The routes driven by the forklifts corresponding to the swimlane diagram can be seen in figure 2.5 for the current situation and for normal flow. This would be the following:

1. Truck arrives in truck bay (location 1)
2. Pallets with bigbags are unloaded from truck bay and placed on staging area (location 2)
3. Big bags are scanned so these are within the computer system of the factory
4. The pallets are moved to a rack within the warehouse and stored there (location 3)
5. Once needed, the forklifts pick up the big bags and bring these to the production area (location 4.2 or 4.3)

6. The bigbag is loaded into a tipping station
7. Once the bigbag is tipped, the materials are transported to the necessary production silos using pneumatic conveying

When moving through the facility, the forklifts can drive on the green paths. While the purple locations 4.2 and 4.3, correspond to the drop off locations for the pallets to production, these are not the exact locations of the tipping stations. However, once dropped at production these bags need to be moved just a couple of meters before being tipped, which is done by hand. Note that 4.1 is a dual conveyor, which does not allow for forklifts to drive past. This point might still be on route for big bags going to point 4.3 as there is not a lot of space for multiple forklifts on the left of the map above point 4.3. Therefore, two forklifts might be needed as materials might be dropped of at location 4.1.

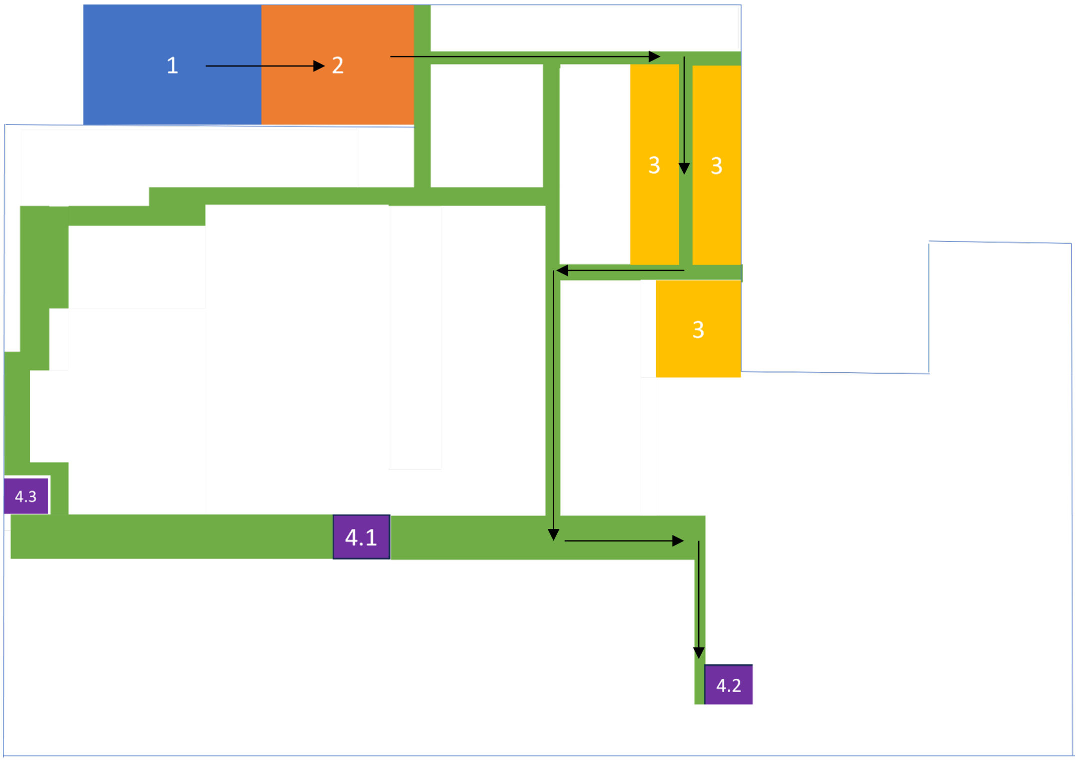


Figure 2.5: Current layout of the warehouse and factory with a possible driving route.

The tipping of big bags itself happens in a stricter hygienic environment than where the forklifts or AGVs are allowed to drive. Currently at location 4.3 in figure 2.5 the big bags go through an air-rinser before they are tipped in a separate room. This is because when a big bag is being tipped, the powder will come into contact with its environment.

Powder movements after drop-off

When using a big bag tipping station, typically the big bag is hoisted by the four straps on top and the moved towards a chute. Here an operator will open the bag on the bottom and the big bag will then discharge itself through the chute into a small silo or a piping system, as can be seen in figure 2.6.

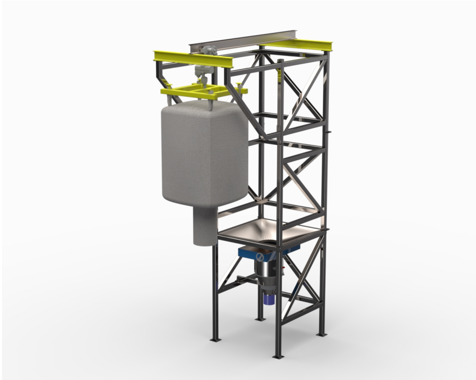


Figure 2.6: Big bag tipping station

Within Nestlé all powders go through the same tipping stations, depending on the production line. This means that after tipping at the Egron production line lactose, skimmed milk powder and maltodextrins go through the same pipe system. Meanwhile at the EHP production line lactose, glucose and maltodextrins go through the same tipping station. After being emptied in the tipping station, the powder will stay in a small silo that can contain the volume of 1 bigbag, see figure 2.7. From here a screw conveyor will transport the powder to a pipe from where it will be pneumatically transported to 25 ton silos. The pneumatic transport consists of dense phase conveying and the silos where the powders will then be temporarily stored are either only used by lactose, maltodextrins or skimmed milk powder. From these silos, the product is then added to the production processes.

Figure 2.7: Small silo beneath bigbag tipping station at Nestlé

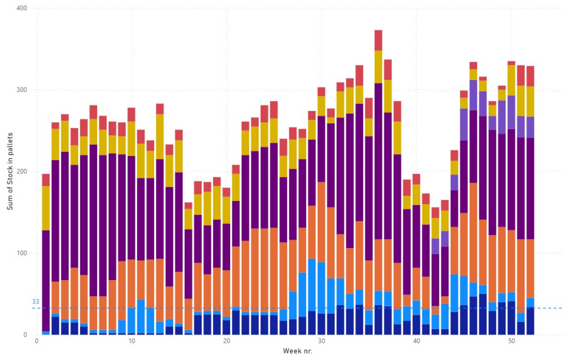
Something important to note in this set up is that the small silo is not cleaned in between the tipping of different powders. Since there is such little material left after each tipping, the mixing of powders is well within the industry standards according to Nestlé experts. Also within the 25 ton silos, different batches of the same material are allowed to be mixed.

2.2.2. Data analysis of current situation

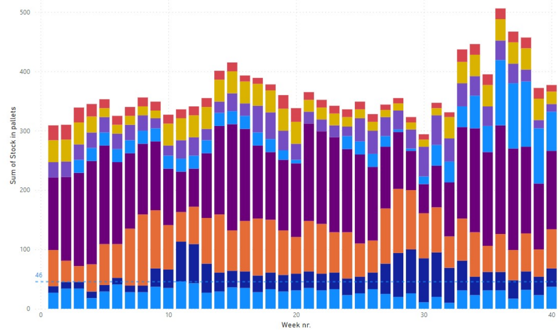
Data for the storage and consumption has been provided for the materials over 2022 and the first weeks of 2023. This data gives an insight of how many pallets are currently used and how many pallets are currently stored.

Regarding incoming powders, about 4 to 7 trucks arrive each week carrying 10 to 24 big bags per truck. Depending on the product that is made, some powders might be used more than others. The trucks either come directly from the supplier itself or these come from a third party logistics supplier warehouse (3PL), where they are stored temporarily before these go to the warehouse of the food processing factory.

In figure 2.8 below, the total stock of all powders can be seen across 2022 and 2023. In 2022 the stock fluctuates around 200 pallets while this grows to 300 pallets in 2023. Also maltodextrin 12 - 1 (in purple) and lactose (in orange) are clearly the materials that are stored most. At the end of 2023 maltodextrin 12 - 2 (in blue) is introduced and also becomes a significant part of the inventory.



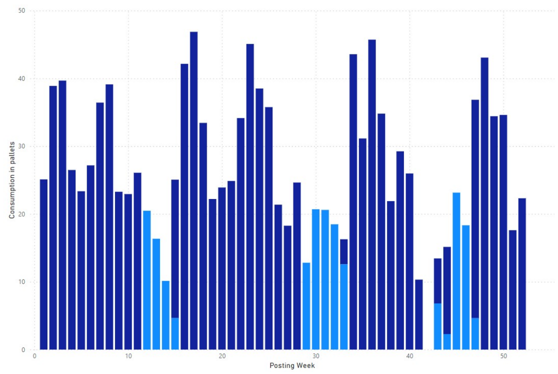
(a) Total bigbag stock in 2022



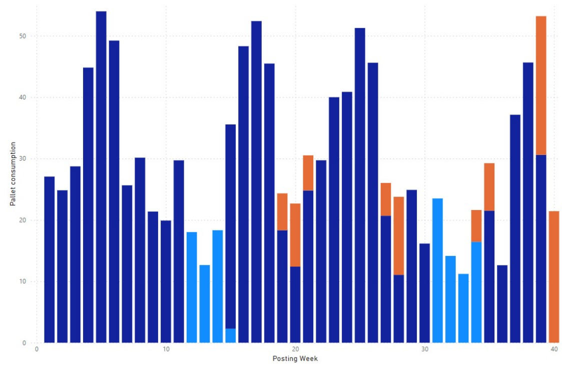
(b) Total bigbag stock in 2023

Figure 2.8: Total amount of pallets stored per week in 2022 and 2023

When looking at the consumption of the EHP (excluding lactose) in figure 2.9, it can be seen that glucose is used almost only when maltodextrin 12-1 is not used. Also its consumption is much lower than the maltodextrin 12-1 consumption. The EHP production line uses maltodextrin 12 - 1 and maltodextrin 12 - 2 for regular production and only uses glucose 3 times a year. Glucose is then used for about a month, if it is used. On average 15 pallets of glucose are used per week, while the average consumption of maltodextrin 12 - 1 is about 30 pallets per week. The consumption of maltodextrin 12 - 2 is about 10 pallets per week.



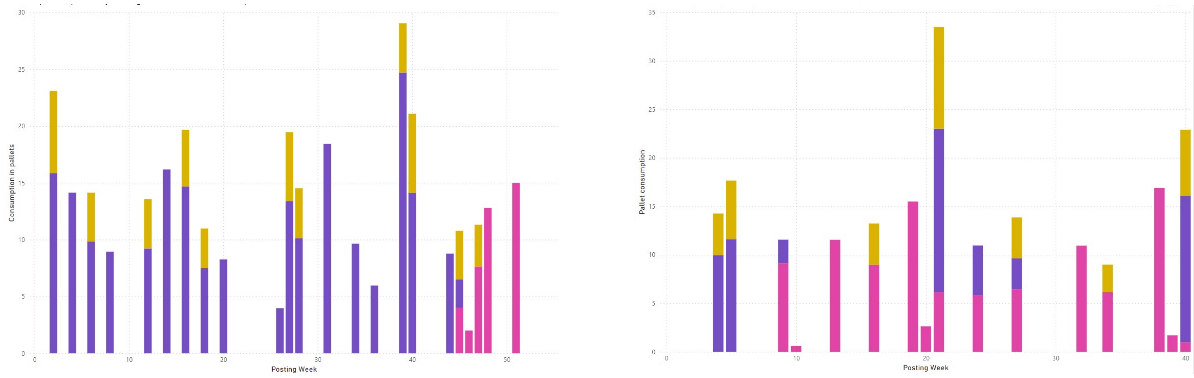
(a) Usage of powders at EHP in 2022



(b) Usage of powders at EHP in 2023

Figure 2.9: Total amount of pallets used by EHP per week in 2022 and 2023. The powders are maltodextrin 12 - 1 (dark blue), maltodextrin 12 - 2 (orange) and glucose (light blue).

When looking at the consumption of maltodextrin 11 - 1 and 11 - 2, as well as maltodextrin 17 by the Egron in fig 2.10, it can be seen that these are used sporadically. This is becomes even more evenly spread in 2023, compared to 2022. Furthermore the Egron, uses maltodextrin 11 - 1 about once per month, maltodextrin 11 - 2 about 3 times per year and maltodextrin 17 about 6 times per year. When maltodextrin 11 - 1 is used, this is about 10 pallets per week. About 8 pallets per week are used for maltodextrin 11 - 2 and 5 of the maltodedxtrin 17 when these are used by production.

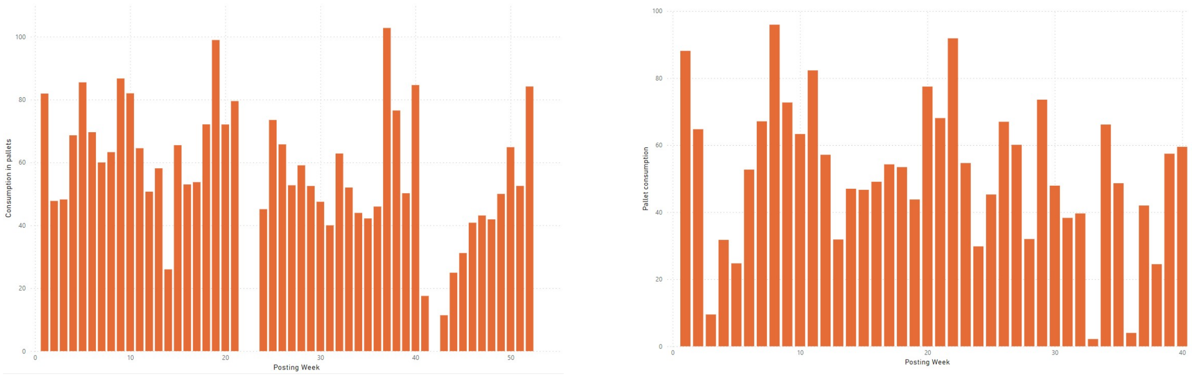


(a) Usage of powders at Egron in 2022

(b) Usage of powders at Egron in 2023

Figure 2.10: Total amount of pallets used by Egron per week in 2022 and 2023.The powders are maltodextrin 11 - 1 (purple), maltodextrin 11 - 2 (pink) and maltodextrin 17 (yellow).

Finally for the lactose consumption, it is clear that this powder is one of the most consumed powders together with the maltodextrin 12 powders, as can be seen in figures 2.9 and 2.11. The total lactose consumption is about 50 pallets per week divided over both production lines.

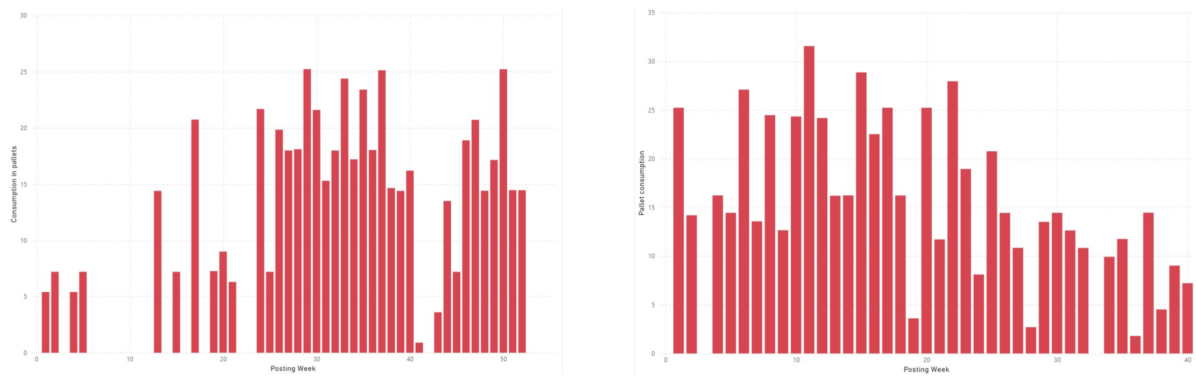


(a) Usage of Lactose in 2022

(b) Usage of Lactose in 2023

Figure 2.11: Total amount of pallets of Lactose used per week in 2022 and 2023

Finally the Egron uses about 15 pallets of skimmed milk powder a week. As can be seen in figure 2.12.



(a) Usage of skimmed milk powder in 2022

(b) Usage of skimmed milk powder in 2023

Figure 2.12: Total amount of pallets of skimmed milk powder used per week in 2022 and 2023

It is clear that of all materials lactose and maltodextrin 12 - 1 and 12 - 2 are used most, while skimmed milk powder is used continuously in smaller amounts. Glucose and maltodextrin 12 have a clear consumption pattern and the consumption of the other materials is very little. The distinction between maltodextrin 12 - 1 and 12 - 2 as well as between 11 - 1 and 11- 2 has not been in place for very long and could fluctuate.

2.3. Future situation

In the future, the following changes will be made to the warehouse:

- AGVs will be implemented in the facility
- A new production line will be added, similar to the EHP
- The Egron line will produce 17 percent more
- The hygienic zoning will change within the warehouse
- Skimmed cow milk powder will be phased out

Impact on materials and production lines

The skimmed cow milk powder will be phased out of production within the next couple of years. This is due to changes within the production of the food processing factory. This will most likely happen within the next four years, but the exact timing is uncertain. It would therefore not make sense to make huge investments for this material, as it will be phased out. Therefore this powder will not be taken into account for the rest of this research.

As a new production line similar to the EHP will be added, the warehouse will have to move more products to the dropoff locations of the EHP. The amount of products moved, will more than double.

Impact on storage and layout

Due to the implementation of the new hygienic zones, the AGVs, pallet changer and the airrinser the layout of the warehouse will change. First of all, forklifts are not allowed to drive in the areas with AGVs anymore. Next, the route to the Egron has been cut-off due to the airrinser. The palletchanger has also been placed. Finally a new alley has been built for the AGVs to travel through. As can be seen in figure 2.13, the dual conveyor has been removed. A new airrinser has been added on location 5 and a new palletchanger has been placed on location 4.1 . A new dropoff point for the new production line is located at 4.3 .

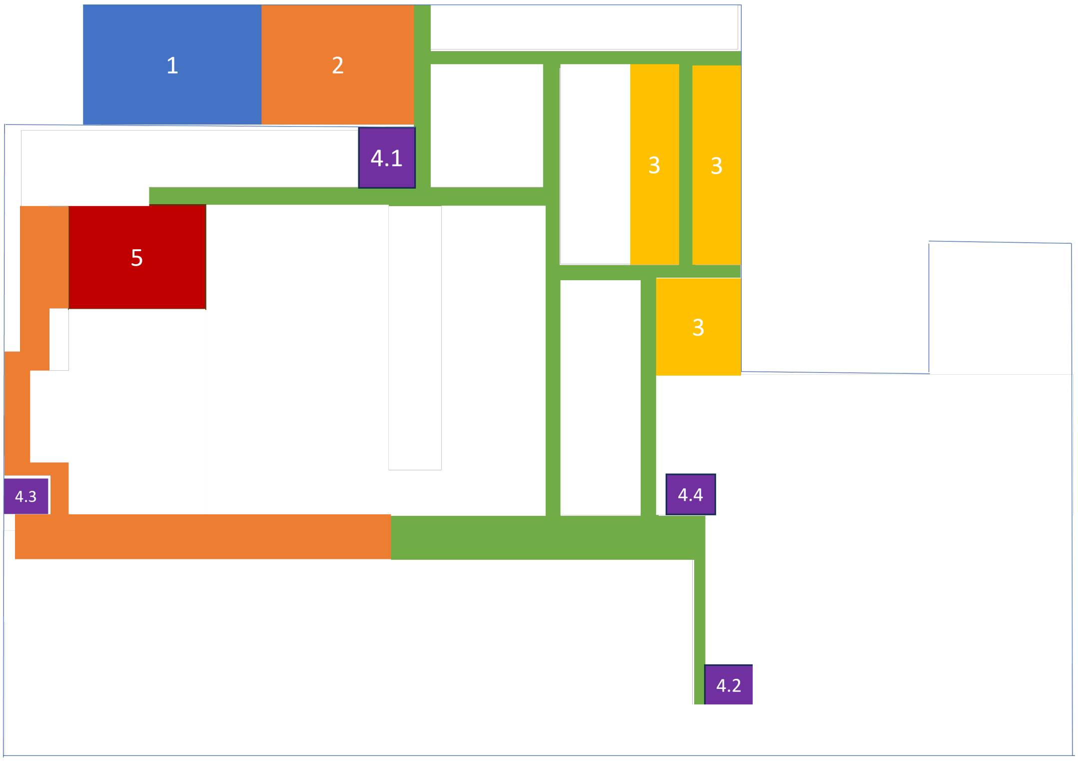


Figure 2.13: Future layout of the warehouse and factory

When looking at the storage space in the future situation, it is difficult to know how much will be used after the implementation of the new production line and the AGVs. Currently forecasts of the sales growth of the products is known and based on the line that produces said products, a rough approximation can be made.

If the assumption is made that the storage policy stays exactly the same, the average amount of maltodextrin 12-1 bigbags would be around 260 bigbags while for lactose this would be about 100. This is almost as much as the average bigbag storage for 2023.

Impact on powder handling process

The process of handling incoming pallets will change due to the AGVs, airrinser, pallet changer and new layout changes. The biggest change is that there are now AGVs in the warehouse that move the powders from the unloading bay to the warehouse and from there to production. Next every pallet with raw materials that arrives in the factory has to be changed, before it can enter production. Also every pallet of raw materials that arrives has to go through an airrinser before going to production. Finally all pallets that go to the Egron, will be handled by forklift after having gone through the airrinser.

2.3.1. Problems in future situation

The coming changes to the warehouse will not be implemented without any added complications. The problems are mainly the handling of the bigbags by the AGVs and the storage space.

Bigbags & AGV incompatibility

A full big bag has a weight varying around 700 to 1000 kg. One of the advantages of using bigbags is that these allow for some flexibility when ordering, due to the ability to order by bigbag. A typical bigbag consists of multiple layers of protective material; handles on the top in order to lift it; and openings on both the top and bottom of the bag for loading and unloading. As can be seen in figures 2.3 and 2.14, a full bigbag might be leaning slighty to one side, unfortunately this can be a problem for AGVs. This is due to the fact that when this bigbag is loaded or unloaded from the racking system, it might tip over. Human forklift drivers can see this happen and react upon it, whereas AGVs cannot. This could cause huge problems, such as damaged AGVs as well as a lot of material spillages. The company that will deliver the AGVs has also mentioned this as something that should be avoided.

Furthermore a bigbag might sag a little when being stored for a longer time and this will result in the bottom of the bigbag hanging over the pallet. These problems have also been listed by the AGV supplier, as it will obstruct the AGV from correctly picking up the pallet with the bigbag. Therefore the powders within the big bags should be handled differently, than is currently done. The bigbag should not sag or be leaning to one side, when the AGVs handle the bigbag.

Figure 2.14: Typical bigbags at Nestlé

Storage space

As only the average amount of maltodextrin 12 - 1 and lactose bigbags would amount to 360 pallets of storage space needed. It is clear that the amount of products in the warehouse would grow tremendously if the same storage strategy is being followed. Especially as this goes not only for the powders, but every material that Nestlé stores in the warehouse.

Unfortunately the warehouse is currently at almost its maximum capacity and the expected storage needs cannot be met in the current warehouse configuration. Due to the fact that the terrain of the factory is almost completely full, no extra warehouse space can be built on the short term. This is a clear problem as the storage capacity will not be enough in the future.

2.4. Conclusion

This chapter has described the current situation and flows within the warehouse conducted by forklifts, as well as the powder handling once the bigbags have been dropped off. Bigbags are received and unloaded from trucks. Next they are scanned and moved towards the warehouse. Once needed, the bigbags will be transported to the bigbag tipping stations. From here the powders will be pneumatically transported through various silos, before being used. The powders that are stored in bigbags are skimmed milk powder, lactose, glucose and several maltodextrins. These are stored within the F-section within the warehouse with and average of 365 pallets. The most stored and used powders are lactose and maltodextrin 12-1.

In the future situation Nestlé will have implemented AGVs, a new production line, a palletchanger and a new air rinser within the warehouse. This will lead to more products being handled and stored, while also leading to some problems. These problems are: the problems that the AGVs have with handling bigbags, due to their instability and the possibility of sagging. Also due to the factory growth, the storage space of the bigbags within the warehouse will come under stress.

Based on these findings, solutions have to be found, that allow for the factory to function normally and safely. The combination of AGVs and bigbags is currently not viable and combined with the stress on the storage a fitting solution has to be found. In the next chapters these will be discussed.

3 Conceptualisation

This chapter will focus on developing possible solutions for the problems mentioned in the previous chapter and compare these solutions to find a set of solutions that can be implemented at the food processing factory. Furthermore, this chapter will answer the following research question:

What are the design alternatives?

3.1. Method

The selection of design alternatives will start of with generating solutions. These can then be put in a morphological overview to select and determine concepts. Relevant criteria will be determined to compare the concepts and weight factors will be added to the criteria. When this has been done, a multi-criteria analysis can be done to select the best concepts.

Generating solutions

First of all, solutions have to be generated for the problems mentioned in the previous chapter. These can be found in the following ways:

- In literature: By taking inspiration from literature that deals with the same kind of problems and seeing what solutions it brings forward.
- Looking at other factories: Other factories within the food processing industry or within Nestlé might have to deal with the same problems. The solutions they have brought forward to this, might also be applicable in this case.
- Looking at other industries: Other industries might also deal with the same problems. The solutions they have brought forward to this might also be applicable in this case.
- Talking to experts: There are many experts within Nestlé and within the industry, who often already have many ideas of how the problem can be solved.

Morphological overview

When the different solutions have been determined, these can be combined to generate concepts. A useful tool for this is the so called 'morphological overview', as can be seen in figure 3.1. In this overview, the found solutions are stated per problem. When these are combined, solution concepts are created.

function	1	2	3	4	5
capture	speech	text	sketch	text & speech	text & speech & sketch
orga-nize	according to Ullman [ULL 91]	according to Aasland [AAS 93]			
store	relational dB	object oriented dB	files	files & relational dB	
play–back	as in [ULL 91]	following [AAS 93]			

Figure 3.1: Example of a morphological overview with combined solutions to form a concept [57]

Select and determine concepts
The next step is to determine which concepts are the best and should be implemented. This can be quite subjective and therefore difficult. There exists a method called the Analytic Hierarchy Process (AHP), which has been developed by Saaty, to make the selection more objective [56] [55]. The general structure of the AHP is the following:

- Determine the concepts.
- Determine relevant criteria by which the alternatives can be viewed.
- Weigh the criteria by attaching numerical values to them based on relative importance.
- Rank the concepts on the selection criteria by attaching numerical values to them.
- Determine a ranking of concepts by processing the numerical values.

Determine relevant criteria
For the determination of the relevant criteria, there is no generic approach available. One of the things to keep in mind when determining the criteria, are the requirements of the process. It is possible that some criteria are conflicting.

Assign weight factors to criteria
AHP makes use of pair-wise comparisons of the criteria. Based on importance, the criteria are given a weight factor. These factors are on a scale from 1 to 9 and an explanation of this scale can be found below in figure 3.2. If criterion A is for example more important than criterion B, the relative weight would be $W_A/W_B = 9$.

Intensity of importance	Definition	Explanation
1[a]	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance is demonstrated in practice.
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed

Figure 3.2: Explanation of the comparison scale, from Saaty [56]

When all criteria have been compared to each other, their relative weights can be put in a comparison matrix M. The weight factors can be calculated by calculating the eigenvalues of the comparison matrix M. The normalised eigenvector related to the largest eigenvalue λ_{max}, contains the criterion weight factors. In case of the AHP, the goal is not to have a unit vector of length 1, but to create a vector of which the sum of elements is 1 [56][55]. In this case, the vector is divided by the sum of its elements.

When creating a comparison matrix M, often there are some inconsistencies within the comparisons. It might not always be that if $W_A/W_B = 4$ and $W_B/WC = 2$, that $W_A/W_C = 8$. Within the comparison matrix M, the degree of inconsistency is indicated by the consistency ratio (CR). For example, a CR of zero would mean a perfectly consistent comparison matrix. The CR is calculated by using the consistency index (CI) and the random consistency index (RCI). The CI can be calculated in the following way: $CI = (\lambda_{max} - n)/(n - 1)$. Where λ_{max} is the largest eigenvalue and n is the size of the comparison matrix M (with size $n * n$). Meanwhile the RCI has been determined from a randomised set of matrices and shows the average expected inconsistency index for different sized matrices, as can be seen in table 3.1. Finally the CR is calculated by dividing the CI by the RCI. If CR is less than 0.10, the inconsistencies are less than 10 percent and the resulting weight factors can be used. If not, the comparison matrix should be revised.

Table 3.1: RCI for comparison matrices of size n x n [55]

n	1	2	3	4	5	6	7	8	9
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Multi-criteria analysis
The last step of determining the most suitable concept is the multi-criteria analysis. In this analysis a ranking is made of all the concepts based on the selection criteria. The concepts get a score per criteria, often on a scale from 1 to 10. These scores are then multiplied with the weights of each criteria. The sum of all scores multiplied with the weights per concept are then compared and ranked. The highest score will probably be the best concept, while the lowest score will probably be the worst concept.

3.2. Initial concept selection

When looking at the problems faced in the previous chapter. These can be summarised as lack of storage space and incompatibility with the AGV. This incompatibility can either be solved by changing the load carrier, such that it is compatible with the AGV, or by changing the AGV/transportation means such that it is compatible with the pallet and bigbag.

When starting with the process of creation solutions, the following have been found:

- Silo storage
- Pneumatic transportation
- Have a case under the bigbag [64]
- Using small silos instead of bigbags
- Have a fence around the pallet
- Have a special bigbag pallet [8]
- Place bigbag on a bigger pallet: done later within the factory
- Build extra warehouse space
- Rent extra warehouse space: already done for some materials
- Reduce storage amount
- Transport bigbags via rails or via a moving crane
- Transport bigbags via forklifts
- Build a new bigbag handling point
- Have a special handling attachment on the AGVs

- Deliver powders in bulk
- Have a special machine to correctly shape bigbag
- Have bigbags delivered elsewhere in the factory

Some of the solutions mentioned above are very similar, such as the bigger pallet, fence around the pallet or having a case under the bigbag. All these solutions change the load carrier where the bigbag is placed on in order to make it more suitable. The crane, forklift and pneumatic transportation all focus on transporting the powder differently within the warehouse without AGVs.

The corresponding morphological overview can be found in figure 3.3 below:

FUNCTION	ALTERNATIVES							
CARRIER	Pipes	Fence around pallet	Bigger pallet	Special bigbag pallet	Bigbag re-shaping	Small silos	Case under bigbag	Current pallet
TRANSPORTATION MEANS	Pneumatic transport	AGV (current)	Crane system	Forklift	AGV with special attachment	Manual (no AGV)		
STORAGE	Silo storage	Rent extra warehouse storage	Build extra warehouse storage	Reduce current inventory				

Figure 3.3: Morphological overview of all the possible solutions

Concepts
The following concepts have been generated after creating the morphological overview. As many concepts only focus on the replacement of the load carrier, these have been combined. The concepts can be seen in figure 3.4.

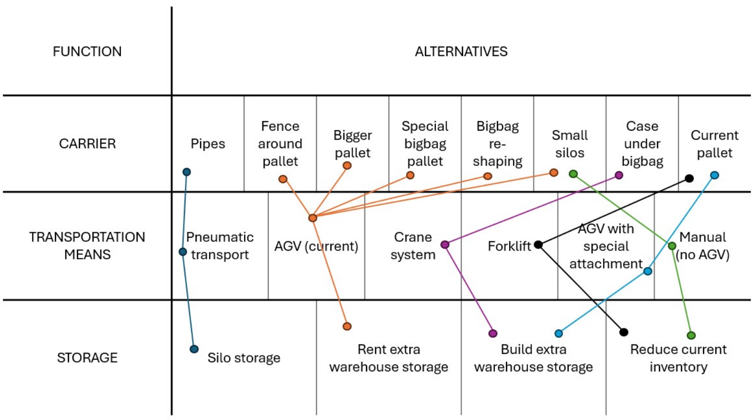


Figure 3.4: Morphological overview with possible concepts

1. *Silo concept (in dark blue):* Storing the powders in silos and transporting them pneumatically in pipes from an unloading point to the silos and also from the silos to production.
2. *Carrier concept (in orange):* This concept focuses on replacing the current load carrier with something else. This can either be an addition to a pallet or a small silo. Furthermore extra storage will be rented. Within this solution, the different load carriers also have to be compared to each other.

3. *Crane concept (in purple):* In this concept extra warehouse storage will be built in order to accommodate a crane system that can pick up cases in which the bigbags will be put and move these around the facility instead of the AGVs.
4. *Inventory concept (in black):* Instead of using AGVs, the forklifts will still be used within the warehouse and focus will be put on reducing inventory. This leaves a solution that doesn't need many changes to the situation within Nestlé.
5. *AGV concept (in light blue):* The AGVs will get a special attachment on their lifting mechanism, such that these can lift the pallets containing bigbags easily. Furthermore, extra warehouse storage space will be built, to store all the bigbags.
6. *Manual concept (in green):* Small silos will be used instead of bigbags and these will be delivered in different dropoff points within the factory, such that these only have to be moved manually. Meanwhile the inventory will be reduced.

Criteria
As there is no generic approach to selecting the criteria, this has been done in collaboration with different employees from Nestlé. The following criteria were determined:

1. *Hygiene:* the concepts have to comply with the rules that are already in place within the food processing factory. These always have to be followed.
2. *Implementation complexity:* As the production cannot be halted for a longer time, the concepts should be easy to implement at the factory. This means simple installation and easy integration with existing systems.
3. *Integration with current workflow:* The concepts should not disrupt the current operations. These should also be compatible with the current process.
4. *Safety and compliance:* The concepts should be safe and there should be no accidents or unsafe situations whatsoever. Furthermore, the concepts should comply with industry standards
5. *Profitability:* The concepts should not cost too much, relative to their gains.

In case of the weighing of the criteria, safety and hygiene are non-negotiable. A concept should always be safe to operate and always comply to all hygiene regulations. Next implementation complexity is the most important and this is only slightly more important than the integration with the current workflow, which is in turn slightly more important than the costs.

These weights have been assigned through pairwise comparison in collaboration with experts at Nestlé. Implementation complexity scores higher than the integration with the current workflow due to the fact that the AGVs are currently still being implemented. If a sudden big change has to be made to the warehouse, this will have a huge impact on the AGV implementation and this could lead to delays within their implementation. These delays could cause immense extra costs. The integration with the current workflow is just slightly less important, due to the fact that the workflow can still be changed slightly. The profitability is ranked lowest as these flow from the other criteria. Furthermore higher costs could still be accepted if the return of investment is within a reasonable margin.

The comparison matrix M can be found in the appendix D. The CR value of the matrix is 0.09555 , which is within the norms. The weights that have been calculated are the following: 0.42 for hygiene and safety, 0.08 for implementation complexity, 0.05 for integration with current workflow and 0.03 for profitability.

Concept selection
The concepts have been scored together with experts from Nestlé and from this a ranking can be made as can be seen in figure 3.5.

	Silo concept	Carrier concept	Crane concept	Inventory concept	AGV concept	Manual concept
Hygiene	7	7	7	7	7	4
Implementation complexity	6	7	1	10	5	4
Integration with current workflow	8	7	3	4	5	5
Safety & Compliance	7	7	6	3	3	5
Profitability	6	7	3	8	3	4
Total score	6,94	7	5,78	5,44	4,94	4,47

Figure 3.5: Concepts and their respective scores

It is good to illustrate why certain scores have been given, so that these values do not seem arbitrarily picked. When presenting the concepts to various experts, the following feedback was given per concept.

Silo concept: This concept will comply to the hygiene and safety & compliance regulations if implemented. This is because silos are already used within the factory and since other Nestlé factories also make use of silos for bulk storage. The implementation complexity is okay since the silos will be built outside of the warehouse and only pipes and minor equipment have to be constructed in order to connect the silos to production. The integration with the current workflow is quite high as it will have minor impact on the AGV operations. For safety & compliance, there are already regulations in place that are standard for silos and these will not give any extra problems. Finally the installation costs are expected to be on the higher side, but the operating costs will be fairly low.

Carrier concept: For the second concept the hygiene and safety & compliance will not be a problem, as bigbags are already stored and handled on pallets. The implementation complexity score is also rather high as little extra machines and or equipment will be needed within the facility. At most an extra pallet changer or a bigbag reshaper. The integration with the current workflow is just a little lower than the silos, due to the fact that multiple types of pallets will increase the complexity just as having an extra warehouse location will slightly increase the process complexity. The costs are very low for investments have to be made, the operational costs will probably be a little higher.

Within this concept there are many possibilities, these will be further explored and reviewed before making a detailed design of this concept.

Crane concept: This concept scores very low on implementation complexity as building a new warehouse or making the current factory crane compatible will be a enormous task. Next to that, Nestlé has almost no room to build extra warehouse space which also makes the implementation complexity score very low. The integration with the current workflow would also be bad as it requires big changes within the layout of the warehouse in order for it host a crane system. Also hoisting heavy weighing bigbags will have an impact on the safety of that part of the warehouse.

Inventory concept: Implementing forklifts driven by operators will be very easy as it is just the case of using already available equipment and infrastructure. However, the integration with the current workflow and the safety and compliance will be very low. This is because AGVs will have to be programmed to drive safely around forklifts, making the workflow more complex. As for safety, collisions might happen sooner as AGVs and forklift drivers will have difficulties predicting what the other will do. Finally reducing the inventory will not be sufficient for the expected workflow increase as only small improvements can be made and since the ordering of materials is done on a global level.

AGV concept: The special attachment for the AGV to safely lift a bigbag, would be an elegant solution if not for the compliance and testing issues. This attachment would be expensive to develop, test and certify. Also it would mean that a choice has to be made on either what AGVs will have this special attachment or when and how this attachment will be used. This will have an impact on operations as either the AGV with special attachment will not be used as much as the other AGVs, while the procedure of attaching and detaching would be a difficult one.

Manual concept: A different drop off station that would completely circumvent the AGVs will not be easy as this requires for new routes within the factory that comply to the hygienic regulations. Furthermore small silos, although already used in the factory, are very heavy for manual operators and cannot easily move these with their current equipment. As mentioned before, reducing storage space will not be enough for the expected growth within the factory. Also it is very difficult to make sure that small silos comply to the hygienic regulations as prove has to be given that these have been hygienically transported, before these can enter the higher level hygienic areas.

Initial chosen concepts
The concepts and their rankings have been shown to experts at Nestlé and based on their feedback the following concepts will be elaborated further. These concepts are the silo concept and the carrier concept, as these concepts have almost the same score and are clearly better than the other concepts. The concepts will be designed in detail and their costs of implementation will be compared, as their impact on operations and the space that is saved by implementing one of these. It might also be the case that a combination of the concepts would be the best option.

3.3. Final concept selection

As the silo concept and the different load carrier concept have been initially chosen as the best concepts, these have to be explored further before the optimal solution for Nestlé can be determined. First of all the best carrier has to be found for the carrier concept.

3.3.1. Selection of carrier solution

If pallets are being used, these should not have the problems that the bigbags cause. Such that the bigbags are stable, cannot tip over, the bags itself will not deform over the edges of the pallet, the pallet itself will not deform and that the AGVs can handle the pallets.

The options mentioned in the carrier concept are the following: placing a fence around the pallet, using a bigger pallet, using a special bigbag pallet, reshaping the bigbag and using small powder silos instead of pallets. Before the concept can be finalised, a choice should be made on the load carrier.

As mentioned before, the small silos are very heavy and can therefore not be lifted by the AGVs that are planned to work within the warehouse. Furthermore the small silos are too heavy for the racking system, where the bigbags are stored. This makes it an unfeasible solution.

Placing fences around the pallets also gives some problems. The main concern experts at Nestlé have is that the fences have to be placed on the pallet manually and when the pallet is changed within one of the palletchangers, this fence has to be removed and attached to the new pallet manually. Furthermore extra storage space will be needed for all the fences, which is unwanted. Also if a bigbag is already sagging, an operator will not be able to place a fence on the pallet as the bigbag is too heavy for this. Therefore fences around pallets are also unwanted.

Using special pallets brings very similar problems to using fences. Due to hygienic regulations, all pallets have to be changed within the Nestlé facility and this would generate a lot of extra work when using a special pallet. When a different kind of pallet is used, this will lead to more storage usage, as well as problems with the handling done by operators. Nestlé has been very clear in its goal of reducing the amount of different pallet types and adding an extra type is unwanted.

Using a bigbag reshaping machine could be a good solution as it can be placed at the beginning of the warehouse and make sure that all incoming bigbags are placed correctly on their pallet. However, in this case pallets have to be monitored when in storage such that these do not sag when stored for a longer time. This is not a problem if pallets are stored at another location and only pallets that are used within a couple of days are stored at the warehouse.

Bigger pallets also add to the complexity within the warehouse and these do not necessarily solve the problem of unstable bigbags. Furthermore, the racking within the warehouse cannot handle bigger pallets, so this option also becomes unfeasible.

When comparing the possible carrier solutions, the bigbag reshaping machine is the clear winner. As the machine does not require any extra pallet types, keeps the pallets compatible with the racking and the AGVS and since the least amount of investment is needed. The downside of needing to reshape the pallets more often is not a problem as the majority of all pallets will be stored elsewhere, such that frequent reshaping of the bigbag will not happen.

3.3.2. Extra considerations

After presenting the best concepts to Nestlé experts, these asked for some extra concepts to be developed. This is because the morphological overview cannot take some complexities into account. One of these is the fact that bulk delivery, although mentioned as an option by the suppliers, might not always be directly possible when implementing the concepts. This means that even though the silos are in place, not all materials could be delivered in bulk. Therefore Nestlé experts have asked for the addition of two extra concepts:

- **Extra concept 1**: Powders arrive in bulk at the factory and the bigbags are tipped at tipping stations. From here, the powder is transported to storage silos. Once needed, the powder is transported from the silos to production.
- **Extra concept 2**: Some powders arrive in bulk and some powders still arrive in bigbags. The powders that arrive in bulk are stored in silos, such as in the silo concept. The powders that arrive in bigbags are stored in the rented warehouse such as in the carrier concept.

The first extra concept would be the situation in which the silos have been built, but suppliers cannot deliver their materials in bulk yet. Some suppliers might have to built a new facility to load their powders in bulk and this requires a lot of time. The experts also mentioned that if Nestlé plans on receiving powders in bulk, the implementation would go in steps, one of these having the powder delivery still in bulk while already having the silos in use. This concept will probably not be cheaper as it needs a bigbag reshaper, silos and extra pipes, but it will give a good overview of this possibility.

The second extra concept combines the initially selected concepts. It might be that for certain powders it is cheaper to store these in silos and for other powders to store these in the extra warehouse. It might also be that some suppliers can deliver their materials in bulk and other suppliers cannot. Therefore the powders that can be handled in bulk will be stored in silos, while the powders that cannot be stored in bulk will be stored in bigbags. This concept could give an even better solution as it combines the previously selected concepts.

3.3.3. Final concepts

After picking the best carrier option and taking the considerations from Nestlé experts into account, the four selected concepts are:

1. Storing the pallets in a rented warehouse and making the bigbag pallets suitable for the AGVs via a bigbag reshaper (Carrier concept).
2. Storing the powders in silos and transporting them in bulk (Silo concept).
3. Storing the powders in silos and transporting them as bigbags (Silo pallet concept).
4. A combination of these solutions: storing some materials in bulk, while storing others in a rented warehouse (Combined silo pallet concept).

The next steps would be to design these concepts in further detail. After this, the concepts can be modelled after which they can be compared and an optimal solution can be given.

3.4. Conclusion

This chapter has presented multiple solutions and concepts that can solve the problems faced at Nestlé. The solutions have been combined to concepts and compared using the AHP and expert inputs. From this process two promising concepts have been identified. Using silos to store the powders and transporting these through pipes instead of AGVs. The other option is to have a bigbag reshaper within the warehouse and to store most of the pallets in a rented warehouse.

Besides these two concepts, two extra concepts have been created as a combination of the selected concepts. This is done after feedback from Nestlé experts, as not all materials might be available in bulk when implementing the silos or at any time. The first extra concept makes use of the bigbag reshaper and a tipping station. From this station the powders are pneumatically moved to the silos, where the powder will be stored until needed. The second extra concept combines the first two concepts by either storing pallets in silos or in the extra warehouse on pallets. This could be the case if some powders cannot be stored in bulk or if it is cheaper to store some materials in pallets.

Now that all the concepts have been determined, the next step is to have a more detailed description of each and to understand what is needed exactly for each concept.

4 Detailed design

This chapter, together with the previous chapter will answer the following research question:

What are the design alternatives?

Where the previous chapter started very broad and used the AHP to determine the best concept, this chapter will continue with these concepts and go into a more detailed design. It will mention the process, extra infrastructure and the considerations of each concept to make sure that the concepts will function well enough.

4.1. Chosen concepts

When looking at the concepts that have been selected in the previous chapter, these have to be further developed. These are the following:

1. Storing the pallets elsewhere and making the bigbag pallets suitable for the AGVs with a bigbag reshaper. (Carrier concept)
2. Storing the powders in silos and transporting them in bulk. (Silo concept)
3. Storing the powders in silos and transporting them as bigbags. (Silo pallet concept)
4. A combination of these solutions: storing some materials in bulk, while putting others on special pallets. (Combined silo pallet concept)

4.2. Storing pallets in a rented warehouse and making the bigbag pallets suitable for AGVs

When storing the pallets elsewhere, a lot of room can be saved as the bulk of the pallets will be stored in the rented warehouse. Only the pallets that are needed on the short term will enter the warehouse and thus there could be a storage reduction. Furthermore the bigbag reshaper will make sure that all pallets entering the warehouse will be suitable for the AGVs.

4.2.1. Process overview

In this situation the process would start at the third party warehouse. Here the pallets would be unloaded by the operators that work there and put into storage. If a pallet is needed, a request for the pallet will be sent to the third party warehouse a few days in advance. Next the pallet is loaded into a truck at the third party warehouse and driven towards the Nestlé production facility. Here it is unloaded from the truck.

Once the pallet has been scanned and checked it is placed in the bigbag reshaper and shaped correctly. From here the AGV picks up the pallet and drives it either to a storage location, where the pallet will be stored until it is needed. Otherwise the AGV will drive the pallet to one of the two pallet changers, where it will be changed. After the pallet changer, the AGV will pick up the pallet once more and place it on the airrinser, after which the pallet will be handled by production. This flow can also be seen in the swimlane diagram in figure 4.1.

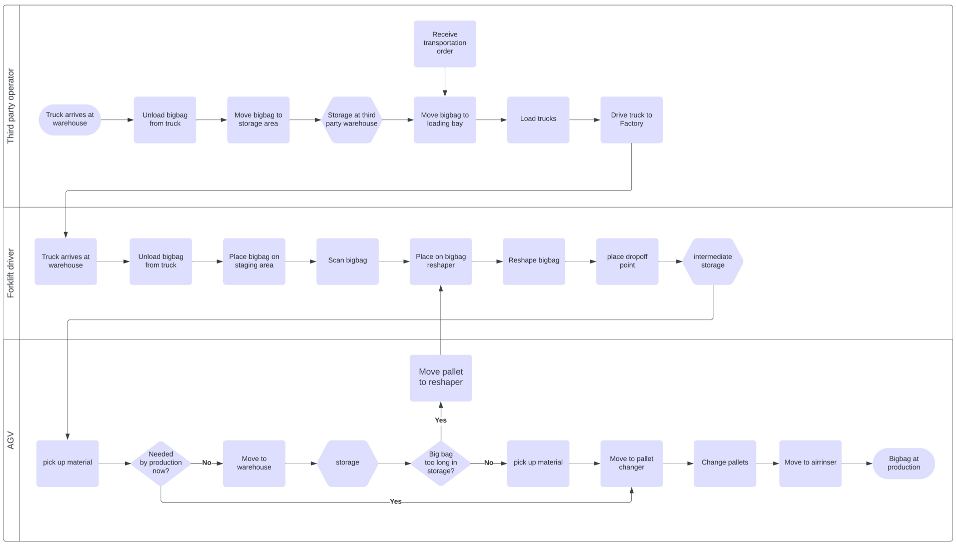


Figure 4.1: Swimlane diagram of the implementation of a bigbag reshaper

4.2.2. Extra infrastructure

When opting for a bigbag reshaper to make the bigbags suitable for AGVs, there are still some problems that need to be addressed. One of them is that the bigbags have to be reshaped before being handled as to make sure that no accidents will happen with the AGVs. This step should always be done within the Nestlé facility to make sure that every bigbag will be suitable. A possible location for this bigbag reshaper can be seen in 4.2 at location 6, where only the forklifts handle the pallets. The AGVs could the pick up the pallets from the other side of the reshaper. Therefore any related infrastructure costs are only based on the bigbag reshaper.

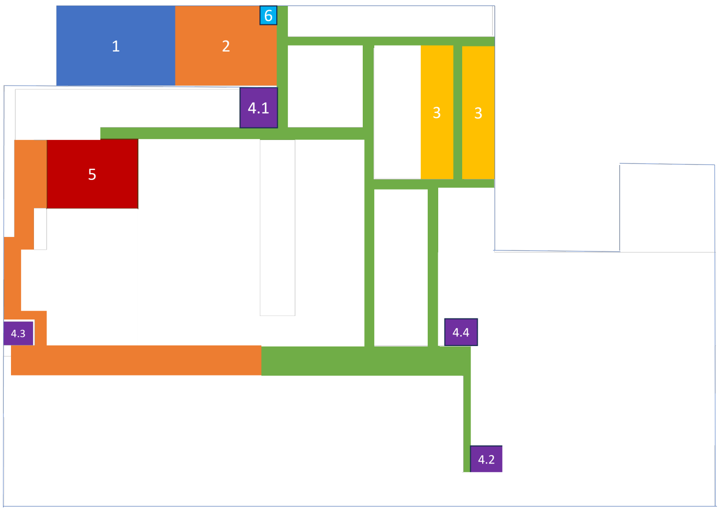


Figure 4.2: Layout of the facility with a bigbag reshaper at location 6

A bigbag reshaper would be very quite similar to a modified pallet changer. Similarly to a pallet changer, a bigbag reshaper would first tip the bigbag so that the pallet would be on top of the bigbag. The it would slowly compress the bigbag a little until it has the desired dimensions. After this it would tip back and place the reshaped bigbag back onto the pallet. Afterwards the AGV can pick it up and transport it to its destination.

4.2.3. Considerations

Nestlé already makes use of a third party logistics supplier (3PL) warehouse and already stores a lot of pallets there. The costs of storing extra pallets at this supplier are already known and are based on the weekly stored amount and incoming amount. Furthermore the 3PL also already drives to and from the factory on a daily basis and has clear costs mentioned for this. However, the factory can only have trucks drive on its premises during weekdays between 7 in the morning and 7 in the evening. Therefore, the warehouse would need at least 3 days of storage during the weekends, when no trucks are allowed to arrive. As the 3PL warehouse is a 20 minutes drive away, pallets that arrive on a given day can immediately go to production. A standard truck can carry 24 pallets per trip and combined with all the other trucks arriving at the warehouse, Nestlé can handle no more than 9 trucks of bigbags per day.

4.3. Silo storage and bulk transport

When implementing silos, both warehouse storage is made free and the AGVs do not have to carry big bags. This could be a win-win situation for the Nestlé. When using silos, powders could be transported in bulk, and moved through the facility in bulk as well. This means that pneumatic conveying also has to be implemented within the factory.

When implementing silos, a lot of factors have to be considered. These are the design of the silo cone angle and outlet diameter, to make sure their is enough powder flow and proper powder flow. Also some powders might not be compatible for the same silo, if these need different angles and diameters. Finally a lot of extra infrastructure is needed to transport the powders to and from the silos.

4.3.1. Process

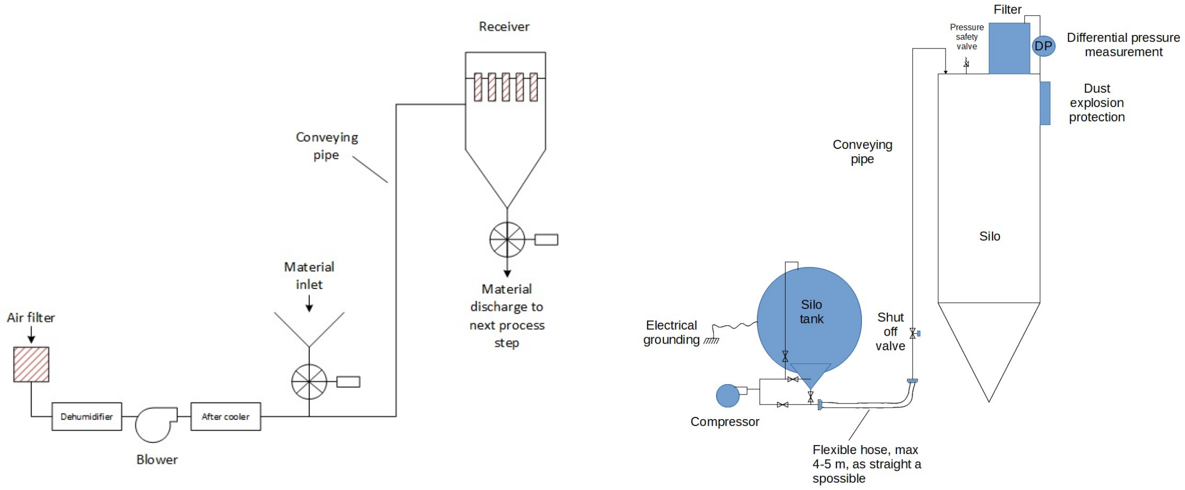
In the case of having silos and powders delivered in bulk, the process would change drastically. The powders would arrive by bulktruck and the truck operator would connect the truck to the silos. From here the powder would be loaded immediately in the silos. After being in storage for some time, when the powders are needed, these would be transported pneumatically from the silos to production, where these can be used immediately.

4.3.2. Necessary silo infrastructure

When installing silos within a production environment, multiple pieces of equipment are needed in order to fill and empty the silos. This includes a means of inserting powder into the system, a means of transporting the powder towards the silos, a means of transporting the powder from the silos to the production areas, and safety measures, sensors and control infrastructure.

As can be seen in figure 4.3 below. Just for loading a silo within the food processing industry, the following components are needed:

1. Air filter
2. Dehumidifier
3. Blower
4. After cooler
5. Inlet (big bag tipping station)
6. Rotary valve
7. Piping
8. Pressure sensors
9. Temperature sensors
10. Filters
11. Explosion suppression mechanisms



(a) Loading a silo via an inlet

(b) Loading a silo via a bulk truck

Figure 4.3: Silo filling configurations, either by big bag or by bulk truck [51] [52]

The process for emptying a silo is the following: the blower sucks in air via the air filter, to make sure that no contaminants are present within the air once it is in contact with the powder. The air goes through the dehumidifier to make sure that the moisture content in the air isn't too high. The blower compresses the air and speeds it up. Shortly after, the aftercooler cools the air down to make sure the air and the powders do not get to hot as dust explosions could happen. The powder is already present at the material inlet and is dosed into the stream by the rotary valve. It is then transported through the piping to the production silo. Once in the production silo, the powder falls down and the abundant air is blown out through a filter. The sensors are placed near the blower to make sure that the transporting air has the right qualities, whereas the explosion suppression mechanisms should be present throughout the system as powders are highly explosive [54] [41]. A material inlet isn't needed anymore since this is already incorporated within the silo.

Often when powders are brought in bulk, this is done via bulk trucks. In this case, the truck would have its own blower system and valves. For connecting the truck to the silo, only piping would be needed. Finally sensors are needed to measure amount of material present within the silo. This is necessary in order to determine when the silo can be filled and by how much.

Silo design

Currently the factory works with the FIFO principle: First In, First Out. Which means that powders that enter the factory first, should also be used first. This is because the powders will deteriorate over time and this is unwanted. The FIFO policy does have implications for the silos, as these should follow the same policy. Fortunately this can be done by enforcing mass flow within the silos. Mass flow is a particular type of flow within silos, where the silo is emptied evenly from the bottom up [61]. If a silo hasn't been designed correctly, a different kind of flow will happen, which is called core flow. In this situation, the middle of the silo will be emptied first, before the sides will flow down. This is unwanted as powder will mix when going out and the FIFO policy will not be met.

The type of flow within a silo depends on the material properties as well as the interaction between the material and the silo wall. The most used method for determining the silo parameters is Jenike's method [36] [61]. For this procedure, certain characteristics of the raw material and the silo material have to be known. These are: bulk density of the material ρ_b, effective angle of internal friction ϕ_e, the unconfined yield strength σ_c and the wall friction angle ϕ_x.

Most of these values can be determined by using a ring shear tester [24]. Unfortunately, these tests couldn't be conducted for this study. In the ideal scenario these values would be determined for every powder, for every supplier. It might be that the same materials from different suppliers have different characteristics and could not be stored in the same silos.

Once these properties have been determined, they can be used to find the hopper angle. If the hopper itself is conical, which is the hopper shape in most cases [61], then a safety factor of 3 to 5 degrees extra would be needed. Next one calculates the hopper flow factor and uses this to calculate the critical stress for flow [24]. This can then in turn be used to finally determine the needed diameter of the outlet for flow. The outlet diameter should always be 6 to 10 times bigger than the biggest particle size [61], but since maltodextrin and lactose have very fine particles this will not be a problem [16] [65].

Finally the outlet diameter is also important to determine the maximum flow of the silo. This can critically affect the number of silos and the costs of building these. The factory will need a certain amount of powder within a certain amount of time. This maximum flow depends on the bulk powder density, the max bulk powder density, the outlet diameter as well as the permeability of the powder at the outlet conditions [18]. These values also have to be known before this can be calculated and verified.

Note that there are currently silos with a maximum volume of 100 m3 placed within the Nestlé facility. The assumption will be made that the silos will have the same size or be smaller.

Silo costs

For the costs, most costs will come from building the silos and the necessary infrastructure. However, these costs will diminish once most of the necessary infrastructure is in place. A blower system, will be used by multiple materials and not every silo needs its own blower. Pipes could also be shared under the assumption that no material stays inside these after usage. And under the assumption that no 2 materials are needed at exactly the same time. This means that once a pipe system has been built for a production line, only a few short extra pipes and valves are needed to connect an extra silo to the system. There are also running and storage costs that should be taken into account when using silos, that are correlated to the amount of powder stored and the amount of powder that is moved to production. However for this concept the worse case will be assumed: powders cannot share the same pipes.

4.3.3. Considerations

When implementing the silos, hygiene, safety and location have to be taken into account as these will have an effect on the outcome and implementation of this concept.

Hygiene regulations for silos

Due to hygiene regulations and traceability, different powders cannot be present in the same silo at the same time. This is due to the fact that if a problem occurs with the end product, it should be easy to determine what ingredient caused it. If the ingredient is found that caused the problem, all products with the same ingredient can be called back. If different powders are mixed within the same silo, it is almost impossible to know which powder was the ingredient that caused the problem. Furthermore it can also cause product degradation, since a too high percentage of material A might be in the product, due to the fact that it was mixed into material B when these were in the same silo.

Another important hygiene requirement is the separation of the two production lines. One of the production lines uses allergens that the other production lines must avoid at all costs. It is therefore of utmost importance that ingredients for these two lines never go through the same system or are stored in the same silo, since allergens could still be present somewhere within the system.

The silos should be cleaned in between the time that different powders enter the silo. Rest material could still be present in the silo and this could contaminate the material that is added afterwards. Cleaning of silos takes about one day and this is a three man job [50]. Another option would be to clean the silo with specially developed orbital cleaners [27], if wet cleaning is allowed. Currently the silos within the factory are only cleaned when there is maintenance done on the silos. For the outside silos, this could be done when their is either maintenance or a possible material change. However, this will be minimal.

For the hygienic unloading of the bulktrucks, Nestlé itself already has guidelines in place. These guidelines mention the proper way of unloading a truck as well as the steps the operator has to do in order to empty it.

Explosion suppression mechanisms

As the powders, especially maltodextrins, are combustible [43], it is important to make sure that all equipment that is in contact with the powders is grounded. This goes for the silos, piping, loading and unloading stations. Also explosion suppression mechanisms have to be installed on the silos and the bulk trucks delivering the powders.

Time consolidation

When materials are stored for longer periods of time, their characteristics can change as well. This is called time consolidation and this results in a bulk powder having an increased unconfined yield strength σ_c [24]. Which will in turn affect the silo dimensions. Therefore measurements should be made were the powders are stored as long as the material is unused. This time can be easily found in the data delivered by Nestlé.

Silo locations

When implementing the silos within the factory grounds, it is important that these are easily accessible for inspections, maintenance and filling. Placing the silos inside does not necessarily help with reducing the used warehouse space and is therefore not viable. When placing the silos outside, the ideal location would be next to the warehouse as these are easily accessible by both employees and bulk trucks.

As the silos are outside, these should be weather proof and be insulated to protect the powder and to keep the storage conditions of the powders as constant as possible in order to facilitate flow. Also the piping to and from the silos should be as short as possible and minimise the number of bends [53]. A possible configuration for the pipes would be seen in figure 4.4:

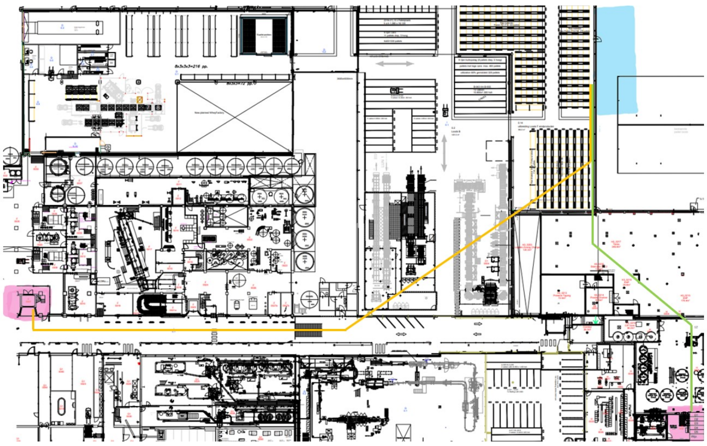


Figure 4.4: Silo location and corresponding pipes. The location for the silos is coloured blue, the bigbag tipping stations (drop off location for materials from the silos) are in pink. The yellow line represents pipes towards the Egron production line. The green line represents the pipes towards the EHP production line

When looking at this location, it is also important to take the driving routes of the trucks into account. The silos should not hinder any traffic and if any supplier can deliver in bulk, these should be accessible. Therefore this location would also allow for easy unloading and least transport distance. The location has an area of roughly 150 m2, with a respective length of 30 meters and width of 5 meters.

Powder transport

The distance for the powder to be transported is 145 meters from the silos to the Egron tipping station and 89 meters from the silos to the EHP tipping station. The possible means of transport are dense phase transport and dilute phase transport with either positive pressure or negative pressure (vacuum) [53]. Typically sugars and milk powders are transported via dilute or dense phase positive transport [51]. If the silos will be implemented within Nestlé, the dilute phase with positive pressure will be implemented as its easiest to tune and has simple tuning parameters. This has also been recommended by an expert process engineer at Nestlé.

Silo insulation

According to the powder suppliers the materials should be stored at temperatures below 25 degrees celcius in case of lactose [28] and not longer than 24 months in suitable conditions. The maltodextrins should be stored at temperatures between 5 and 30 degrees [54] for a maximum duration of 24 months as well. This means that the silos have to be insulated to accomodate these conditions.

4.4. Silo storage and bigbag transport

If the powders cannot be delivered in bulk, it might still be feasible to store them in silos. In this case, the bigbag reshaper would be needed. The pallets would be transported to a tipping station before being transported to the silos.

4.4.1. Process

In this case the process would consist of two parts. The first part would be the handling of the bigbags and transporting these to the tipping station. This process is almost the same as the process of handling the pallets through AGVs with a bigbag reshaper. However, in this case the powders would be transported pneumatically from the tipping stations to the silos first, before going back to be used.

4.4.2. Extra infrastructure

The extra infrastructure that would be needed for this situation is the following: extra pipes from a tipping station to the silos, extra blower systems and potentially an extra tipping station. The extra piping installation would be very similar to 4.3, except that the first subfigure is now also used for filling the silos with bigbags. Lactose would be tipped at the EHP station to make sure that no materials containing peptides would get into the EHP via the tipping installation from the Egron.

Tipping station

If the chosen tipping station is the current tipping station of each line, the problem of the bigbags and the AGVs being incompatible still isn't solved. This would mean that a bigbag reshaper would have to be implemented and that a transportation system would have to be build from the tipping stations to the silos and back.

An option would be to create a tipping station near an unloading point of the trucks and to transport the powders from this station towards the silos. This would result into building at least 2 tipping stations (one peptide-free) and their corresponding hygienic zones. This means that changing rooms have to be built as well as extra airrinsers and palletchangers for the incoming powders.

Since there is already a shortage of space within the factory at the best option would be to use the current tipping stations within the factory and build extra pipes to transport the powders to and from the silos. The locations of the silos would still be the same as in 4.4, as it allows for future bulk delivery.

Costs

The costs would consist of costs made for the silos with bulk deliveries and the pallets stored at another location. The costs would consist of silos, piping to and from the silos, a bigbag reshaper, pallet handling costs and pneumatic handling costs.

4.4.3. Considerations

When implementing this concept, it is important to know how many extra blowers are needed due to the extra powder movements as well as the amount of pallet spots that are needed. It might be that the AGVs or the tipping stations cannot handle all the incoming bigbags immedialely due to other orders having a higher priority. This means that the incoming bigbags will have to be stored temporarily in the warehouse and that a certain amount of spaces have to be reserved for bigbags.

4.5. Storing materials in bulk and on pallets

It might be more suitable to have certain powders being delivered in bulk, while other powders not. This could lead to a solution where some powders are stored in silos and other powders are stored in the 3PL warehouse on pallets. In this case the costs would be a combination of the costs for handling the powders on pallets and handling them in bulk.

4.6. Determining the best concept

In order to determine the best concept a lot of information needs to be known. These include:

- Number of silos
- Silo sizes
- Number of blowers
- Number of sensors
- Number of pallets arriving at the same time
- Number trucks arriving on a daily basis
- Costs of infrastructure
- Yearly handling costs
- Area needed for all silos
- Number of pallet spots needed for bigbags in the warehouse
- etc.

As there are many things that determine if a concept can be implemented and how it would look like, it is very difficult to determine the best concept. As the future changes happening in the warehouse have not been implemented yet, the concepts can not be simply compared or implemented. As the concepts feasibility and final implementation depends on a lot of different factors, the best way of comparing them would be by modelling them for the future situation. This way all of the important information can be calculated and via these models the concepts can be compared relatively easily to each other. Before modeling the concepts, it would be useful to see if any relevant models already exist and if these can be implemented for some of the concepts.

4.7. Conclusion

Together with the previous chapter, this chapter has answered the research question 'What are the design alternatives?' These have been reduced from six to two concepts. From these two concepts, two extra concepts have been created by combining these. The concepts have been described more thoroughly in this chapter, focusing on the process of each concept as well as the needed infrastructure and considerations.

The possible solutions are either storing the materials at a third party warehouse and using a bigbag reshaper within the factory warehouse, reducing both used space and allowing the AGVs to handle the pallets. Another option would be to build silos and store the powders there. The powders could either be delivered in bulk or still in pallets and then be loaded in silos. From the silos the powders would then be transported pneumatically to the production areas. Finally these solutions could be combined such that some materials are stored in silos and others are stored on pallets.

It might be that one solution might be more suitable than another one. As for every solution there are things to be considered such as powder properties, storage time, extra needed infrastructure and costs. In order to determine which solution will give the best results, these have to be modeled to calculate the costs of each solution and to see the impact of them on the operations as well as for management at Nestlé to make a decision on how to handle and store their powders.

The next step would be to model the concepts, optimise their configurations and compare these. The considerations mentioned in this chapter, will have an impact on the models and thus their outcome.

5

Literature Review

Before the concepts can be modelled, it is important to know what has already been done in earlier research and if there is any overlap between these formulated models and the situation at Nestlé. Therefore this chapter will answer the following subquestions:

How to evaluate the performance of the conceptual designs?

The situation at Nestlé is unique since it consists of multiple different sub-problems that have to be modelled, these can be solved either in order or all at the same time. The problems consist of a warehouse/ storage sizing problem, lot sizing problems, a storage allocation problem as well as a bin packing problem. This chapter will describe all relevant problems as well as similar ones. First it will start with describing relevant literature for handling the bigbags on pallets and storing these in a third party warehouse. Next the chapter will describe relevant literature for the option of storing the pallets in bulk, by looking at storage alloaction problems and bin packing problems. It will conclude with the scientific gap that has been found following the literature study.

5.1. Warehouse/storage sizing problems

One of the first papers on determining the optimal size of a warehouse has been published by Hung, as mentioned in the introduction [31]. Hung distinguishes between the static and the dynamic warehouse sizing problem: for the static situation a warehouse is built/bought at the start of the planning horizon, while in the dynamic situation the size of the warehouse can change over time [72].

The static model can be formulated in the following way [31]:

Table 5.1: Notation for warehouse sizing problem

Sets and indices	
T	Sets of nodes $i \in Y$ time periods
Parameters	
C_0	overhead costs of the private warehouse per square meter
C_v	costs of private warehouse per square meter
C_p	costs of public warehouse per square meter
D_t	demand for storage space in square meters in period t
f	fraction of the total warehouse space that can be used for storage
Variables	
X	size of warehouse in square meters
Y_T	amount of private warehouse space in square meters used in period t

The mathematical formulation then follows as:

$$\min \quad EC = \sum_{t=1}^{T} (C_0 X + C_v Y_t + C_p (D_t - Y_t)) \tag{5.1}$$

Subject to:

$$Y_t = f \cdot X \qquad \forall t \in T \tag{5.2}$$

$$Y_t \leq D_t \qquad \forall t \in T \tag{5.3}$$

$$X \geq 0, \quad Y_t \geq 0 \qquad \forall t \in T \tag{5.4}$$

Equation 5.1 determines the total costs of using both a public warehouse and a private warehouse. These costs consist of the overhead costs of building a private warehouse, the costs of using a private warehouse and the costs of storage in a public warehouse when the private warehouse is too small. Equation 5.2, makes sure that the warehouse is always bigger than the storage that is used. Equation 5.3 makes sure that the warehouse cannot store more than the storage demand. Finally equation 5.4 makes sure that the used space is non negative. This mathematical model could thus be used to determine how much square meters should be bought and rented for the cheapest storage solution.

Later on, additions have been made to the problem such as multiple warehouses as well as incompatibility. Alexiou [2] used graph theory to determine the minimum number of warehouses and the needed space for storage. Alexiou does not take changing demand into consideration as well as time changes. Another of these studies has been done by Basnet [6]. Here Basnet minimises the number of warehouses needed for items which might or might not be compatible, when the warehouse sizes are already predetermined. The corresponding mathematical model is very similar to the knapsack problem and a variation on it: the bin-packing problem (BBP). Still Basnet only optimises for fixed warehouse size and does not consider the option of different storage types or changing demand.

In case of storing pallets in a third party logistics warehouse, the dynamic warehouse sizing problem becomes relevant. In such a case, a firm has a primary contract which is negotiated prior to the planning horizon and the secondary contract is negotiated at the start of each time period [42]. The secondary contract is there to obtain extra warehouse storage capacity if this is necessary. The warehouse manager responsible for choosing how much space is rented, can adjust the warehouse space within a certain range based on the warehouse expansion and reduction capacity [59], or in other words how much the storage can grow or be reduced. If there is no room for expansion or reduction the contract turns into the static warehouse sizing problem and if there is infinite room, the contract becomes fully flexible.

Due to the fact that the Nestlé already stores many materials at the third party logistics warehouse, the extra increase of storing pallets there can be assumed to be under a fully flexible contract.

5.2. Two warehouse inventory systems

Two warehouse inventory systems have first been mentioned by Hartley [30]. In this system, a rented warehouse (RW) and a owned warehouse (OW) are locations where a company can store its inventory. Usually the OW has a fixed amount of spaces and lower holding costs than the RW, which has an abundance of space. These models describe the storage costs, order costs and sometimes the transport costs [76]. However, these models try to find the optimal order times and order sizes for a known demand rate as these are based om the economic order quantity (EOQ). This is different from the situation within Nestlé where demand and supply are already fixed and only the optimal storage division is needed.

A very similar problem to this is the lot sizing problem. In case the demand of the EOQ is changing, the lot sizing problem becomes relevant. Reviews on this problem and all its variants have been done by Ullah [67], Karimi [37] and Bushuev [7]. Ullah classifies the lot sizing problem based on the following aspects: planning horizon, number of items, order quantity, frequency of review, lead time, capacity, demand, stocking points and unsatisfied demand. In case of storage at the third party warehouse and at the factory warehouse, the following version of the lot sizing problem would be the most relevant: multi item/ single item, two stage, variable order quantity, with zero lead time, static dynamic demand lot sizing problem. The multi item single stage capacitated lot sizing problem has been treated by Barani [4] and is very much alike the situation at Nestlé.

An example of the two stage single item lot sizing problem can be seen in the paper by Hwang [33]. Where two inventories are being described, the first supplying the second. The main difference with the case at Nestlé is that Hwang has a model where the incoming amount of items for the first warehouse can be chosen by the model itself. In the case of Nestlé, this has been simplified as the incoming products cannot be changed due to the way procurement is set up within Nestlé. Also most lot sizing models, make use of a set up cost, as this is related to production. However, this is not needed when it is used to model inventory of almost similar items. The case at Nestlé is officially multi item such as has been done by Sitompul [62], but since the items can be transported together, the transportation costs of these items become equal. Finally some extra constraints will be needed to make sure that the lot sizing model will be precise enough for the case at Nestlé.

5.3. Storage allocation problems

Silo storage design has first been mentioned by Schlifer in the sixties [60]. Here the silo storage problem is introduced for the first time. This study creates a model that determines the size of a silo, the number of compartments it is split in and how big each compartment should be, in case demand is already known. In this model, a small amount of leftover material is allowed and this can be stored somewhere else for some extra costs.

This problem has been coined as a subset of the segregated storage problem (SSP) by White and Francis, who used an algorithm to solve it [73]. SSP is concerned with the distribution of products among existing storage compartments with the constraint that no more than one product may be stored in a given compartment [21]. Evans mentions multiple ways of solving SSP, as well as algorithms developed by others in his papers [21] [22], giving a good overview of the work done on SSP in the seventies.

The generalised segregated storage problem (GSSP) has first been introduced by Barbucha [5] and is a more generalised version of SSP. The main difference with the SSP is that an extra constraint is introduced which makes sure that some materials are not allowed to be in adjacent compartments.

Formulation of the SSP

The segregated storage problem can be formulated as follows in its most elementary way [21]:

Table 5.2: Notation for segregated storage problem

Sets and indices	
m	Sets of nodes $i \in m$ materials
n	Sets of nodes $j \in n$ compartments
Parameters	
a_i	storage demand for product i
b_j	capacity of storage compartment j
c_{ij}	negative costs of storing material i in compartment j
Variables	
x_{ij}	amount of product i stored in compartment j
Y_{ij}	binary variable, 1 if material i is stored in compartment j and 0 otherwise

The mathematical formulation then follows as:

$$\min \quad \sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij}x_{ij} \tag{5.5}$$

Subject to:

$$\sum_{j=1}^{n} x_{ij} \leq a_i \qquad \forall i \in m \tag{5.6}$$

$$x_{ij} - b_j Y_{ij} \leq 0 \qquad \forall i, j \in m, n \tag{5.7}$$

$$\sum_{i=1}^{m} Y_{ij} \leq 1 \qquad \forall j \in n \tag{5.8}$$

$$x_{ij} \geq 0, \quad Y_{ij} \in 0, 1 \qquad \forall i, j \in m, n \tag{5.9}$$

Equation 5.5 minimises the costs of storing items in the different compartments. Equation 5.6 formulises that the storage of a product can only be as big as the maximum amount of product that needs to be stored. Equation 5.7 guarantees that a compartment cannot be overfilled. Equation 5.8 makes sure that only one item can be put into a compartment. Finally equation 5.9 restricts the decision variables. Note that the elementary form of the SSP is only for one moment in time. The goal of this model is to store all items as cheaply as possible in the least amount of compartents.

5.4. Bin-packing problems

One of the more recent reviews on the Bin Packing Problem (BPP) has been done by Munien [47]. The BPP is defined as a combinatorial optimization problem that deals with packing a finite sets of items with weights into a finite number of bins without exceeding the maximum capacity of the bins. Within the bin packing problem, there are multiple variants. The main variants are the 1D-BPP, the 2D-BPP and the 3D-BPP. Where the difference is in the amount of dimensions being 1, 2 or 3. 1D-BPP focuses on filling containers with only weights, whereas the 2D-BPP has an extra dimension, this could be an example of placing rectangles within a given area [26]. The 3D-BPP has applications in container loading where boxes of different sizes have to be fitted within a container [46]. The main difference between BPP and SSP is the objective of the problem: BPP aims to minimise the number of bins used, while SSP aims to minimise the costs.

The 1D-BPP can be modelled as an integer linear program [45] and the corresponding mathematical model for the 1D-BPP is the following:

Table 5.3: Notation of the bin packing problem

Sets and indices	
u	Sets of nodes $i \in u$ bins
n	Sets of nodes $j \in n$ materials
Parameters	
c	capacity of each bin
w_j	weight of material j
Variables	
x_{ij}	binary variable, 1 if material j is stored in bin i and 0 otherwise
y_i	binary variable, 1 if bin j is in use and 0 otherwise

The mathematical formulation then follows as:

$$\min \quad EC = Z = \sum_{i=1}^{u} y_i \tag{5.10}$$

Subject to:

$$\sum_{j=1}^{n} (w_j x_{ij}) \leq c * y_i \qquad (1 \leq i \leq u) \tag{5.11}$$

$$\sum_{i=1}^{u} x_{ij} = 1 \qquad (1 \leq j \leq n) \tag{5.12}$$

$$y_i \in 0,1 \qquad (1 \leq i \leq u) \tag{5.13}$$

$$x_{ij} \in 0,1 \qquad (1 \leq i \leq u; 1 \leq j \leq n) \tag{5.14}$$

Equation 5.10 minimises the number of bins used, equation 5.11 makes sure that the weight of the items does not exceed the capacity of the bins. Equation 5.12 makes sure that each material is stored in one bin and equations 5.13 and 5.14 make sure that y_i and x_{ij} are binary. The goal of this model is to distribute all materials over the different bins, while using the least amount of bins possible.

In recent years many variations have been made to the BPP. One of the more relevant is the Bin Packing Problem with Conflicts (BPC ot BPPC), which has been introduced by Jansen and Öhring [35]. In this specific case some items cannot be stored in the same container and have to be separated, as is the same for the materials within the silos. Another related variation of the BPP is the bin packing problem with item fragmentation (BPPIF) where items are allowed to be placed in multiple bins and do not have to be placed in one sole bin. This has first been introduced by Mandal [44]. Another related BPP is the variable sized bin packing problem (VSBPP), where the bins can have different sizes. This is first introduced by Friesen [25] and Murgolo [48]. Wäscher [71] and Haouari [29] consider the VSBPP with bin costs proportional to its szes. Following this, the variable sized and costs bin packing problem (VCSBPP) has been coined, where there are different sizes of bins with different costs [14].

These variations can also be combined, an example of this is the bin packing problem with conflicts and item fragmentation (BPPC-IF), which was first introduced by Ekici [19]. The variable sized bin packing problem with item fragmentation (VSBPP-IF) has been first introduced by Casazza [9]. The variable sized bin packing problem with conflicts and item fragmentation (VSBPPC-IF) has been introduced by Ekici as well [20]. Ekici also gives a good overview of all research that has been done on these variations within his last study [20].

Another variation that is relevant for this study is the dynamic bin packing problem (DBPP). In this variation, the items that have to be divided over the bins arrive and depart at random times [10]. This has been generalized even further in the fully dynamic bin packing problem (FDBPP), where items are also allowed to be repacked in different bins [34]. An overview of all variations till 2013 has been given by Coffman [11]. However these dynamical models do not take variable bins, or item conflicts into consideration. Furthermore the items within these bins have predetermined arrival and departure times, whereas powders distributed over silos do not necessarily have this, as a percentage of the incoming powder is used and not all of it. Furthermore in the dynamic case, the algorithm does not know which item arrives at what time.

Related to the DBPP, is also the multi-period bin packing problem. In the multi-period BPP, all the items can also stay longer within certain bins, however this is known beforehand. One of the variations on this problem is the multi-period variable sized and variable cost bin packing problem [12] [13], where the bins have different sizes and different costs. However, these formulations do not take conflicts and item fragmentation into consideration.

When looking at the situation at Nestlé with determining the sizes of the silos and the powder storage, the following BPP variation would be necessary: MPVSBPPC-IF. This is multi period, as the the amount of powders stored throughout the year differs. It would also be variable sized as the optimal silo sizes depend on the amount of powder stored. Next to this there are item conflicts as not all items can be stored in the same silo at the same time. Finally since the powders are bulk goods, these can be divided over multiple silos. Hence, the problem also has item fragmentation.

5.5. Similar problems in different industries

As mentioned in the Introduction, Hvattum [32] has developed a model for determining the distribution of liquids within the hulls in a set of ships, taking weight distribution as well as compatibility into account. This model does not try to minimise the used storage space, since this is predetermined when building a ship and it only checks if it is feasible to store all items within the ships route.

Within the maritime industry this is often referred to as the tank allocation problem (TAP). It is used to see if a specific sailing route for a ship is feasible given the cargo it has to pick up and deliver on the route. The first simple variant of the TAP has been introduced by Vouros [70], but it only describes the approach. Related to this is the tramp ship problem by Fagerholt [23], where a cargo hold can be partitioned into smaller holds. Finally Vilhelmsen [69] continues on Hvattums work by developing a heuristic to solve the TAP faster.

However, these problems almost only focus on assigning storage space to materials, but not determining how much storage space is needed to host the materials as well. Neither do these problems focus on minimising the amount of storage used. Therefore the TAP can be seen as a variation on the BPP.

Another option is the carousel storage system [3] [40]. But carousels have fixed lengths and are afterwards divided into compartments, which is very different from designing sole silos that can only handle one material at the time. Therefore these are not very relevant.

Similar to this is a study from van Vianen [68] that creates a simulation tool for the determination of the stockyard area for a bulk import terminal. However, a stockpile doesn't need cleaning and can have multiple materials next to each other. It only looks into dividing a fixed area into multiple smaller areas to store bulk. Therefore this is also not relevant for this study.

5.6. Scientific gap

It is clear that a lot of developments have already been done on different models regarding the sizing of storage space and the division of items among this storage space. To the students knowledge, there is no published literature on the combination of the following problems: multi-period bin packing problem, variable sized bin packing problem with conflicts and item fragmentation, segregated storage problem and warehouse sizing.

The problem faced by the food processing factory can be described as a multi-period variable sized bin packing problem with conflicts and with item fragmentation (MPVSBPPC-IF), with extra constraints that resemble the SSP, TAP and warehouse sizing problem. The MPVSBPPC-IF is in itself unique as it has not been studied in the literature, while the extra constraints are specific to the situation.

The problem of the pallet storage at a third party warehouse is a simplified version of the multi-item two stage lot sizing problem. Due to the fact that it is simplified, it might be that this already exists although the extra constraints from this situation might make it unique. However, it is certainly unique when combined with the MPVSBPPCIF.

6 Model Development

This chapter will answer the following research question:

How to model and solve the conceptual designs?

This will be done by creating conceptual models first. Once the conceptual models are in place the mathematical models will be developed. For the design alternatives a couple of new models will be developed by combining the insights gained in the previous chapters to create two silo models, a pallet model and a combination of all of these.

The models that will be developed are the Pallet Movement Model (PMM), Silo Model (SM), Silo Pallet Model (SPM) and the Combined Silo Pallet Model (CSPM). The PMM will cover the case of using pallets and storing these in a third party warehouse. The SM will cover the case of only using silos to store the materials. The SPM, will cover the case of using silos but also needing pallets to transport the bigbags to the tipping stations. Finally the CSPM will consist of both the SM and PMM.

6.0.1. Conceptual models

Each concept needs to be modelled in order to be compared to the other models. The comparisons will be made on the following points, which are thus the KPIs of each model:

- Investment costs
- Handling costs
- Trucks arriving at Nestlé
- Needed area or number of pallets

The conceptual models take the following data as inputs or constraints: SAP data, powder properties data, equipment data, operations data and equipment cost data. The model will then use this to optimise the silos, pallets, cleaning times and storage policy, based on costs. Next the output will be a data overview, a cost overview as well as a storage policy that has been used.

6.0.2. PMM

The goal of this model is to optimise the implementation of storing the pallets in the rented warehouse and using a bigbag reshaper to make the pallets suitable for the AGVs. The concept will be optimised regarding costs.

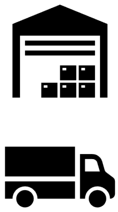


Figure 6.1: The PMM will model the flow from the rented warehouse to the factory warehouse

The PMM should do the following:
Given the daily demand, the model should determine how many pallets should arrive at the warehouse. Based on this it will determine when a pallet should be moved from the rented warehouse to the factory warehouse. This in turn results in the amount of stored pallets at the rented warehouse. The model should then try to find the cheapest solution for this.

6.0.3. SM

The goal of this model is to optimise the implementation of storing powders in silos and moving these pneumatically. The model will also be optimised regarding costs.

Figure 6.2: The SM will model the storage fluctuations of powders in different sized silos

The SM should do the following:
Given the daily supply and demand, the model should determine how many silos are needed to store all the powders and what their sizes should be. Furthermore the model should determine when to fill or empty a silo with what material. This should be done while taking hygienic constraints and infrastructure constraints into account. When this is done, the model should make sure that it is done as cheap as possible.

6.0.4. SPM

The goal of this model is to optimise the implementation of storing powders in silos and moving these pneumatically, while the powders arrive in bigbags. The model will then have to find the cheapest solution.

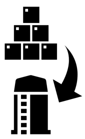


Figure 6.3: The SPM will model the storage fluctuations of powders in different sized silos

The SPM should do the same as the SM, which is the following:
Given the daily supply and demand, the model should determine how many silos are needed to store all the powders and what their sizes should be. Furthermore the model should determine when to fill or empty a silo with what material. This should be done while taking hygienic constraints and infrastructure constraints into account. When this is done, the model should make sure that it is done as cheap as possible.

6.0.5. CSPM

The goal of this model is to optimise the option of storing powders either in pallets in the rented warehouse or in silos. The model will compare the SM and PMM for each powder and determine the cheapest solution for it.

Figure 6.4: The CSPM will model the storage fluctuations of powders in different sized silos, as well as the flows between the rented warehouse and the factory warehouse

6.1. Model for the pallet storage and movements (PMM)

When creating the mathematical model for storing pallets in a third party warehouse and moving these to the factory warehouse during weekdays, the mathematical model can be modelled as 2 'dynamic' bins with costs relating to movements, pallet handling costs and storage costs. These are based on the costs structure presented by the third party logistics supplier.

The input for the model is very similar. This model will need the amount of incoming pallets of materials per day, the consumption per day as well as the pallet storing and handling costs. It will then give an output of number of pallets stored at both warehouses, number of pallets moved per day, the costs and the amount of trucks needed.

As mentioned in chapter 4, there are certain constraints that the model has to take into account. First of all, the factory does not allow any trucks to enter the facility on Saturdays and Sundays. As a truck can only handle a maximum of 24 pallets, this also has to be taken into account. The handling costs of the third party warehouse are known and are used as a basis for the transportation and handling costs. As trucks arrive on a daily basis, it would make the most sense to also make the model based on a time step of a day. Finally the handling costs of AGVs and employees have been added as well as the costs of a bigbag reshaper.

The mathematical model can be seen below and is largely based on the mathematical models presented by Barani [4] and Sitompul [62]. This model has been combined with the constraints special to the case at Nestlé as can be seen in table 6.1.

Table 6.1: Notation of the pallet movement model (PMM)

Sets and indices	
V	Sets of nodes $i \in V$ materials
T	Sets of nodes $t \in T$ time periods
W	Sets of nodes $w \in W$ weekly time periods
Parameters	
a_{it}	amount of incoming pallets of material i at time period t
p_{it}	amount of pallets requested by production of material i at time period t
ci	cost of handling an inbound pallet at third party warehouse
cs	weekly storage cost per pallet
co	cost of loading a pallet in a truck
cp	cost of handling an inbound pallet at the warehouse
ca	cost of man-hours per outgoing order in third party warehouse
ct	cost of administration per order
$cldm$	cost of full truck driving to warehouse
cot	other costs such as a palletchanger and bringing pallets to production
$I0$	initial amount of pallets stored at warehouse of material i
$pl0$	initial amount of pallets stored at third party warehouse of material i
Variables	
Pl_{it}	integer variable, amount of pallets of material i stored at third party warehouse at time period t
d_{it}	integer variable, amount of pallets of material i moving from third party warehouse to factory warehouse at time period t
I_{it}	amount of pallets of material i stored at warehouse at time period t
Plw_{iw}	integer variable, amount of pallets of material i stored at third party warehouse at time period w
Tr_t	integer variable, amount of trucks used for delivery at time period t
$maxst$	maximum amount of special pallets present in warehouse at any time

The mathematical formulation then follows as:

$$\begin{aligned} \min \quad & \sum_{i\in V}\sum_{t\in T}(ci * a_{i,t}) + \sum_{i\in V}\sum_{t\in T}(cs * a_{i,t}) + \sum_{i\in V}\sum_{w\in W}(cs * Plw_{i,w}) + \\ & \sum_{i\in V}\sum_{t\in T}((co + cp) * d_{i,t}) + \sum_{t\in T}((ct + ca + cldm) * Tr_t + cot \end{aligned} \tag{6.1}$$

Subject to:

$$PL_{i,t} = plo_i + a_{i,t} - d_{i,t} \qquad \forall i \in V, t = 0 \tag{6.2}$$

$$Pl_{i,t} = Pl_{i,t-1} + a_{i,t} - d_{i,t} \qquad \forall i \in V, t \in \{1, T\} \tag{6.3}$$

$$I_{i,t} = I0_i + d_{i,t} - p_{i,t} \qquad \forall i \in V, t = 0 \tag{6.4}$$

$$I_{i,t} = I_{i,t-1} + d_{i,t} - p_{i,t} \qquad \forall i \in V, t \in \{1, T\} \tag{6.5}$$

$$Plw_{i,w} = Pl_{i,w*7} \qquad \forall i \in V, w \in W \tag{6.6}$$

$$\sum_{i\in V} d_{i,t} \leq 24 * Tr_t \qquad \forall t \in T \tag{6.7}$$

$$d_{i,t} = 0 \qquad \forall i \in V, t \in \{(t \mod 7 = 3 \vee 4)\} \tag{6.8}$$

$$maxst \geq \sum_{i \in V} (I0_i + d_{i,t}) \qquad t = 0 \tag{6.9}$$

$$maxst \geq \sum_{i \in V} (I_{i,t-1} + d_{i,t}) \qquad \forall t \in \{1, T\} \tag{6.10}$$

$$Pl_{i,t} \geq 0 \qquad \forall i \in V, t \in T \tag{6.11}$$

$$Plw_{i,w} \geq 0 \qquad \forall i \in V, w \in W \tag{6.12}$$

$$I_{i,t} \geq 0 \qquad \forall i \in V, t \in T \tag{6.13}$$

$$d_{i,t} \geq 0 \qquad \forall i \in V, t \in T \tag{6.14}$$

$$Tr_t \geq 0 \qquad \forall t \in T \tag{6.15}$$

Objective function 6.1 aims on minimising the storage costs of the pallets, the inbound costs of the pallets, the outbound costs of the pallets and the handling costs at the warehouse. This cost function is based on the material handling costs as been sent by the third party warehouse.

Constraints 6.2, 6.3, 6.4 and 6.5 model the inventory of both the warehouses. However it is important to note that $I_{i,t}$ is continuous, whereas $Pl_{i,t}$ is an integer due to the fact that the warehouse can store half used pallets and the third party warehouse cannot. Constraint 6.6 refers to the stock at the beginning of each week and is used purely since this is how the costs are built up.

Next constraint 6.7 models the amount of trucks driving to the warehouse, while assuming that these can take 24 pallets. Constraint 6.8 is special as it makes sure that no pallets will be delivered during the weekends as this is not allowed at the factory. Constraints 6.9 and 6.10 model the maximum amount of pallets that are being used within the warehouse. This situation assumes the worst situation where pallets arrive first before any are send to production. This constraint does not change anything for the model, but is purely there to know what the maximum of stored pallets is. If the goal is to minimise the amount of pallets stored at the warehouse, this can be used to change the objective function.

6.2. Silo model (SM)

The silo model will optimise for silo storage if the powders arrive in bulk. The silo model will need the powder consumption in cubic meters, the arrival of the powders as well as the costs as inputs. This will allow a mathematical solver to find the optimal solution. The silo model should then give an overview of how many silos are being used, what powder is in what silo at what time, the sizes of the silos as well as the costs of implementing them.

It will also have to take the considerations of chapter 4 into account, such as the cleaning time of 1 day, the material incompatibilities, blower constraints and costs of piping, sensors and explosion suppression mechanisms.

6.2.1. Combination of existing BPP models

The variable sized bin packing problem with item fragmentation and conflicts (VSBPPC-IF) is a good starting point for the silo model and has been formulated as a MIP in the following way by Ekici [20]:

Table 6.2: Notation of the variable sized bin packing problem with item fragmentation and conflicts problem

Sets and indices	
V	Sets of nodes $i \in V$ materials
E	Sets of nodes $i, j \in E$ incompatible materials
U	Sets of nodes $u \in U$ bins
k	Sets of nodes $k \in B$ bin types
Parameters	
C_k	cost per bin type k
w_i	total weight of material i
W_k	Size of bin k or weight that bin k can accommodate
Variables	
f_{iu}	amount of material i packed into bin u
x_{iu}	binary variable, 1 if material i is packed into bin u and 0 otherwise
y_{uk}	binary variable, 1 if bin u is of type k and 0 otherwise

The mathematical formulation then follows as:

$$\min \quad \sum_{u \in U} \sum_{k \in B} C_k y_{uk} \tag{6.16}$$

Subject to:

$$\sum_{i \in V} f_{iu} \leq \sum_{k \in B} W_k y_{uk} \qquad \forall u \in U \tag{6.17}$$

$$\sum_{u \in U} f_{iu} = w_i \qquad \forall i \in V \tag{6.18}$$

$$f_{iu} \leq w_i x_{iu} \qquad \forall i \in V, u \in U \tag{6.19}$$

$$\sum_{k \in B} y_{uk} \leq 1 \qquad \forall u \in U \tag{6.20}$$

$$x_{iu} + x_{ju} \leq \sum_{k \in B} y_{uk} \qquad \forall i \in E, j \in E, u \in U \tag{6.21}$$

$$\sum_{i \in V} f_{i,u} \leq \sum_{i \in V} f_{i,u-1} \qquad \forall u \in U \tag{6.22}$$

$$x_{iu} \leq \sum_{k \in B} y_{uk} \qquad \forall i \in V, u \in U \tag{6.23}$$

$$x_{iu} \in \{0, 1\} \qquad \forall i \in V, u \in U \tag{6.24}$$

$$y_{uk} \in \{0, 1\} \qquad \forall u \in U, k \in B \tag{6.25}$$

$$f_{iu} \geq 0 \qquad \forall i \in V, u \in U \tag{6.26}$$

Equation 6.16 is the objective function and aims to minimise the total costs of the bins used. The capacity of the bins is constrained by equation 6.17 since the sum of items packed into a bin cannot be bigger than the size of the bin.

The sum of the number of fragments of item i always have to be equal to its weight as can be seen in equation 6.18. Related to this equation 6.19 makes sure that no more than the total weight of an item can be stored in a single bin. Equation 6.20 determines that each bin can only be of 1 type.

Equation 6.21 introduces a new set E, which is a subset of V containing incompatible materials. This equation thus guarantees that incompatible items cannot be stored in the same bin.

The next two equations are redundant constraints. Equation 6.22 resolves symmetry problem along the bins, by arranging the bins in order to their contents. Equation 6.23 forces bin usage if an item is packed in it. The remaining equations 6.24, 6.25 and 6.26 restrict the decision variables.

Creating the MVSBPPC-IF

In order to make this problem multi period, the formulation of items entering and leaving the model has to be added. This can be done by adding set T which contains multiple time periods t.

Table 6.3: Notation of the multi period variable sized bin packing problem with item fragmentation and conflicts problem

Sets and indices	
V	Sets of nodes $i \in V$ materials
E	Sets of nodes $i, j \in E$ incompatible materials
U	Sets of nodes $u \in U$ bins
k	Sets of nodes $k \in B$ bin types
t	Sets of nodes $t \in T$ time periods
Parameters	
C_k	cost per bin type k
W_k	Size of bin k or weight that bin k can accommodate
w_{it}	total weight of material i at time period t
Variables	
f_{iut}	amount of material i packed into bin u at time period t
x_{iut}	binary variable, 1 if material i is packed into bin u at time period t and 0 otherwise
y_{ukt}	binary variable, 1 if bin u is of type k at time period t and 0 otherwise

The mathematical formulation then follows as:

$$\min \quad \sum_{u \in U} \sum_{k \in B} \sum_{t \in T} C_k y_{ukt} \tag{6.27}$$

Subject to:

$$\sum_{i \in V} f_{iut} \leq \sum_{k \in B} W_k y_{ukt} \qquad \forall u \in U, t \in T \tag{6.28}$$

$$\sum_{u \in U} f_{iut} = w_{it} \qquad \forall i \in V, t \in T \tag{6.29}$$

$$f_{iut} \leq w_{it} x_{iut} \qquad \forall i \in V, u \in U, t \in T \tag{6.30}$$

$$\sum_{k \in B} y_{ukt} \leq 1 \qquad \forall u \in U, t \in T \tag{6.31}$$

$$x_{iut} + x_{jut} \leq \sum_{k \in B} y_{ukt} \qquad \forall i \in E, j \in E, u \in U, t \in T \tag{6.32}$$

$$\sum_{i \in V} f_{i,u,t} \leq \sum_{i \in V} f_{i,u-1,t} \qquad \forall u \in U \tag{6.33}$$

$$x_{iut} \leq \sum_{k \in B} y_{ukt} \qquad \forall i \in V, u \in U, t \in T \tag{6.34}$$

$$x_{i,u,t-1} + x_{j,u,t} \leq 1 \qquad \forall i \in E, j \in E, u \in U, t \in \{1, T\} \tag{6.35}$$

$$x_{iut} \in \{0, 1\} \qquad \forall i \in V, u \in U, t \in T \tag{6.36}$$

$$y_{ukt} \in \{0, 1\} \qquad \forall u \in U, k \in B, t \in T \tag{6.37}$$

$$f_{iut} \geq 0 \qquad \forall i \in V, u \in U, t \in T \tag{6.38}$$

(6.39)

The main difference with the work done by Ekici [20] is that the mathematical model now has a time component. Besides this, nothing much changes. However, the model does allow for repacking in this configuration as there is no restriction on inflow or outflow, as the total weight of the items has to be distributed every time.

Addition of other properties

Since the current modification of the VSBPPC-IF only made it multi period, the goal is still to minimise all the costs. This can be done by adding holding costs to each bin. Also in the case of silos, only 1 material can be present in the silo at the same time. This thus changes some of the constraints. In this model a new w_{it} determines how much of material i is present within the system and creates a so called 'flow'. This value is changed by the incoming and outgoing material, respectively a_{it} and d_{it}. This also changes how the model is build up: instead of focusing on how to divide the material over the bins, it should now focus on where to add and remove material. This is very much similar to the way that inventory is modelled in lot sizing problems such as done by Kirca [38].

Finally a new constraint has to be added, that makes sure that once a material is present in a bin, it stays within the bin. This can be done by adding a constraint, that doesn't allow for 2 materials to be put in a bin right after each other.

The silo model becomes the following:

Table 6.4: Notation of the silo model

Sets and indices	
V	Sets of nodes $i \in V$ materials
U	Sets of nodes $u \in U$ bins
k	Sets of nodes $k \in B$ bin types
t	Sets of nodes $t \in T$ time periods
Parameters	
a_{it}	amount of incoming material i at time period t
C_k	cost per bin type k
d_{it}	amount of outgoing material i at time period t
W_k	size of bin k or weight that bin k can accommodate
c	running costs of a bin
ccl	cleaning costs of a bin
$mrem$	maximum material that can be removed due to blower constraints
co	other costs of implementing silos, such as pipes and blowers
$csilo$	costs for sensors and explosion measures
Variables	
f_{iut}	amount of material i packed into bin u at time period t
x_{iut}	binary variable, 1 if material i is packed into bin u at time period t and 0 otherwise
y_{ukt}	binary variable, 1 if bin u is of type k at time period t and 0 otherwise
rem_{iut}	amount of material i that is removed from bin u at time period t
add_{iut}	amount of material i that is added to bin u at time period t
w_{it}	total weight of material i at time period t
cl_{ut}	binary variable, 1 if bin u is cleaned at time period t and 0 otherwise

The mathematical formulation then follows as:

$$\begin{aligned}\min \quad & \sum_{u\in U}\sum_{k\in B} C_k y_{ukt} + \sum_{i\in V}\sum_{u\in U}\sum_{t\in T} c * x_{iut} + \\ & \sum_{u\in U}\sum_{t\in T} ccl * cl_{ut} + \sum_{u\in U}\sum_{k\in B} csilo * y_{u,k,t} + co \end{aligned} \tag{6.40}$$

Subject to:

$$\sum_{u\in U} rem_{i,u,t} = d_{i,t} \qquad \forall i \in V, t \in T \tag{6.41}$$

$$\sum_{u\in U} add_{i,u,t} = a_{i,t} \qquad \forall i \in V, t \in T \tag{6.42}$$

$$f_{i,u,t} = -rem_{i,u,t} + add_{i,u,t} \qquad \forall i \in V, u \in U, t = 0 \qquad (6.43)$$

$$f_{i,u,t} = f_{i,u,t-1} - rem_{i,u,t} + add_{i,u,t} \qquad \forall i \in V, u \in U, t \in \{1, T\} \qquad (6.44)$$

$$\sum_{i \in V} f_{iut} \leq \sum_{k \in B} (W_k * y_{ukt}) \qquad \forall u \in U, t \in T \qquad (6.45)$$

$$\sum_{u \in U} f_{iut} = w_{it} \qquad \forall i \in V, t \in T \qquad (6.46)$$

$$f_{iut} \leq w_{it} x_{iut} \qquad \forall i \in V, u \in U, t \in T \qquad (6.47)$$

$$\sum_{k \in B} y_{ukt} \leq 1 \qquad \forall u \in U, t \in T \qquad (6.48)$$

$$\sum_{i \in V} x_{iut} \leq \sum_{k \in B} y_{ukt} \qquad \forall i \in V, u \in U, t \in T \qquad (6.49)$$

$$x_{iut} \leq \sum_{k \in B} y_{ukt} \qquad \forall i \in V, u \in U, t \in T \qquad (6.50)$$

$$y_{u,k,t} \leq y_{u,k,t+1} \qquad \forall i \in V, u \in U, t \in \{0, T-1\} \qquad (6.51)$$

$$a_{i,t} - d_{i,t} = w_{i,t} \qquad \forall i \in V, t = 0 \qquad (6.52)$$

$$a_{i,t} + w_{i,t-1} - d_{i,t} = w_{i,t} \qquad \forall i \in V, t \in \{1, T\} \qquad (6.53)$$

$$x_{i,u,t-1} + x_{j,u,t} \leq 1 \qquad \forall i \in V, j \in V, u \in U, t \in \{1, T\} \qquad (6.54)$$

$$\sum_{k \in B} (W_k * y_{ukt}) \leq \sum_{k \in B} (W_k * y_{u-1,k,t}) \qquad \forall u \in \{1, U\}, t \in T \qquad (6.55)$$

$$\sum_{i \in V} \sum_{u \in U} rem_{iut} \leq mrem \qquad \forall t \in T \qquad (6.56)$$

$$\sum_{i \in V} (x_{i,u,t-1} - x_{i,u,t}) \leq cl_{u,t} \qquad \forall u \in U, t \in \{1, T\} \qquad (6.57)$$

$$x_{iut} \in \{0, 1\} \qquad \forall i \in V, u \in U, t \in T \qquad (6.58)$$

$$y_{ukt} \in \{0, 1\} \qquad \forall u \in U, k \in B, t \in T \qquad (6.59)$$

$$f_{iut} \geq 0 \qquad \forall i \in V, u \in U, t \in T \qquad (6.60)$$

$$rem_{iut} \geq 0 \qquad \forall i \in V, u \in U, t \in T \qquad (6.61)$$

$$add_{iut} \geq 0 \qquad \forall i \in V, u \in U, t \in T \qquad (6.62)$$

$$cl_{ut} \in 0, 1 \qquad \forall u \in U, t \in T \qquad (6.63)$$

In this new formulation 6.40 also takes the running costs of storing materials within a silo into account as well as the costs for cleaning a silo. In this model the assumption has been made that once a bin is used, it will always be active, as in most applications one cannot easily add bins or remove them. Therefore a constraint has been added that guarantees this, as well as that it makes sure that a bin cannot change its type. This can be seen in equation 6.51.

As the current amount of material present in the system now depends on the incoming and outgoing material. This incoming and outgoing material then has to be divided over the present bins. Therefore equation 6.41, makes sure that the amount of outgoing material of all the silos is equal to the demand. While equation 6.42 makes sure that the incoming material is divided over the silos.

The current amount of material in a bin is determined by what was inside a moment ago as well as what is added to it and removed from it, as can be seen in equations 6.43 and 6.44. In the case of $t = 0$ there is no prior amount of material in the silo, so this is taken into account by adding the initial stock to the incoming material at the start. Most of the other constraints are fairly similar to the model presented by Ekici. However, equation 6.30 has been dropped as demand may be cyclical which is in conflict with this constraint.

Another equation that is needed, is the relation to time for the problem. With this relation, the varying incoming and outgoing materials are related to the amount of material that is present within the bins. Therefore parameter $w_{i,t}$, becomes a 'normal' variable, as can be seen in equation 6.52 and 6.53.

Constraint 6.54 makes sure, that different materials cannot be stored right after each other. Constraint 6.55 is a symmetry constraint that reduces the amount of possible silo configurations and makes the model run faster. Constraint 6.56 makes sure that the total outflow of the materials is limited to certain blower settings. This constraint can also be modified such that the outflow per silo is restricted. Constraint 6.57 defines that a bin should be cleaned when a it is completely emptied.

6.2.2. Mathematical complexity

Ekici has proven that the variable sized bin packing problem with conflicts and item fragmentation (VSBPPC-IF) is NP hard, since it is a generalised version of the bin packing problem with conflicts and item fragmentation [20] [19].

Hvattum proves that the tank allocation problem (TAP) is generalisation of the single instant tank allocation problem (SITAP) [32]. The TAP is a multi period version of the SITAP and is therefore a generalisation of the SITAP. Using this reasoning, the MPVSBPPC-IF is a generalisation of the VSBPPC-IF and is therefore also NP hard.

The implication of this is that as the SM model will use more inputs, variables and/or parameters, the time to find the optimal solution will grow exponentially. Although this is not proven to be NP-hard, it is very likely NP-hard. This means that if possible, the model should be kept as small as possible. If not, a heuristic method should be proposed in order to solve the model. As there are many extra constraints due to the material incompatibilities and hygienic regulations, the choice has been made to not to do this. Since the extra constraints will already greatly reduce the number of possibilities.

6.2.3. Silo model with pallets (SPM)

In case the powders cannot be delivered in bulk, these have to be delivered to the warehouse in bigbags. These bigbags will then be put onto special pallet by an extra palletchanger and then transported immediately to the tipping stations. From here the materials will be transported to the correct silo to be stored. In this case the model will need some extra parameters and constraints. In this case, the extra output compared to the silo model (SM), the silo model with pallets (SPM) also determines how many pallets have to be stored. Furthermore there are extra costs due to the bigbag reshaper, pallet handling costs and the extra piping that is needed.

The silo model with pallets becomes the following:

Table 6.5: Notation of the silo model with pallets

Sets and indices	
V	Sets of nodes $i \in V$ materials
U	Sets of nodes $u \in U$ bins
B	Sets of nodes $k \in B$ bin types
T	Sets of nodes $t \in T$ time periods
Parameters	
a_{it}	amount of incoming material i at time period t
ap_i	amount of pallets per cubic meter of material i
C_k	cost per bin type k
d_{it}	amount of outgoing material i at time period t
W_k	size of bin k or weight that bin k can accommodate
c	running costs of a bin
ccl	cleaning costs of a bin
$mrem$	maximum amount of material that can be removed due to blower constraints
$madd$	maximum amount of material that can be added due to blower constraints
co	other costs such as piping and a bigbag reshaper
$csilo$	costs for sensors and explosion measures
Variables	
f_{iut}	amount of material i packed into bin u at time period t
x_{iut}	binary variable, 1 if material i is packed into bin u at time period t and 0 otherwise
y_{ukt}	binary variable, 1 if bin u is of type k at time period t and 0 otherwise
rem_{iut}	amount of material i that is removed from bin u at time period t
add_{iut}	amount of material i that is added to bin u at time period t
w_{it}	total weight of material i at time period t
cl_{ut}	binary variable, 1 if bin u is cleaned at time period t and 0 otherwise
$maxst$	maximum amount of pallets present within the warehouse at any time

The mathematical formulation then follows as:

$$\min \quad \sum_{u\in U}\sum_{k\in B} C_k y_{ukt} + \sum_{i\in V}\sum_{u\in U}\sum_{t\in T} c * x_{iut} + \sum_{u\in U}\sum_{t\in T} ccl * cl_{ut} + \sum_{u\in U}\sum_{k\in B} csilo * y_{u,k,t} + co \tag{6.64}$$

Subject to:

$$\sum_{u\in U} rem_{i,u,t} = d_{i,t} \qquad \forall i \in V, t \in T \tag{6.65}$$

$$\sum_{u\in U} add_{i,u,t} = a_{i,t} \qquad \forall i \in V, t \in T \tag{6.66}$$

$$f_{i,u,t} = -rem_{i,u,t} + add_{i,u,t} \qquad \forall i \in V, u \in U, t = 0 \tag{6.67}$$

$$f_{i,u,t} = f_{i,u,t-1} - rem_{i,u,t} + add_{i,u,t} \qquad \forall i \in V, u \in U, t \in \{1, T\} \tag{6.68}$$

$$\sum_{i\in V} f_{iut} \leq \sum_{k\in B} (W_k * y_{ukt}) \qquad \forall u \in U, t \in T \tag{6.69}$$

$$\sum_{u\in U} f_{iut} = w_{it} \qquad \forall i \in V, t \in T \tag{6.70}$$

$$f_{iut} \leq w_{it} x_{iut} \qquad \forall i \in V, u \in U, t \in T \tag{6.71}$$

$$\sum_{k\in B} y_{ukt} \leq 1 \qquad \forall u \in U, t \in T \tag{6.72}$$

$$\sum_{i\in V} x_{iut} \leq \sum_{k\in B} y_{ukt} \qquad \forall i \in V, u \in U, t \in T \tag{6.73}$$

$$x_{iut} \leq \sum_{k \in B} y_{ukt} \qquad \forall i \in V, u \in U, t \in T \qquad (6.74)$$

$$y_{u,k,t} \leq y_{u,k,t+1} \qquad \forall i \in V, u \in U, t \in \{0, T-1\} \qquad (6.75)$$

$$a_{i,t} - d_{i,t} = w_{i,t} \qquad \forall i \in V, t = 0 \qquad (6.76)$$

$$a_{i,t} + w_{i,t-1} - d_{i,t} = w_{i,t} \qquad \forall i \in V, t \in \{1, T\} \qquad (6.77)$$

$$x_{i,u,t-1} + x_{j,u,t} \leq 1 \qquad \forall i \in V, j \in V, u \in U, t \in \{1, T\} \qquad (6.78)$$

$$\sum_{k \in B} (W_k * y_{ukt}) \leq \sum_{k \in B} (W_k * y_{u-1,k,t}) \qquad \forall u \in \{1, U\}, t \in T \qquad (6.79)$$

$$\sum_{i \in V} \sum_{u \in U} rem_{iut} \leq mrem \qquad \forall t \in T \qquad (6.80)$$

$$\sum_{i \in V} \sum_{u \in U} add_{iut} \leq madd \qquad \forall t \in T \qquad (6.81)$$

$$\sum_{i \in V} (x_{i,u,t-1} - x_{i,u,t}) \leq cl_{u,t} \qquad \forall u \in U, t \in \{1, T\} \qquad (6.82)$$

$$\sum_{i \in V} (a_{it} * ap_i) \leq maxst \qquad \forall t \in T \qquad (6.83)$$

$$x_{iut} \in \{0, 1\} \qquad \forall i \in V, u \in U, t \in T \qquad (6.84)$$

$$y_{ukt} \in \{0, 1\} \qquad \forall u \in U, k \in B, t \in T \qquad (6.85)$$

$$f_{iut} \geq 0 \qquad \forall i \in V, u \in U, t \in T \qquad (6.86)$$

$$rem_{iut} \geq 0 \qquad \forall i \in V, u \in U, t \in T \qquad (6.87)$$

$$add_{iut} \geq 0 \qquad \forall i \in V, u \in U, t \in T \qquad (6.88)$$

$$cl_{ut} \in \{0, 1\} \qquad \forall u \in U, t \in T \qquad (6.89)$$

$$maxst \geq 0 \qquad (6.90)$$

The new addition to the objective function 6.64 makes sure that the costs of the extra special pallets are also taken into account. Parameter ap_i makes sure that the incoming raw materials are recognised as pallets. Constraint 6.81 makes sure that the blower parameters are taken into account for the incoming materials. Finally constraint 6.83 makes sure that the maximum of pallets that arrive on a single day are available in special pallets, such that the AGVs can handle all the pallets.

6.3. Combination of silo and pallet models (CSPM)

When combining the models for silo storage and pallet storage, it is important to note that a material can either be stored in a silo via bulk transport or on pallets within the third party warehouse. It is not possible to have both at the same time or at any time at all. This could either be done by hand, determining what materials should be stored at which place and by running the models separately. If this has to be done via the combined silo pallet model, the model should be able to make the choice which items will be stored within the silos and which items not. As well as knowing which materials are compatible to be stored in the same silo. Therefore some new decision variables are needed as well as some new constraints.

The model takes the the production and arrival of materials in cubic meters as well as some constraints as input, to then determine the costs of storing a material either in silos or in pallets. This will be the main new output, as well as all the outputs mentioned for the previous models. The formulation of the model can be seen below:

Table 6.6: Notation of the combined silo pallet model

Sets and indices	
V	Sets of nodes $i \in V$ materials
U	Sets of nodes $u \in U$ bins
B	Sets of nodes $k \in B$ bin types
T	Sets of nodes $t \in T$ time periods
W	Sets of nodes $r \in W$ weekly time periods
Parameters	
a_{it}	amount of incoming material i at time period t
C_k	cost per bin type k
d_{it}	amount of outgoing material i at time period t
Ws_k	size of bin k or weight that bin k can accommodate
c	running costs of a bin
ccl	cleaning costs of a bin
$mrem$	maximum material that can be removed due to blower constraints
ap_i	amount of pallets per kg of material i
ci	cost of handling an inbound pallet at third party warehouse
cs	weekly storage cost per pallet
co	cost of loading a pallet in a truck
ca	cost of man-hours per outgoing order
ct	cost of administration per order
$cldm$	cost of full truck driving to warehouse
cp	cost of handling an inbound pallet at the warehouse
$incomp_{i,j}$	incompatibility of materials i and j, 1 if materials are incompatible and 0 otherwise
M	big number
cot	other costs such as piping and a bigbag reshaper
$csilo$	costs for sensors and explosion measures
$I0$	initial amount of pallets of material i stored at warehouse
$pl0$	initial amount of pallets stored at third party warehouse of material i
Variables	
f_{iut}	amount of material i packed into bin u at time period t
x_{iut}	binary variable, 1 if material i is packed into bin u at time period t and 0 otherwise
y_{ukt}	binary variable, 1 if bin u is of type k at time period t and 0 otherwise
rem_{iut}	amount of material i that is removed from bin u at time period t
add_{iut}	amount of material i that is added to bin u at time period t
w_{it}	total weight of material i at time period t
cl_{ut}	binary variable, 1 if bin u is cleaned at time period t and 0 otherwise
Pl_{it}	integer variable, amount of pallets of material i stored at third party warehouse at time period t
dp_{it}	integer variable, amount of pallets of material i moving from third party warehouse to factory warehouse at time period t
I_{it}	amount of pallets of material i stored at warehouse at time period t
Plw_{ir}	integer variable, amount of pallets of material i stored at third party warehouse at time period w
Tr_t	integer variable, amount of trucks used for delivery at time period t
$maxst$	maximum amount of pallets present in warehouse at any time
xp_i	binary value, 1 if material i will be handled in pallets and 0 otherwise
xs_i	binary value, 1 if material i will be handled in silos and 0 otherwise
$add0_{iu}$	amount of material i that are already present in silo u
sm_{iu}	binary value, 1 if material i has been present in silo u

$$\min \sum_{u\in U}\sum_{k\in B} C_k y_{ukt} + \sum_{i\in V}\sum_{u\in U}\sum_{t\in T} c * x_{iut} +$$
$$\sum_{u\in U}\sum_{t\in T} ccl * cl_{ut} + \sum_{i\in V}\sum_{t\in T}(ci * ap_i * xp_i * a_{i,t}) +$$
$$\sum_{i\in V}\sum_{t\in T}(cs * ap_i * xp_i * a_{i,t}) + \sum_{i\in V}\sum_{r\in W}(cs * Plw_{i,r}) +$$
$$\sum_{i\in V}\sum_{t\in T}((co + cp) * dp_{i,t}) + cot +$$
$$\sum_{t\in T}((ct + ca + cldm + clc) * Tr_t + \sum_{u\in U}\sum_{k\in B} y_{u,k,t} * csilo \tag{6.91}$$

Subject to:

$$\sum_{u\in U}(rem_{i,u,t}) = xs_i * d_{i,t} \qquad \forall i \in V, t \in T \tag{6.92}$$

$$\sum_{u\in U}(add_{i,u,t}) = xs_i * a_{i,t} \qquad \forall i \in V, t \in T \tag{6.93}$$

$$f_{i,u,t} = -rem_{i,u,t} + add_{i,u,t} \qquad \forall i \in V, u \in U, t = 0 \tag{6.94}$$

$$f_{i,u,t} = f_{i,u,t-1} - rem_{i,u,t} + add_{i,u,t} \qquad \forall i \in V, u \in U, t \in \{1, T\} \tag{6.95}$$

$$\sum_{i\in V} f_{iut} \leq \sum_{k\in B}(W_k * y_{ukt}) \qquad \forall u \in U, t \in T \tag{6.96}$$

$$\sum_{u\in U} f_{iut} = w_{it} * xs_i \qquad \forall i \in V, t \in T \tag{6.97}$$

$$f_{iut} \leq w_{it} x_{iut} \qquad \forall i \in V, u \in U, t \in T \tag{6.98}$$

$$\sum_{k\in B} y_{ukt} \leq 1 \qquad \forall u \in U, t \in T \tag{6.99}$$

$$\sum_{i\in V} x_{iut} \leq \sum_{k\in B} y_{ukt} \qquad \forall i \in V, u \in U, t \in T \tag{6.100}$$

$$x_{iut} \leq \sum_{k\in B} y_{ukt} \qquad \forall i \in V, u \in U, t \in T \tag{6.101}$$

$$y_{u,k,t} \leq y_{u,k,t+1} \qquad \forall i \in V, u \in U, t \in \{0, T-1\} \tag{6.102}$$

$$a_{i,t} - d_{i,t} = w_{i,t} \qquad \forall i \in V, t = 0 \tag{6.103}$$

$$a_{i,t} + w_{i,t-1} - d_{i,t} = w_{i,t} \qquad \forall i \in V, t \in \{1, T\} \tag{6.104}$$

$$x_{i,u,t-1} + x_{j,u,t} \leq 1 \qquad \forall i \in V, j \in V, u \in U, t \in \{1, T\} \tag{6.105}$$

$$\sum_{k \in B}(W_k * y_{ukt}) \leq \sum_{k \in B}(W_k * y_{u-1,k,t}) \qquad \forall u \in \{1, U\}, t \in T \tag{6.106}$$

$$\sum_{i \in V}\sum_{u \in U} rem_{iut} \leq mrem \qquad \forall t \in T \tag{6.107}$$

$$\sum_{i \in V}(x_{i,u,t-1} - x_{i,u,t}) \leq cl_{u,t} \qquad \forall u \in U, t \in \{1, T\} \tag{6.108}$$

$$Pl_{i,t} = pl0_i + a_{i,t} * xp_i - dp_{i,t} \qquad \forall i \in V, t = 0 \tag{6.109}$$

$$Pl_{i,t} = Pl_{i,t-1} + a_{i,t} * xp_i - dp_{i,t} \qquad \forall i \in V, t \in \{1, T\} \tag{6.110}$$

$$Ii,t = I0_i + dp_{i,t} - xp_i * d_{i,t} \qquad \forall i \in V, t = 0 \tag{6.111}$$

$$Ii,t = I_{i,t-1} + dp_{i,t} - xp_i * d_{i,t} \qquad \forall i \in V, t \in \{1, T\} \tag{6.112}$$

$$Plw_{i,r} = Pl_{i,r*7} \qquad \forall i \in V, r \in W \tag{6.113}$$

$$\sum_{i \in V} dp_{i,t} \leq 24 * Tr_t \qquad \forall t \in T \tag{6.114}$$

$$dp_{i,t} = 0 \qquad \forall i \in V, t \in \{(t \mod 7 = 3 \vee 4)\} \tag{6.115}$$

$$maxst \geq \sum_{i \in V} I0_i + dp_{i,t} \qquad \forall t = 0 \tag{6.116}$$

$$maxst \geq \sum_{i \in V} I_{i,t-1} + dp_{i,t} \qquad \forall t \in \{1, T\} \tag{6.117}$$

$$xp_i + xsi = 1 \qquad \forall i \in V \tag{6.118}$$

$$sm_{iu} * M \geq \sum_{t \in T} x_{iut} \qquad \forall i \in V, u \in U \tag{6.119}$$

$$sm_{iu} * incomp_{i,j} + sm_{ju} * incomp_{j,i} \leq 1 \qquad \forall i, j \in V, u \in U \tag{6.120}$$

$$x_{iut} \in \{0, 1\} \qquad \forall i \in V, u \in U, t \in T \tag{6.121}$$

$$y_{ukt} \in \{0, 1\} \qquad \forall u \in U, k \in B, t \in T \tag{6.122}$$

$$f_{iut} \geq 0 \qquad \forall i \in V, u \in U, t \in T \tag{6.123}$$

$$rem_{iut} \geq 0 \qquad \forall i \in V, u \in U, t \in T \tag{6.124}$$

$$add_{iut} \geq 0 \qquad \forall i \in V, u \in U, t \in T \tag{6.125}$$

$$cl_{ut} \in \{0, 1\} \qquad \forall u \in U, t \in T \tag{6.126}$$

$$Pl_{i,t} \geq 0 \qquad \forall i \in V, t \in T \tag{6.127}$$

$$Plw_{i,w} \geq 0 \qquad \forall i \in V, w \in W \tag{6.128}$$

$$I_{i,t} \geq 0 \qquad \forall i \in V, t \in T \tag{6.129}$$

$$dp_{i,t} \geq 0 \qquad \forall i \in V, t \in T \tag{6.130}$$

$$Tr_t \geq 0 \qquad \forall t \in T \tag{6.131}$$

$$xs_i \in \{0,1\} \qquad \forall i \in V \tag{6.132}$$

$$xp_i \in \{0,1\} \qquad \forall i \in V \tag{6.133}$$

$$sm_{i,u} \in \{0,1\} \qquad \forall i \in V, u \in U \tag{6.134}$$

In this combined model a couple of extra constraints have been added, while a few have been modified. The most important are the variables xp_i and xs_i, that allow for a material to be either used in pallets or in silos. This has been added in constraints 6.93 and 6.118. Also the addition of ap_i to constraints 6.92 and 6.93 allows for the materials to be either in pallets or not. Finally constraints6.119 and 6.120 determine that if a material has been put in a silo, this silo has been made specifically for this material, and other materials cannot go into the same silo later on.

In the case that the materials cannot be delivered in bulk, but have to be stored in silos, constraints 6.116 and 6.117 changes to become the following:

$$maxst \geq \sum_{i \in V}(I0_i + dp_{i,t} + ap_i * add_{i,t}) \tag{6.135}$$

$$maxst \geq \sum_{i \in V}(I_{i,t-1} + dp_{i,t} + ap_i * add_{i,t}) \tag{6.136}$$

In this case the amount of special pallets needed changes with the extra incoming pallets via the trucks.

6.4. Conclusion

This chapter has seen the development of multiple mathematical models that try to replicate the processes of the proposed solutions in chapter 2. Before these were presented, a conceptual models have been made, on which the mathematical models are based. For each process a model has been developed that tries to have as many constraints as necessary to relate it to the real world, while also building on mathematical models that have already been described in literature. The results are the following five optimisation models: PMM, SM, SPM and the CSPM. Each model can be used to model a possible solution and will give an expected costs and storage policy which can then be compared to the other models in order to find the optimal solution for Nestlé.

7

Verification and validation

Before the silo model (SM), the silo model with pallets (SPM), the pallet model (PMM) and the combined model (CSPM) can be implemented in a case study, it is important to conduct a series of tests to determine whether the models are implemented correctly and are generating the expected results. Therefore this chapter will focus on exactly that, by answering the following research question:

Are the developed models an accurate representation of the design alternatives?

Model verification focuses on the question: 'Is my model right?', while validation focuses on 'Do I have the right model?' [58] [39]. When the models behave as was intended and these comply with the problem description, the verification and validation steps are completed. After this, the models can be put into practice in the case study.

7.1. Sample data and parameters

For the verification of the models, a sample data set is needed. This has been done using a random function in Excel. The data represents the incoming and outgoing amounts of materials in kg or pallets or any other value. As can be seen in table D.1, the materials have one fairly constant material, one fluctuating material and one growing material for 30 time periods.

For the silos and their sizes also sample sizes and costs have been made, as can be seen in table D.2:

Silo model (SM)

When choosing the base case for the verification model, some extra parameters are needed. Such as the number of silos, the cleaning costs and the holding and or setup costs. The number of materials is 3 and the number of silo types is 7. The maximum amount of silos is 6. The initial storage values are zero. For this case, the storage costs are 10 and the cleaning costs are 100. The other costs are 0. In case of the SPM, the pallet handling costs are put to 5.

Pallet movement model (PMM)

For the PMM, the initial storage at the third party warehouse and the warehouse are set to zero. the inbound costs, storage costs and outbound costs are set to 1. The truck related costs are all set to 10. The pallet handling costs are set to 5.

Combined silo pallet movement model (CSPPM)

For this model the same parameters are used as described in the models above. The materials are compatible.

7.2. Verification cases

The applied verification techniques are initially developed for simulation models [58] [39], but due to the lack of specialised verification techniques for optimisation models, the most relevant of these will be applied. The following has been tested and checked for each model:

1. **Input check:** the input data should always result in a stock equal or greater than zero. Also the powder density and volume, should be coupled to the pallet sizes. This has been done for every model and these values are correct. The solving algorithm sometimes places minuscule powder amount in non-active silos, but this is due to the solvers approximation means. These outputs can thus be ignored and they do not impact the results.
2. **Continuity test:** this test encompasses the model runs with slight change in input factors, costs capacity factors and demand needs (up to 5%). The findings here are that the models continue to generate output under the 5% parameter change. The output does change in terms of costs and some other parameters. This will be further elaborated in chapter 6, where sensitivity analyses will be carried out on the existing data.
3. **Extreme values test:** these tests are done to see whether the models perform under extreme conditions. For this the parameter values are changed extremely. The findings here are:
   - When the silo costs become 0, more silos then needed will be used in the SM and SPM. This is because the model has no incentive to reduce the use.
   - When the cleaning costs become lower than the storage costs, it becomes feasible to clean the silos more often in the SM and SPM as storage is more expensive than cleaning. However, if no cleaning is needed, the SM and SPM will not start any cleaning.
   - When the cleaning costs become very high, the SM and SPM will keep minimal levels of inventory within a silo. This might become a problem later, but this could be solved by adding extra constraints forcing a minimal inventory in a silo or by forcing cleaning if the amount of material stored within a silo becomes lower than a certain value.
   - For the PMM, when the storage costs at the third party warehouse become huge. Almost all material will be moved to the warehouse. However, due to the transportation costs and the fact that the storage costs are calculated on a weekly basis, the inventory will not always stay as low as possible. However, clear drops can be seen at the beginning of a week when the storage costs are calculated.
   - When the pallet handling costs at the PMM become zero, more pallets are being used. However, the transportation costs still limit the amount of pallets going to the warehouse. When the costs are enormous, only the needed amount of pallets is transported.
   - For truck costs within the PMM, the trucks will be minimised if their costs are enormous. While the truck usage will grow a little if the costs are 0.
4. **Consistency checks:** a doubling in in demand and supply, also leads to a doubling in trucks used for the PMM. For the SM and SPM, more silos are being used, but these depend on the cheapest configuration. Also for the CSPM, incompatible materials will never be stored in the same silo types.
5. **Computational limits:** this will be treated later in this chapter.

In table D.3, the verification cases can be seen as well as their results. The results for the SM, SPM and PMM also apply for the CSPM as this model is a combination of the SM and PMM.

For the SM, the costs and constraints keep each other in balance. Even if one silo type becomes very cheap, the holding costs might still make it cheaper to built another silo that is more expensive. For the models including silos, it is clear that the cleaning costs can become a problem if not handled correctly. This is because the models tend to keep the silos filled just slightly when the cleaning costs become very high. Currently this is solved by having very small holding costs, making it more expensive to have multiple almost empty silos. This behaviour is not expected to give any problems during the model implementation, because at that moment, the cleaning costs will be very small compared to the silo costs. If the model would show such behaviour, it can be recognised and some parameters could be changed to solve this problem without affecting the results.

For the PMM, the weekly calculation of the storage costs has a big impact on the model as a clear drop in storage when these costs are calculated. At the end of the time periods of the model, the storage at the third party warehouse goes up. This can be explained: the final few days will not have a storage cost as these are not at the beginning of a week anymore. These costs thus become lower than the transportation costs and slightly more material is stored in the final weeks. It is therefore a good idea to possibly use a larger horizon for this model to make sure that this effect is minimal. Another option would be to have 1 or 2 extra weeks of data, such that this peak is after the relevant data.

For the CSPMM, there are so many parameters and options, such that the cheapest option will always be chosen. In case of material incompatibility the model nudges to storing the powders as pallets instead of in silos.

7.3. Computational limits

To determine the limitations of all the models, given the used computer system, multiple test cases have to be set up for each model. These test cases will have varying sizes and will help determine the limitations in solving time and memory resources before results are being generated by each model. The test-cases differ in number of materials, number of silos, number of time periods and number of silo sizes.

7.3.1. Optimality gap

Before comparing all the test cases of each model, the concept of the optimality gap has to be explained. The optimality gap (OG) is a value to measure the progress of a optimisation run from a model and therefore a common measure. The OG can be described as the difference between the current best integer solution and the current lower bound [17]. The current lower bound can be described as the optimal solution for a relaxation of the model. If the OG converges to 0, the true optimal solution of the model has been found [63].

7.3.2. Test cases

Test cases will be run for a maximum of 300 seconds and the results will be shown per model in tables D.4, D.5 and D.6.

It can be seen that the amount of powders, the amount of silos and the amount of timesteps add the most complexity to the models. Especially for the SM and CSPMM the complexity peaks at 3 materials, 10 silos, 6 silo types and 10 time periods. This can be partially explained due to the fact that for the sample data, there are the most options in this scenario. When the amount of materials increases further, the calculation time decreases due to the fewer amount of possible options. However, the amount of silos has a lower impact than expected, due to the fact that only 4 silos are used in every situation and not the maximum of 6 silos. This means that optimising from little silos to the maximum amount of used silos makes more sense than starting at a lot of silos.

Another clear reason for the growth of the optimality gap, is the fact that the MPVSBPPC-IF is NP-hard. Although the SM and SPM, are not exactly the same as the MPVSBPPC-IF, these are based on it. Therefore the assumption can be made that these models would also be NP-hard.

7.4. Validation

After verification of the models, the next step is the validation of the model. As mentioned before in this chapter, validation focuses on the question 'Do I have the right model?' [58] [39].

Since there is no historical data available for which the models can be compared, the models cannot be compared to this to see if they behave right. This is because the bigbags are currently handled differently than proposed in the models. Therefore the models will be validated via expert reviews. In these reviews, the models will be explained to several experts within Nestlé and feedback will be gathered. During the review, feedback is gathered on the input parameters, the the model logic as well as the possible outcomes. The experts within Nestlé are warehouse managers, supply chain managers, demand planners, project engineers, process engineers, warehouse operators and process operators.

The received feedback differs per model. For the PMM, the costs calculation had to be changed in several ways. First of all, the diesel costs of the trucks were missing. Next some of the transportation costs were too high and could be removed. Also the costs of manual labour should be taken into account as these contribute most to the costs of pallet handling. The model does not take the storage costs of the pallets into account. Due to the complexity of correctly getting this value, this value can be estimated and easily added to the model. Finally, the model does not take the current storage strategy into account, but this is not an issue as this can be solved easily by changing the input values. Once these and the costs are changed, the model is approved.

The feedback for the SM is more extensive. The costs have to be calculated more precisely as pipes have to be laid down, silos have to be insulated and this is not yet seen in the costs. Also the installation of blowers, sensors, air filters and rotary valves have to be taken into account. While also not forgetting the costs of operators. These changes mostly affect the cost functions of this model, but not its specifically its behaviour.

Two other important cases for the silo model are the following. As has been mentioned before in the model verification, the model tends to not empty the silos when the cleaning costs are too high. This behaviour is unwanted and does not represent the real situation. However, the costs will never get this high compared to the silo costs. Therefore this will not cause problems when implementing this. Next the silo models need to fill the current silos with the stock and the incoming material at time zero. This would be impossible in real life, as the silos would already be filled over time to reach the initial stock. This can be accounted for by not having a maximum filling constraint at time zero and by not taking this into account when calculating the filling costs.

Although the models containing silos have some flaws, these have been approved by the Nestlé experts since the flaws will not cause problems when implementing the models.

7.5. Conclusion

In this chapter, the models have been verified and validated. The goal of this was to make sure that the models are an accurate enough representation of the design alternatives. The models are accurate enough and behave as expected, when undergoing certain tests.

The only thing that has to be kept in mind is that the models tend to keep a silo almost empty when the cleaning costs are relatively high. This will not give a problem when implementing the models, but it is important to be aware of this.

The models have also been validated by experts at Nestlé and these delivered some minor recommendations in the costs of the models. These changes did not fundamentally change the models and their outcomes. Therefore the models are accurate enough representations of the design alternatives and these can thus be implemented.

8 Case study and Results

Now that all the models have been verified, the concepts can be tested and compared to each other. The models can thus be tested and implemented at Nestlé, to see what is the best solution. This chapter will therefore focus on the last subquestion:

Can the design alternatives be implemented in a food processing environment?

This chapter will implement the created models and use data from Nestlé to run optimisations. For this, the correct data has to be created first and some assumptions have to be made. When these are clear, the results of the models can be compared. Finally a sensitivity analysis will also be conducted, to make sure that the results are usable.

As the main goal is to safely handle pallets and to reduce the inventory, these values will be calculated per case and compared. As a baseline, the expected amount of needed storage will be calculated and the amount of pallets used per situation will be calculated as well. This will give insights in the reduction of pallets per solution and at what costs.

8.1. Data and assumptions

Nestlé has provided data on the arrival and consumption of the powders on a daily level in both 2022 and 2023. Nestlé has also provided the expected growth percentage of both the EHP and the Egron at the time when the AGVs will be implemented. As there is no daily data available when the AGVs will be implemented, this will have to be generated. In order to do this, the historical data has to be cleaned and analysed. Based on the trends, new data will be generated and this will be checked and verified. This is written in Appendix C. The cost inputs can be found in Appendix A.

A couple of assumptions are made when running the models. First of all, consumption does not always happen in full bigbags and sometimes only parts of a bigbag are used. This could be a problem for the PMM as only complete bigbags can be stored at the third party warehouse. Therefore the assumption is made that the bigbags can be stored in parts within the warehouse. In reality, full bigbags are tipped and only part is used, meaning that fewer storage is actually needed.

Furthermore the models will run with a timestep of 1 day. This is because trucks arrive on a daily basis and these can give quite some fluctuations. Smaller timesteps would make the model unnecessarily slow. Bigger timesteps would not be accurate enough.

When looking at the average amount of pallets stored per powder, these can be summarised in the table 8.1 below. Note that the biggest reductions on powder storage can be made by reducing the storage of maltodextrin 12, lactose and glucose.

Table 8.1: Powders and the respective expected amount of stored bigbags

Material	Minimum	Average	Maximum
Glucose	54	82	175
Lactose	56	169	307
Maltodextrin 12 - 1	230	397	562
Maltodextrin 12 - 2	89	188	327
Maltodextrin 11 - 1	4	22	52
Maltodextrin 11 - 2	7	23	33
Maltodextrin 17	6	13	29

When looking at the total amount of bigbags that would be stored, an average of 894 bigbags is expected, while the maximum of bigbags would be around 1229. It is therefore clear that the warehouse would not suffice anymore when the AGVs are implemented.

8.2. Experimental plan

All of the models will be optimised for different scenarios, using the newly generated data. For each separate model, multiple cases will be tested and compared.

8.2.1. Pallet storage options

As the PMM has no storage costs for the factory warehouse, it tries to store as much pallets there as possible since these are cheaper than the transportation costs and storage costs at the third party warehouse. Therefore the optimisation will be ran for multiple maximum amounts of pallets allowed in the warehouse, as well as with warehouse storage costs. Furthermore, it is a managerial choice of determining how many pallets should be stored in the warehouse. This will allow for the cheapest costs for multiple situations, giving a good overview of the solution.

The test cases are the following:

- 300 pallets allowed in the warehouse
- 200 pallets allowed in the warehouse
- 100 pallets allowed in the warehouse
- pallet storage costs in warehouse are 1000

Another important parameter for determining the costs is the initial amount of pallets stored in the warehouse. This has been set to 0 pallets stored initially at the warehouse and all other pallets stored in the rented warehouse.

8.2.2. Silo cases

The silo configurations depend on what materials can be stored in the same silos and on the production line hygienic requirements. Therefore the materials have to be subdivided per production line and on compatibility in the silos. Lactose should be kept separate however, as it is used by both production lines and will need silos connected to both production lines. These cases will be used for both the Silo Model (SM) and the Silo Pallet Model (SPM).

Case 1

This can be described as the worst case scenario as in this scenario, the least amount of materials can be combined per silo set resulting in the most amount of silos and piping installations. Therefore lactose needs its own silo, Maltodextrin 12 - 1 and maltodextrin 12 - 2 can be combined, glucose needs its own silo, maltodextrin 17 needs its own silo and maltodextrin 11 - 1 and maltodextrin 11 - 2 can be combined.

Case 2

This case can be described as the best case scenario due to the fact that most materials can be combined. In this case Maltodextrin 11 - 1, maltodextrin 11 - 2 and maltodextrin 17 can be combined.

Also maltodextrin 12 - 1, maltodextrin 12 - 2 and glucose can be combined. In this case lactose is still treated in a separate silo.

SPM loading stations
When handling the bigbags and moving these to the tipping stations, extra choices have to be made. One of these is where to tip the lactose bigbags as these are used by both production lines. Lactose will be tipped at the EHP production line as it could contaminate this line when tipped at the other production line, due to the fact that peptides are also handled here.

8.2.3. Combined model cases

As this model combines the options of storing pallets in the rented warehouse or in silos, choices have to be made from the cases for the PMM and SM. For this model the worst case is assumed for the silos, meaning that the powders cannot be stored in the same silos. Also if the powders are stored on pallets, it is assumed that the starting inventory in the warehouse is 0 pallets and all pallets are stored in the rented warehouse.

Besides looking into the situation of handling all powders in either silos or pallets, the model setup can be changed such that it also explores the options of storing some particular powders in silos, while others in the rented warehouse. The options that will be compared are the following:

- Storing maltodextrin 12 in silos
- Storing lactose in silos
- Storing glucose in silos
- Storing maltodextrin 12 and lactose in silos
- Storing maltodextrin 12 and glucose in silos
- Storing all powders except maltodextrin 12 in silos

8.3. Case study results

When running the different models, each will come with a solution comparing investment costs, handling costs, needed storage space and the amount of trucks arriving at the warehouse.

8.3.1. Pallet model

If all powders excluding cow milk powder are implemented in the PMM, the minimum costs would depend on the allowable amount of pallets in the warehouse. Therefore a few simulations have been done for 300, 200 and 100 pallets allowed. Also a simulation has been done with a pallet storage costs of 1000, which leads to a minimum amount of stored pallets at the warehouse. This run with storage costs does not necessarily give a valid result, but it will give the result when there is an absolute focus on having almost no pallets in the warehouse. The costs for these optimisations can be seen below in table 8.2.

Table 8.2: PMM and respective outcomes

Option	Total costs (€)	Handling costs (€)	Number of trucks	Pallet storage in warehouse
Minimum pallets	375.670	345.670	414	83
300 pallets max	331.007	301.007	303	300
200 pallets max	338.879	308.879	303	200
100 pallets max	347.287	317.287	305	100

When looking at the amount of pallets stored at Nestlé, the minimum amount could be 83 pallets. Finally about 5 to 6 trucks would drive to Nestlé per week with a maximum of 9 per day. This maximum of trucks is only due to the fact that at the start of the simulation no pallets are stored at the factory warehouse. It would also be possible with a maximum of 5 trucks per day arriving at the warehouse.

If the warehouse had the same storage costs as the third party warehouse, this would be the outcome:

Table 8.3: PMM and respective outcomes

Option	Total costs (€)	Handling costs (€)	Number of trucks	Pallet storage in warehouse
300 pallets max	349.748	319.748	303	300
200 pallets max	349.753	319.753	303	200
100 pallets max	351.123	321.123	306	100

8.3.2. Silo model

When looking at the silo model the costs, these depend on the possible silo configurations. These depend on the powder compatibility as these determine how the silos sizes can be optimised. The amount of trucks does not depend on the model but on the truck sizes, for the silos 266 trucks would arrive at the facility. The cases are the following:

Silo sizes
For the worst case scenario, the silos would have the following sizes:

Table 8.4: SM and worst case outcomes

Materials	Silos & sizes	Investment costs (€)	Handling costs (€)	Area
Glucose	3x 100 m3 40 m3	561.931	4.018	44,64 m2
Lactose	4x 100 m3	675.111	43.993	51,84 m2
Maltodextrin 17	1x 100 m3	169.224	482	12,96 m2
Maltodextrin 11 - 1 & Maltodextrin 11 - 2	100 m3 60 m3 20 m3 10 m3	398.461	11.906	27,16 m2
Maltodextrin 12 - 1 & Maltodextrin 12 - 2	16x 100 m3 10 m3	2.522.198	43.125,73	209,32 m2

This would result in the investment costs of €4.370.985,- . and the following handling costs of €103.526. The silos would need a total area of about 346 m2. The total investments are a bit higher due to the extra blower costs being made. The blowers do not depend on the models, but purely on the demand of powder by the factory.

In the best case scenario, the sizes would be the following:

Table 8.5: SM and best case outcomes

Materials	Silos & sizes	Investment costs (€)	Handling costs (€)	Area
Lactose	4x 100 m3	675.111	43.993	51,84 m2
Maltodextrin 11 - 1 & Maltodextrin 11 - 2 & Maltodextrin 17	2x 100 m3 2x 40 m3	499.446	7.388	37,44 m2
Maltodextrin 12 - 1 & Maltodextrin 12 - 2 & Glucose	19x 100m3 60 m3	3.050.499	72.143	255,24 m2

When looking at the best case scenario, the investment costs would be €4.269.066,- and the handling costs would be €123.525. The silos would need a total area of about 345 m2.

For both models the number of trucks arriving at the factory stays the same. The amount of trucks arriving is 266 during the year. However, these trucks do not arrive at the warehouse and thus alleviate the stress on the warehouse handling. There would be no pallets used in this model, thus saving about 900 pallet spots in total.

8.4. Silo pallet model

When looking at the situation of combining pallets with silos, the silo sizes and the handling costs change. A little more trucks arrive due to the fact that there is less powder per truck. In total 311 trucks arrive at the Nestlé terrain. Below the worst case scenario results can be seen:

Table 8.6: SPM and worst case outcomes

Materials	Silos & sizes	Investment costs (€)	Handling costs (€)	Max. pallets	Area
Glucose	3x 100 m3	510.026	16.094	23	38,88 m2
Lactose	3x 100 m3 60 m3	712.661	173.404	69	47,88 m2
Maltodextrin 17	100 m3	153.723	2.145	20	9 m2
Maltodextrin 11 - 1 & Maltodextrin 11 - 2	100 m3 60 m3	315.617	8.923	24	21,96 m2
Maltodextrin 12 - 1 & Maltodextrin 12 - 2	16x 100m3	2.614.640	148.977	48	207,36 m2

The investment costs now also include extra blowers and pipes as the bigbags have to be tipped in advance. The investment costs become €4.446.818,- . The handling costs also increase to €349,546. Finally the needed area for the silos is 325 m2 and a maximum of 93 pallets are stored at any time.

In the best case scenario, the silo sizes become the following:

Table 8.7: SPM and best case outcomes

Materials	Silos & sizes	Investment costs (€)	Handling costs (€)	Max. pallets	Area
Lactose	3x 100 m3 60 m3	712.661	173.404	69	47,88 m2
Maltodextrin 11 - 1 & Maltodextrin 11 - 2 & Maltodextrin 17	2x 100 m3 60 m3	438.911	11.069	24	30,96 m2
Maltodextrin 12 - 1 & Maltodextrin 12 - 2 & Glucose	18x 100m3	2.938.425	215.072	70	233,28 m2

The investment costs now become €4.229.848,- and the handling costs become €399.546. Finally an area of 312 m2 is needed and a maximum of 93 pallets are stored at any time. For both cases, 311 trucks arrive per year.

8.4.1. Combined model

In the case of building silos and renting extra storage space for pallets, the clear option is to have all the materials being stored at the third party warehouse. This is because the storage and handling costs are significantly cheaper than building silos for every material.

When looking at the results of choosing materials to be stored in silos and materials to be stored in pallets, the options are: storing maltodextrin 12 in silos together, with one other powder or storing everything but maltodextrin 12 in silos. This is due to the fact that maltodextrin 12 needs the most space. If the options are only storing maltodextrin 12 in silos; storing maltodextrin 12 and lactose in silos; storing only lactose in silos or storing everything but maltodextrin 12 in silos. The results can be seen in table 8.8 below:

Table 8.8: CSPM outcomes

Materials	Total costs (€)	Investment costs (€)	Handling costs (€)	Trucks used	Max. pallets	Area (m2)
Maltodextrin 12 in silos	2.825 k	2.574 k	251 k	275	51	209,32
No maltodextrin 12 in silos	2.086k	1.857 k	229 k	258	67	136,60
Maltodextrin 12 & Lactose in silos	3.389 k	3.249 k	140 k	234	24	261,16
Lactose in silos	956 k	727 k	229 k	268	48	51,84
Maltodextrin 12 & Glucose in silos	3.370 k	3.136 k	234 k	284	51	253,96
Glucose in silos	941 k	614 k	327 k	301	67	44,64

8.5. Sensitivity analysis

The sensitivity analysis has been done for every model, regarding its total costs, its investment costs and its handling costs. The sensitivity parameters include costs of the infrastructure elements, storage costs, different handling costs, the density and starting stock as well as the sizes of the silos. Deviations of 10% and -10% have been made in the values to see how much the costs change.

8.5.1. PMM sensitivity analysis

For the PMM the sensitivity analysis has been done regarding the costs of the bigbag reshaper, the factory warehouse handling costs, rented warehouse handling costs and the rented warehouse storage costs. This can be seen in table 8.9.

Table 8.9: Percentual change of total costs of the PMM

Parameter	sensitivity Δ
Bigbag reshaper	0,86%
Warehouse handling costs	4,94%
Rented warehouse handling costs	2,36%
Rented warehouse storage costs	1,93%

It is clear that the warehouse handling costs have the most impact on the total costs as all pallets entering the warehouse have to be handled. Furthermore the rented warehouse costs have quite some influence on the pricing and these are expected to go up according to Nestlé.

8.5.2. SM and SPM sensitivity analysis

For the SM and SPM, the following parameters have been checked. Silo building costs, extra infrasructure costs, blower system costs, pipes, bigbag reashper, pneumatic handling costs, pallet handling costs, cleaning costs, material density and the initial stock. The results can be seen in the table 8.10 below.

Table 8.10: Percentual change of total costs of the SM and SPM

Parameter	SM best case sensitivity Δ	SM worst case sensitivity Δ	SPM best case sensitivity Δ	SPM worst case sensitivity Δ
Silo costs	8,91%	8,88%	7,62%	7,65%
Silo sensors costs	0,59%	0,61%	1,01%	1,00%
Blower costs	0,10%	0,10%	0,24%	0,23%
Piping costs	0,13%	0,18%	0,20%	0,31%
Bigbag reshaper	x	x	0,06%	0,06%
Pneumatic transport costs	0,19%	0,19%	0,37%	0,35%
Pallet handling costs	x	x	0,38%	0,36%
Powder density	8,15%	9,17%	18,81%	9,88%
Initial stock	6,23%	3,02%	5,80%	5,82%

It is clear that the silos have a big impact on the costs as these are the most expensive to install. Also the density of the powders can have a big impact on the amount of needed silos, stressing the need of double checking this. The enormous outlier in the powder density sensitivity, can be explained with the silo sizes. If the sizes increase over a certain threshold, a new silo is needed. This happens in the best case for the SPM, where it just fitted before, but a huge investment was needed due to the leap in silo sizes. Finally the starting stock is often the biggest amount of powder already, meaning that if it can be reduced it will have a significant impact on the price.

8.5.3. CSPM sensitivity analysis

Finally the CSPM has more parameters in it due to the combination of both models. The results can be seen below in table 8.11.

Table 8.11: Percentual change of total costs of the CSPM

Parameter	MD. 12 in silos sensitivity Δ	No MD. 12 in silos sensitivity Δ	MD. 12 & lactose silos sensitivity Δ	Lactose silos sensitivity Δ	MD 12 & glucose silos sensitivity Δ	Glucose silos sensitivity Δ
Bigbag reshaper	0,11%	0,14%	0,09%	0,31%	0,09%	0,32%
Pallet handling costs warehouse	0,26%	0,29%	0,07%	2,64%	0,21%	1,04%
Pallet handling costs rented warehouse	0,35%	0,34%	0,04%	2,83%	0,27%	1,72%
Storage costs rented warehouse	0,12%	0,18%	0,04%	2,49%	0,08%	0,68%
Silo costs	8,40%	7,66%	8,72%	6,10%	8,58%	5,50%
Silo sensors costs	0,48%	0,65%	0,59%	0,67%	0,50%	0,34%
Blower costs	0,08%	0,11%	0,06%	0,23%	0,07%	0,23%
Piping costs	0,04%	0,34%	0,12%	0,29%	0,07%	0,13%
Pneumatic transport costs	0,12%	0,24%	0,23%	0,46%	0,11%	0,04%
Powder density	9,30%	8,55%	8,13%	8,20%	9,76%	9,41%
Initial stock	3,74%	1,42%	3,11%	0%	3,93%	2,84%

It is clear that the powder density and the silo costs have the most influence on the model as these costs are always higher then the costs used for the rented warehouse. It is however interesting to see that in case of only storing lactose or glucose in silos, that the warehouse handling costs have a bigger impact on the total costs. This is because the amount of maltodextrin 12 handled is so big that it even influences the costs a little bit when stored in the rented warehouse.

8.6. Findings

From all the solutions, the cheapest option is the option of using a bigbag reshaper and storing the pallets in a rented warehouse. As the total costs will be the lowest for this configuration. This is also due to the fact that implementing silos for all materials will not be possible due to space constraints.

When looking at the amount of trucks arriving at the factory, the bulk trucks have the definite least amount of trucks arriving at the factory. This is due to the fact that a bulk truck can transport more powder than a normal truck with pallets can. Besides this, the models containing silos already assume having the initial amount of pallets stored within the system, while the PMM starts with no inventory within the warehouse. If the PMM were to start with the same amount of pallets already within the warehouse, it would have less trucks used: 288. Still these are more trucks, due to the huge size difference

If silos where to be used, the amount of them could be reduced significantly. This can be seen in the data. Especially for lactose, maltodextrin 12 and glucose, some silos are full almost all the time. This could be reduced by about 5 silos. Without changing this, only maltodextrin 12 could not be placed in silos. If the amount of storage is reduced, all of the powders could be stored in silos.

When looking at the storage space reduction, lactose would be the best product to store in silos as it has the highest bulk density. This means that per cubic meter, the biggest space savings can be made on lactose. For the other materials, the densities are more or less the same, so the difference is smaller. However, lactose has to be treated with the utmost care at Nestlé. It has the highest hygiene requirements of any powder and therefore even if it is the best material to store, it might not be possible due to all the strict regulations. Also it is used almost every day, meaning that there will be little powder consolidation. This is also why it would be preferred over glucose or over any of the maltodextrins.

If pallets with bigbags are to be present within the warehouse at any time, about 100 spots would be needed to make sure that the warehouse could function. This is due to the fact that the maximum amount of pallets needed is 83 pallets, while the maximum amount of pallets arriving on a single day is 93. Having 100 pallet spots ready would be enough to always cover this.

The handling costs are far higher when the silos have to be cleaned. For the worst case scenarios the handling costs are actually lower than the best case handling costs, while for the bulk situation the used area is almost the same. It might therefore actually be better to keep most of the materials apart as it is cheaper for the handling and makes the processes less complex.

Looking at the sensitivity analyses, the silo costs, density and starting stock have the most influence on the overall costs. This stresses once more that the storage should be reduced if possible. Furthermore the influence of maltodextrin 12 in combination with either lactose or glucose is quite high on the system due to the fact that there are so many pallets moved of these powders.

Finally the CSPM had little practical value during this research. This is because the costs for using pallets are significantly lower than using silos and therefore the model would always result in having pallets as the cheapest option. For long term solutions, it might offer some guidance, but this would take too long in terms of calculation times. Also due to the fact that so little different powders can be stored together, the different combinations can be done by running the PMM and SM seperately.

8.7. Short term or long term solution

Although the solution of implementing a bigbag reshaper and using pallets is definitely the best solution for 2026, it might not be the best solution for the long term. This is because the handling costs per pallet are the highest in this situation. The handling costs themselves are highest for the combination of pallets and silos, but this is due to the fact that every pallet has to be handled in this situation in order to enter the silos. If this was not the case, this option would also have lower handling costs than the pallet storage at the third party warehouse. Also the storage costs are practically zero for the silos.

When looking at the handling costs per pallet, this becomes the following:

- Receiving pallet at 3PL warehouse: €1,27
- Transport from 3PL warehouse to warehouse: €9,92
- Receiving pallet at warehouse: €14,83
- Moving pallet to tipping station: €8,60
- Moving pallet equivalent from silo to production: €14,27

The daily storage costs at the third party warehouse are about 22 cents per pallet per day, while this is as good as zero in the warehouse or the silos.

Now when comparing this, it is clear that receiving powders in bulk and storing these in silos is the cheapest option. The unloading of the powders is free as this is provided by the bulk truck provider and moving a pallet worth of powder to production costs about 14 euros.

The handling of the pallets within the warehouse cost the most and should definitely be avoided. Still, the reduction of the costs at the third party warehouse would significantly reduce the yearly handling costs. The option of handling pallets and storing them in bulk is the most expensive option, as the handling costs are even higher due to the double powder handling costs. When looking at the yearly handling costs, some trends can be seen in figure 8.1.

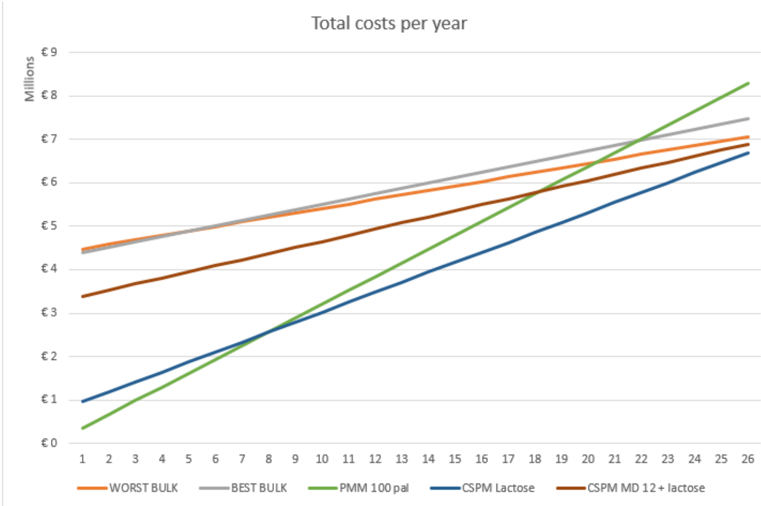


Figure 8.1: Costs per solution over a time span of 25 years

When investing in silos, it would take about 18 to 20 years to have a return of investment, assuming that the same amount of pallets are handled. The best option would be to only have silos for lactose powder, while handling the other powders on pallets. This graph also clearly shows that it is worth it to minimise the amount of powders stored, especially for maltodextrin 12 as it has very low handling cost but becomes impractical due to the huge amount of silos needed.

8.8. Conclusion

The goal of this chapter is to implement the different models for the situation at Nestlé and to find the best option to implement. When looking for only a short term solution, the best option is to use a bigbag reshaper and to store all the pallets in a third party warehouse. When looking at the long term implications of these solutions, having lactose delivered in bulk is the best option as it has little investment costs and low handling costs. Assuming the consumption and arrivals stay the same, this would be the cheapest option after 8 years.

When comparing the results, it is interesting to see that the size of the bulk trucks has such an influence on the silos sizes. Since the bulk trucks have been chosen with a maximum possible size, it clearly shows that this greatly effects the outcomes as well as the costs. Another interesting result is that for most materials the amount of stored material can be reduced drastically. This is because almost every powder has a silo that is filled all the time.

Also the silos would not be feasible as these would use up to much space. If silos would have to be used, it would only be feasible if maltodextrin 12 is stored in the third party warehouse.

9
Conclusion and recommendations

Now that the results have been compared, the research can be summarised and concluded.

9.1. Answer to the research questions

The goal of this research was to determine the best option of powder handling at Nestlé. By comparing different solutions, engineers and managers can make an informed decision on how to handle the powder starting from 2026 and how to solve the challenges of not having enough storage space and the handling problems of the bigbags with the AGVs. Once more the main research question is the following:

What is the optimal solution for powder handling and storage at Nestlé?

There are to answers to this question, one for the short term and one for the long term.

- **Short term solution:** Store the biggest part of all the bigbags within a third party warehouse and place a bigbag reshaper in the warehouse. The pallets would be driven to the factory on a daily basis and consumed almost immediately after arriving. This has the lowest total costs and would result in needing just 100 pallet spots.
- **Long term solution:** Store lactose in silos and have it bulk. The other powders would be stored in the third party warehouse. This option would be thhe cheapest after 8 years.

These answers have been found after answering the subquestions before. This began by looking at the status quo of the warehouse and looking into the changes the warehouse would undergo. The findings were that the implementation of AGVs in the warehouse could lead to handling problems according to the suppliers. Furthermore, there will not be enough space within the warehouse under the projected growth.

Multiple concepts have been generated and have been compared in order to find the best possible solutions for the powder handling. Two concepts were the best: storing powder in silos and storing powder in a third party warehouse and reshaping the bigbags to make them suitable for AGV handling. Two extra concepts have been added by request of Nestlé as there is extra complexity that could not be put in a morphological overview. This is due to the fact that not all suppliers might be able to deliver powders in bulk any time soon after building silos or at all. Therefore the solutions of filling the silos via bigbags has been added, as well as the option of dividing the powders over either silos or pallets in the third party warehouse.

These concepts have been further developed in order to prepare models that can compare the concepts on a more detailed level with the following KPIs: amount of trucks used, amount of storage space needed, handling costs and investment costs.

Before the models could be created, a literature study was done to determine if any relevant models already exist. For the silo simulation, the bin packing problem is relevant, but has never been done in this specific way. The variant discussed is the MPVSBPPC-IF. For the pallet handling, there already exist a description of this: the two stage multi item lot sizing problem. After this the models have been created and optimised for the data generated for Nestlé.

10 Discussion

The previous chapter has discussed the conclusions of this research. It is still important to mention what gaps this research has left open, what its limitations are and what would be the follow up steps for Nestlé.

10.1. Limitations

Most limitations in this research are focused on the accessibility of the data for the mathematical models. The limitations will focus on two subjects. The limitations of the research and the limitations of the models.

10.1.1. Research limitations

This research omitted a couple of things that will have an impact on the final results. Those things will be mentioned below.

Blower locations

This research mentions the implementation of root blowers, dehumidifiers, filters and aftercoolers. These equipment pieces also take up space and have to be installed somewhere. This research has not looked into any location for this equipment and this could cause problems. As the goal of the research is not looking for a suitable spot thoughout the whole factory, this has not been done. In the worst case a small building would have to be build next to the silos, but this could be acceptable.

Bigbag tipping station

When using the tipping stations to fill the silos, some things should be taken into account. As the tipping stations need to accommodate multiple powders in different hygienic zones, the peptide free tipping station will be under the most stress. This is because lactose would only be tipped here in order to prevent any contamination of the line. Since maltodextrin 12 - 1 and maltodextrin 12 - 2 are also used most and are also tipped in this tipping station, this would stress the tipping station a lot. For this the assumption is made that a tipping station can handle about 2 tons of powder per hour. When looking at the generated data, this would result in 15 days where not all bags could be tipped. As the stock is high enough in the simulated data, this is not a problem. But it could be a problem when more materials are needed in the future.

Pricing

Since for accurate pricing quotes from multiple companies would be needed, the results all have some noise in them and a low level of accuracy. This is not a problem as this is not the goal of the models. But it is a limitation as it does not fully represent reality and could lead to somewhat different results.

Next to this, no maintenance costs costs have been taken into account. This means that even though a silo might be a good fit, with low handling costs. It could still be that the maintenance costs are sufficient enough to make the option of building one too expensive.

When looking at the costs build up from the third party logistics supplier, these also included waiting costs and extra costs for receiving or moving pallets during the weekends. In the ideal case (as modelled), this will not be a problem. But if there are delays somewhere else in the factory, these costs would need to be added too. Or if a supplier delivers a shipment too late, this would also result in a lot of extra costs that have not been modelled.

Flexibility

Bigbags offer a lot of flexibility in adding or removing material, since this can be done per bigbag. However, once a bulk truck arrives, it has to be used fully. If a material defect would be present in the truck. This would mean that all of the powder in this bulk truck would be defect. If the powder would already be loaded into a silos when this has been discovered, this could mean that all of the powder in the whole of the silo might have to be rejected, resulting in a greater loss of powders.

10.1.2. Model limitations

Then model limitations include the following.

Data generation

The models optimise for the silos under the given data. This has been generated with some randomness, but is in no case the exact situation of 2026. It is thus very important to keep this in mind. Also this data has been generated under an expected growth for the year 2026. If this growth forecast is incorrect, it means that all of the generated data is incorrect too and that the models would have to be optimised again.

The implications of this could be big. If a bulk truck arrives a day earlier than expected it might not fit in the silos anymore and it should have to be send back. Most of the times this will not be a problem as there are probably clear reorder points, but the unexpected delivery could cause a problem.

The data retrieved from Nestlé is from SAP and only shows when a material is used by production. However, the movements of materials to production would happen before this is reported. Also bigbags would only be tipped in full and then stored in a production silo. This means that there would never be half bigbags of storage as this is in the production silos. Therefore the models would actually need to be based on the demand from thoses silos and not the actual demand. This is most relevant for the PMM as this has half pallets of storage possible in the factory warehouse.

Time step inaccuracy

When using a time step of a day, it will capture most of the flows and movements happening within the factory. However, if 3 trucks would arrive at the same time this would put extra pressure on the blowers and it might not be that all the powders can be moved for a short time period. Or if lactose is needed by both production lines at the same time, the system might not be able to handle it.

Filling strategy

When looking at the filling of the silos, bulk trucks can unload partially in a silo. This makes the calculations more complex but it allows for the construction of fewer silos. If this is not the case, it would mean that more silos are needed, but also that smaller bulk trucks would be a plus as it allows for more flexible silo filling.

Besides this, the assumption has been made that silos can be filled and emptied at the same time. This also allows for less silos being used and less stock being needed. If this would also not be the case, more silos would be needed as well as more storage for some materials.

Other movements rented warehouse

Besides the bigbags, other materials are also stored within the rented warehouse. Only assuming that bigbags are stored in the warehouse simplifies the reality quite a lot. As the goal of this research was to find the costs of the option of storing bigbags there, this simplification is fine. Hwoever, when implementing this solution, other movements to and from this rented warehouse should also be taken into account as the optimal configuration calculated in the model might not be a good fit anymore.

10.2. Recommendations

The recommendations for Nestlé are explained below. These are purely focused on the constraints given by Nestlé and the constraints chosen in this research. The recommendations are: looking into bigger silo sizes, optimising for different bulk truck sizes and reducing the inventory.

10.2.1. Silo sizes

When looking at the results, it is clear that for some materials more than 20 silos are needed. The enormous sizes of the silos and the large number of them can be explained quite easily. A single bigbag of powder has a typical volume of 1 to 2 cubic meters at Nestlé. If there are for example 100 bigbags needed in storage at any time, this would result in 1 or 2 silos of 100 cubic meters. Therefore, the costs of storing materials in silos rise quite quickly. Due to the little available space at Nestlé, the only way to possibly be able to fit all materials in silos would be by allowing the usage of bigger silos. This is because bigger silos, can be built higher and therefore can store more material in the same area. If Nestlé would want to implement silos, it would be good idea to look into getting permits for this.

10.2.2. Bulk truck sizes

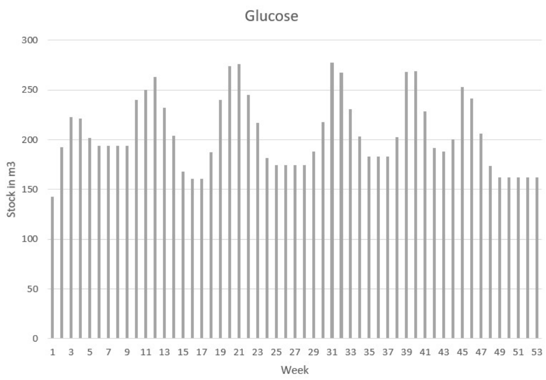
When looking at maltodextrin 11 - 1, maltodextrin 11 - 2 and maltodextrin 17, there is a clear difference in silo sizes if bulk trucks are used or not. This can be explained due to the fact that the biggest size bulk truck has been chosen. It does demonstrate however, that the size of the bulk truck influences the size of the silos. Meaning that there is an optimal bulk truck size for each powder. This is most closely related to the expected powder storage and consumption. If powders are stored in huge quantities, bigger trucks might be cheaper, while for smaller quantities smaller trucks might be cheaper.

10.2.3. Inventory reduction

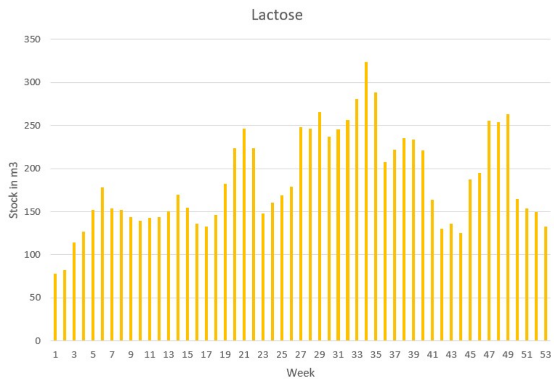
The stock of most powders is very high to the actual powder usage. This is due to the fact that the current data has been extrapolated to the future situation. It might actually be in the future however, that a reduction of the inventory would make a different solution the best option for Nestlé.

As can be seen in figure 10.1, the reduction per material could go as far as:

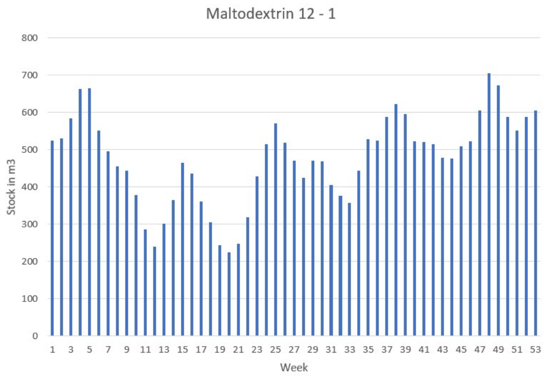
- Glucose: 1 silo of 100 m3, as the lowest inventory is 108 m3
- Lactose: 1 silo of 60 m3, as the the lowest inventory is 61 m3
- Maltodextrin 12 - 2: 2 silos of 100 m3 as the lowest inventory level is 207 m3
- Maltodextrin 12 - 2: 2 silos of 100 m3 as the lowest inventory is 208 m3



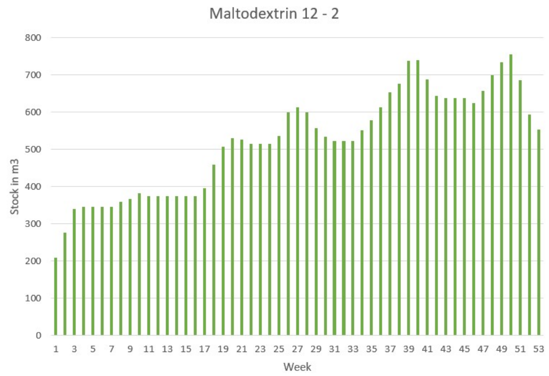
(a) Glucose stock in 2026



(b) Lactose stock in 2026



(c) Maltodextrin 12 - 1 stock in 2026



(d) Maltodextrin 12 -2 stock in 2026

Figure 10.1: Powder stocks in 2026

10.2.4. Heuristic solution method

As the models used to determine the needed silos and their filling strategy have been optimised for data based on daily consumption, it gives a good overview of what the costs might be in the future. One of the next steps before implementing the silos, would be to model these for a period of over 1 year. However, in this case the models would have even more parameters and take even longer to solve. Therefore a heuristic solution method should be developed for this variant of the bin packing problem. In line with this, the complexity of the variant used for this problem should be further explored.

10.3. Business implementation

As the the research has given a clear business case of why the silos should be implemented, the next step would be making the results implementable. When looking at future improvements of this research, a few things clearly need to be addressed. Not that the goal of this research was not to determine the exact costs of every solution, but to roughly calculate the costs of these to compare these. The future research steps would now become the following:

- Determine the powder properties
- Determine powder properties after storing them for a long time
- Design the bigbag reshaper
- Have more detailed calculations
- Optimise for bulk truck sizes

10.3.1. Powder properties

As has been mentioned in chapter 4, the powders have to be tested on their properties. These properties determine some of the silo parameters that can impact the process. For every powder, from every supplier, these have to be determined as to make sure that the powder will flow through the silo. These parameters, would also determine if some powders could be stored in the same silo or that each powder needs a separate silo.

Furthermore, these properties can also determine the maximum outflow of a silo. This is crucial information as multiple silos would be needed if the outflow of a silo would be very low, making it impractical to use silos at all. If the outflow is sufficient of a silo, this would not cause any problems or extra constraints to the model.

Bulk materials can cake after being stored for a very long time. It could be that for some materials that are currently used by Nestlé, this would happen after a month for example. This means that if the powder is not used for longer than a month, its properties might change and the powder will not flow anymore. If this is the case, the powder must be manually handled to make it flowable again. This would result in huge extra costs and is thus unwanted.

10.3.2. Bigbag reshaper

Currently Nestlé is investigating the usage of a bigbag reshaper, based on a pallet shape already in use. Together with an external company, designs are being made to see if it is possible and feasible. Although mentioned as a solution, the bigbag reshaper should be thoroughly designed and tested to know its throughput speed and its limits.

10.3.3. Detailed calculations

Whenever a model is made of a situation to optimise it, a choice has to be made in how detailed the model can be. One of the limiting factors for this research was the amount of available data on the pricing of the necessary infrastructure. Few silo sizes were available and a lot of costs could only be roughly estimated based on this data. This is because these costs depend on the complete working within the factory. Just determining where to place all the pipes, their diameter and the exact height of every sub-piece would take months on its own. Besides the pipes, this also has to be done for the pumps, energy needs, the control systems that run the silos, the AGV costs and the installation costs. This is especially important when a real choice is being made.

10.3.4. Optimal bulk truck properties

As the bulk truck size influences the size of the silos and thus the costs and the outcomes, it makes sense to also optimise for their sizes. This would be a whole different kind of problem as now, not only the silo sizes would have to be optimised, but the bulk truck sizes as well. The mathematical models would become more complex and would need more constraints in order to optimise this too.

10.4. Scientific contribution

This research has described a new variant of the bin packing problem that has never been used before and has been altered and optimised for in a practical case study. The new version of the bin packing problem is the multi period variable sized bin packing problem with conflicts and item fragmentation. It describes the problem of packing items over multiple bins over multiple periods. These items can be fragmented and thus divided over multiple bins. The bins have variable sizes and the optimal sizes can be chosen. Finally the items can have conflicts and may not be stored in the same bin, this has also been added.

10.5. Contribution to practice

This thesis has given managers and engineers at Nestlé a first step into solving their problems related to implementing AGVs. With the help of this study a choice can be made based on the available funds and the goals of Nestlé in terms of powder handling. If the option of pallets storage in a third party warehouse will be implemented, the PMM can be used as a tool for determining what powders to order at what time from the third party warehouse. This will result in the least amount of trucks arriving at the factory with the optimal mix of materials in the trucks, resulting in the cheapest possible transport to the warehouse.

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A

Scientific paper

Multi period variable sized bin packing problem with conflicts and item fragmentation - A powder handling case study at an infant formula factory

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***Abstract*—This research introduces a new variant of the bin backing problem when being modelled for the powder handling. This is the *Multi Period Variable sized Bin Packing Problem with Conflicts and Item Fragmentation* (MPVBPPC-IF). This version of the bin packing problem describes the distribution of items over bins with different sizes during multiple periods. The items can be split over multiple bins, but not all items can be stored in the same bin at the same time. This variant of the bin packing problem is also NP hard.**

Besides this, a use case will be presented where the MVSBPPC-IF will be applied in modified form. This is for a infant formula factory, that wants to revise its powder handling in the warehouse. One of the options to improve this, could be implementing silos, to store these powders. As the powders can be divided over different silos and cannot be placed in the same silo together, this becomes a modification of the MVSBPPC-IF.

***Index Terms*—Bin Packing Problem, Multi period, Variable sized, Conflicts, Item Fragmentation, Powder handling, Silo**

I. Introduction

A Dutch factory of infant for infant formula is looking for new ways of storing the powders it currently handles. The factory makes use of 8 different powders, distributed over 2 production lines. Due to hygienic regulations the powders from one production line cannot be stored together with powders from the other production line. As the factory produces different products with different powder mixes throughout the year, the storage need for each powder fluctuates. This means that there is room for optimally allocating which powder to store in which silo. The factory has a lot of historical data available and this can be used to determine how many silos would be needed to invest in. As one cannot simply build or remove silos on a daily basis, the amount of silos, the silo sizes and what powders to store in which silo, have to be determined beforehand.

Determining which powder to store in which silo, has a lot in common with deciding which item to store in which bin. Determining which item to store in which bin, is formally known as the bin packing problem (BPP) and this has applications in many fields, such as in the supply chain. Here it can be used for production planning, distribution and inventory management (Elııyı and Elııyı, 2009). In this study a new variant of the BPP is analysed that combines different aspects of its applications in various fields. More specifically, the bins will have different sizes and different costs; not all items can be present in the same bin at the same time; items can be split up and distributed over different bins; and this is determined for multiple time periods.

To the best of the authors' knowledge, the MVSBPPC-IF has never been described in literature before. We are the first to analyse this variant of the BPP and discuss its complexity. The problem is described and formulated as a mixed integer linear programming model and its complexity is discussed. Finally the model is modified and used for a real life case at an infant formula factory.

The aim of this paper is to present a new variant of the MVSBPPC-IF and versions of it in a use case. The rest of the paper is organised as follows. Section II will review the related literature. Section III will formulate the problem, present a mixed integer model for the problem and discuss its complexity. Section IV will provide a case study of the variant and section V will conclude.

II. Literature review

Determining which powder in which silo has a lot in common with the bin packing problem (BPP), where items have to be distributed over different bins. One of the more recent reviews on this has been done by Munien and Ezugwu, 2021. The BPP is defined as a combinatorial optimisation problem that deals with packing a finite sets of items with weights into a finite number of bins, without exceeding the maximum capacity of the bins. Bin packing problems have many variants and can be subdivided into many categories. One of these is the dimensions of the BPP, from which the main variants are the 1D-BPP, 2D-BPP and 3D-BPP. The standard BPP is also knwon as the 1D-BPP. The 2D-BPP has an extra dimension and could for example be a problem of placing rectangles within a given area as has been described by Gass and Harris, 1997. The 3D-BPP has applications in container loading, where boxes of different sizes have to be fitted within a container as has been done by Martello et al.,

2000. As powders and silos can be expressed in volume only, the 1D-BPP variant is most relevant.

As the silos have different sizes, the bins would have variable sizes as well. This would be named the variable sized bin packing problem (VSBPP) and this has first been introduced by Friesen and Langston, 1986 and Murgolo, 1987. Both assume that the bin cost is equal to its capacity and develop heuristics algorithms for it. Wäscher et al., 2007 and Haouari and Serairi, 2009 consider the VSBPP with bin costs proportional to its sizes. Finally, there is also a variant to this where the costs are not related to the bin sizes, as has been described by Crainic et al., 2011. As the silo costs follow the size, the situation where the costs are proportional to the sizes become relevant.

As the powders cannot be stored in the silo at the same time or at all, the bin packing problem with conflicts (BPC) becomes relevant. This has first been introduced by Jansen and Öhring, 1997 and has been applied to warehouse storage by Basnet and Wilson, 2005. When looking at the possibility of storing one batch of powder over multiple bins, the item could be said to be fragmented. In this case the bin packing problem with item fragmentation (BPPIF) has been coined by Mandal et al., 1998. The combination of these two problems has first been described by Ekici, 2021, where he combines the BPPC with the BPP-IF into the bin packing problem with conflicts and item fragmentation (BPPC-IF). Casazza, 2019 has combined the VBPP with the BPP-IF into the variable sized bin packing problem with item framgmentation (VBPP-IF). Quite recently Ekici, 2022 has introduced the variable sized bin packing problem with conflicts and item fragmentation (VBPPC-IF), proposed a heuristic approach to solve it and proved that it is NP-hard. This version of the BPP is very relevant for this research, as it has almost all the relevant properties for the needed model. However, to determine the silos and their sizes, the inflow and outflow of powder also has to be modelled.

When looking at the BPP with a time component, the dynamic bin packing problem (DBPP) comes to mind. In this variation the items that have to be divided over the bins arrive and depart at random times, according to E. G. Coffman et al., 1983. This variant has been generalised even further by Ivkovic and Lloyd, 1998 in the fully dynamic bin packing problem (FDBPP), where items are also allowed to be prepacked in different bins. An overview of all variations till 2013 has been given by Coffman et al., 2013. However all these dynamical formulations do not take variable sizes, item conflicts or item fragmentation into consideration. Furthermore, in these variations the items have a predetermined arrival and departure time, where the powders in the silos do not have this. As the silos will be built once and cannot be added or removed easily, a static version with multiple time periods would be more in its place than the dynamic variant.

The multi period variants of the bin packing problem, this has been introduced by Crainic et al., 2021 as the multi period bin packing problem. there exists a multi period variable sized and variable cost bin packing problem with assignment costs (MPVCBPP-AC) as has also been introduced by Crainic et al., 2019. Still, there is no version that also includes the conflicts and item fragmentation.

Besides looking just at the BPP variants, it is also good to look at similar problems within different industries. One research in particular is relevant. This is the tank allocation problem (TAP) as has been introduced by Vouros et al., 1996 and it is used to see if a specific sailing route for a ship is feasible given the cargo it has to pick up and deliver on the route. Hvattum et al., 2009 has continued on the TAP by also developing a MIP model for the TAP, that tries to minimise the used storage space of set hulls within a ship.

As powders can be split over multiple silos, not all powders can be mixed in the same silos and as the number of silos and their sizes as well as the bins they are stored in have to be determined beforehand, this would be a multi period variable sized bin packing problem with conflicts and item fragmentation. To the best of the authors' knowledge, this variant has not been described before and presents a clear scientific gap.

III. Formulation of the MPVBPPC-IF

The multi period variable sized bin packing problem with conflicts and item fragmentation will be formulated mathematically, building on the work done by Hvattum et al., 2009, Ekici, 2022 and Crainic et al., 2021 Crainic et al., 2019. In its simplest form the MVSBPPC-IF, would just be the same as the formulation done by Ekici, 2022, but with a time step. Allowing for items to be moved over to another bin after being placed in a bin for a certain time period. Later in this section, variations will be added to make this formulation suitable for powder handling.

TABLE I
Notation of the variable sized bin packing problem with item fragmentation and conflicts problem

Sets and indices	
V	Sets of nodes $i \in V$ materials
E	Sets of nodes $i, j \in E$ incompatible materials
U	Sets of nodes $u \in U$ bins
k	Sets of nodes $k \in B$ bin types
t	Sets of nodes $t \in T$ time periods
Parameters	
C_k	cost per bin type k
w_{it}	total weight of material i at time period t
W_k	Size of bin k or weight that bin k can accommodate
Variables	
f_{iut}	amount of material i packed into bin u at time period t
x_{iut}	binary variable, 1 if material i is packed into bin u at time period t and 0 otherwise
y_{ukt}	binary variable, 1 if bin u is of type k at time period t and 0 otherwise

The mathematical formulation then follows as:

$$\min \quad \sum_{u \in U} \sum_{k \in B} \sum_{t \in T} C_k y_{ukt} \tag{1}$$

Subject to:

$$\sum_{i \in V} f_{iut} \leq \sum_{k \in B} W_k y_{ukt} \quad \forall u \in U, t \in T \tag{2}$$

$$\sum_{u \in U} f_{iut} = w_{it} \quad \forall i \in V, t \in T \tag{3}$$

$$f_{iut} \leq w_{it} x_{iut} \quad \forall i \in V, u \in U, t \in T \tag{4}$$

$$\sum_{k \in B} y_{ukt} \leq 1 \quad \forall u \in U, t \in T \tag{5}$$

$$x_{iut} + x_{jut} \leq \sum_{k \in B} y_{ukt} \quad \forall i \in E, j \in E, u \in U, t \in T \tag{6}$$

$$\sum_{i \in V} f_{i,u,t} \leq \sum_{i \in V} f_{i,u-1,t} \quad \forall u \in U, t \in T \tag{7}$$

$$x_{iut} \leq \sum_{k \in B} y_{ukt} \quad \forall i \in V, u \in U, t \in T \tag{8}$$

$$x_{iut} \in \{0, 1\} \quad \forall i \in V, u \in U, t \in T \tag{9}$$

$$y_{ukt} \in \{0, 1\} \quad \forall u \in U, k \in B, t \in T \tag{10}$$

$$f_{iut} \geq 0 \quad \forall i \in V, u \in U, t \in T \tag{11}$$

Equation 1 is the objective function and aims to minimise the total costs of the bins used. The capacity of the bins is constrained by equation 2 since the sum of items packed into a bin cannot be bigger than the size of the bin.

The sum of the number of fragments of item i always have to be equal to its weight as can be seen in equation 3. Related to this, equation 4 makes sure that no more than the total weight of an item can be stored in a single bin. Equation 5 determines that each bin can only be of 1 type.

Equation 6 introduces a new set E, which is a subset of V containing incompatible materials. This equation thus guarantees that incompatible items cannot be stored in the same bin.

The next two equations are redundant constraints. Equation 7 resolves symmetry problem along the bins, by arranging the bins in order to their contents. Equation 8 forces bin usage if an item is packed in it. The remaining equations 9, 10 and 11 restrict the decision variables.

A. *Mathematical complexity*

Ekici has proven that the variable sized bin packing problem with conflicts and item fragmentation (VSBPPC-IF) is NP hard, since it is a generalised version of the bin packing problem with conflicts and item fragmentation Ekici, 2022 Ekici, 2021.

Hvattum proves that the tank allocation problem (TAP) is generalisation of the single instant tank allocation problem (SITAP) Hvattum et al., 2009. The TAP is a multi period version of the SITAP and is therefore a generalisation of the SITAP. Using this reasoning, the mulit-period VSBPPC-IF is a generalisation of the VSBPPC-IF and is therefore also NP hard.

The Bin Packing Problem is generally known to be NP Hard, as mentioned by Korte et al., 2011. Therefore most authors also propose new heuristic solution methods. Due to the fact that the case at the infant formula factory does not consist of many parameters, this has not been done for this study.

B. *Model variants*

If powders are stored in silos, one cannot simply remove them from a silo and move them to another silo. This means that once a silo is built, it has to stay put. Therefore the focus of the variant should be on how how much powder is removed and added per time period. These constraints thus have implications for the model and change its objective function and constraints accordingly.

First of all a couple of new parameters and variables have to be introduced. The parameters are a_{it} and d_{it}, representing the amount of incoming and outgoing powder i at time period t. The extra variables in this case are the following: add_{iut} as the amount of powder added to bin u at time period t. rem_{iut} as the amount of powder removed from bin u at time period t. Also the parameter w_{it} no becomes sort of a redundant variable. When looking at the new objective function and added constraints these are the following:

$$\min \quad \sum_{u \in U} \sum_{k \in B} C_k y_{ukt} \tag{12}$$

$$\sum_{u \in U} rem_{i,u,t} = d_{i,t} \quad \forall i \in V, t \in T \tag{13}$$

$$\sum_{u \in U} add_{i,u,t} = a_{i,t} \quad \forall i \in V, t \in T \tag{14}$$

$$f_{i,u,t} = add_{i,u,t} - rem_{i,u,t} \quad \forall i \in V, u \in U, t = 0 \tag{15}$$

$$f_{i,u,t} = f_{i,u,t-1} - rem_{i,u,t} + add_{i,u,t} \quad \forall i \in V, u \in U, t \in \{1, T\} \tag{16}$$

$$y_{u,k,t} \leq y_{u,k,t+1} \quad \forall i \in V, u \in U, t \in \{0, T-1\} \tag{17}$$

$$a_{i,t} - d_{i,t} = w_{i,t} \quad \forall i \in V, t = 0 \tag{18}$$

$$a_{i,t} + w_{i,t-1} - d_{i,t} = w_{i,t} \quad \forall i \in V, t \in \{1, T\} \tag{19}$$

$$rem_{iut} \geq 0 \quad \forall i \in V, u \in U, t \in T \tag{20}$$

$$add_{iut} \geq 0 \quad \forall i \in V, u \in U, t \in T \tag{21}$$

Equation 12 is the objective function, that tries to minimise the total costs of the bins used. The current amount of material present in the system now depends on the incoming and outgoing material. This incoming and outgoing material then has to be divided over the present bins. Therefore equation 13, makes sure that the amount of outgoing material of all the silos is equal to the demand. While equation 14 makes sure that the incoming material is divided over the silos.

The current amount of material in a bin is determined by what was inside a moment ago as well as what is added to it and removed from it, as can be seen in equations 15 and 16. In the case of $t = 0$ there is no prior amount of material in the silo, so this is taken into account by adding the initial stock to the incoming material at the start.

Most of the constraints are fairly similar to the model presented before. However, the constraint of having the most material in the first bin has been removed as this could cause problems due to cyclic material stock. In this model the assumption has been made that once a bin is used, it will always be active, as in most applications one cannot easily add bins or remove them. Therefore a constraint has been added that guarantees this, as well as that it makes sure that a bin cannot change its type. This can be seen in equation 17.

Another equation that is needed, is the relation to time for the problem. With this relation, the varying incoming and outgoing materials are related to the amount of material that is present within the bins. Therefore parameter $w_{i,t}$, becomes a 'normal' variable, as can be seen in equation 18 and 19. The remaining equations 20 and 21 restrict the decision variables.

IV. Case study and results

For the case study some extra constraints have to be added to the variant that allows for powder flow. This is because of the hygiene regulations at the factory. Therefore only one powder is allowed in every bin, making all the powders incompatible. Furthermore there are 2 production lines, each having at most 3 powders in its system. The powders of the 2 production lines will not be able to go in the same silos as this is also in conflict with the hygienic regulations. Furthermore when a silo is emptied, it has to be cleaned before a different powder can enter the silo. Also the outflow of each silo is limited by a blower, meaning that the total outflow of all the silos cannot be too high. The extra constraints allowing cleaning are the following:

$$x_{i,u,t-1} + x_{j,u,t} \leq 1 \quad \forall i \in V, j \in V, u \in U, t \in \{1, T\} \tag{22}$$

$$\sum_{i \in V} \sum_{u \in U} rem_{iut} \leq mrem \quad \forall t \in T \tag{23}$$

$$\sum_{i \in V} (x_{i,u,t-1} - x_{i,u,t}) \leq cl_{u,t} \quad \forall u \in U, t \in \{1, T\} \tag{24}$$

In constraint 22 two different powders are not allowed to be in the same bin right after each other, forcing a time period where the bin is empty in between. Constraint 23 reduces the total outflow of each silo, having the maximum outflow per time period smaller than or equal to $mrem$. Finally constraint 24 forces the cleaning of silos with the new binary cl_{ut} which has an associated cost.

For the case study a new dataset has been generated for the expected volumes in 2026. This data has been used to run different scenarios of the models, where certain powders have been stored in silos and others not. The baseline where the silo storage is compared with, is storing the powders in a rented warehouse. The powders used at the factory are lactose, glucose, maltodextrin 12, maltodextrin 11 and maltodextrin 17.

A. Results

Due to the large number of silos needed, storing all powders in silos is infeasible. The main reason for this is that the maltodextrin 12 powders would be stored in about 16 100m3 silos, which would take up too much space. The baseline storage is the cheapest option, as it needs the least infrastructure. The model behaves as it should, below the powder storage can be seen of an overflow silo in Fig. 1.

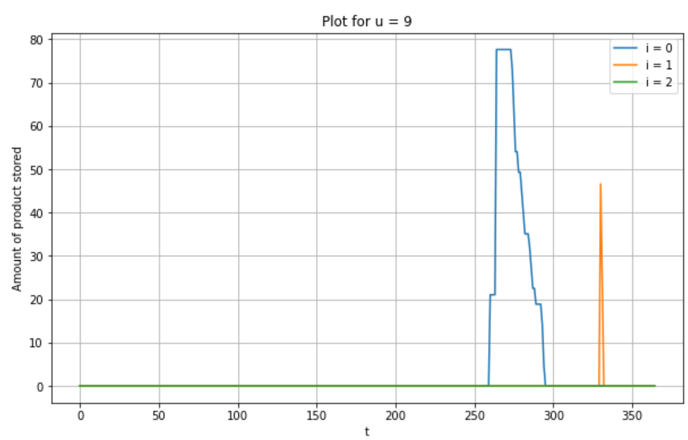

Fig. 1. Amount of powder stored in m3, at time period t in days for 2 of 3 powders in silo 9

When looking at the option of storing not all powders in silos, but just a few, the most interesting option is the storage of lactose in silos, while the other materials are stored in the rented warehouse. This can be seen in Table II. It has relatively low investment costs and handling costs, meaning that it could be implemented. This can be explained due to the fact that lactose has a relatively high density compared to the other powders according to its suppliers (“globaldairytrade.info”, n.d.) and (Roquette, n.d.).

Materials	Total costs (€)	Investment costs (€)	Handling costs (€)	Trucks used	Max. pallets	Area m2
Maltod. 12 in silos	2.825 k	2.574 k	251 k	275	51	209
Maltod. 12 not in silos	2.086k	1.857 k	229 k	258	67	137
Maltod. 12 & Lactose in silos	3.389 k	3.249 k	140 k	234	24	261
Lactose in silos	956 k	727 k	229 k	268	48	52
Maltod. 12 & Glucose in silos	3.370 k	3.136 k	234 k	284	51	254
Glucose in silos	1.037 k	614 k	423 k	301	67	45

TABLE II
CSPM OUTCOMES

When looking purely at the costs per year made, the lactose silos turn out to be the best solution. This is because it has lower handling costs than storing the pallets in a rented warehouse. After about 8 years, the investment of the lactose silos and all infrastructure will have been returned. This can be seen in Fig. 2.

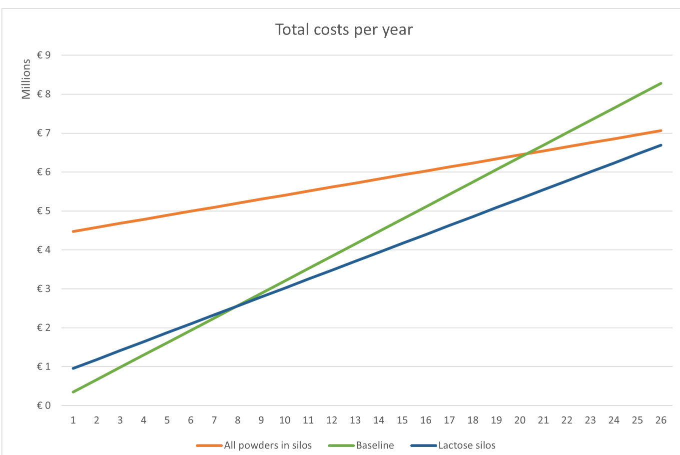

Fig. 2. Costs per solution over a time span of 25 years

V. Conclusion

This research has introduced a new version of the bin packing problem: the multi-period variable sized bin packing problem with conflicts and item fragmentation. It has presented a MILP mathematical formulation of the bin packing problem and has given a variant suitable for powder storage. This has been implemented at an industrial case, illustrating the applicability of the problem. The results of this implementation are:

- **Short term solution:** Store the powders in a rented warehouse and have trucks deliver these to the factory warehouse when needed. The silos are infeasible due to the huge amount of needed silos.
- **Long term solution:** Store lactose in silos and have it delivered in bulk. The other powders are stored in the rented warehouse. This would be the best solution after 8 years with investment costs of €727 k and €229 in yearly handling costs.

VI. Recommendations

As the models used to determine the needed silos and their filling strategy have been optimised for data based on daily consumption, it gives a good overview of what the costs might be in the future. One of the next steps before implementing the silos, would be to model these for a period of over 8 years. However, in this case the models would have even more parameters and take even longer to solve. Therefore a heuristic solution method should be developed for this variant of the bin packing problem.

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B

Cost calculations and assumptions

When looking at the cost inputs of all the models, these have to be accurately predicted in order for the models to give any useful values. When looking at the different kinds of costs, these can be divided into two main categories: infrastructure costs and (yearly) operating costs.

B.1. Infrastructure costs

The infrastructure costs consist of structures and machines that have to be bought and installed once in order to handle the powders. These consist of the following:

- Silos
- Silo insulation
- Piping
- Blowers
- Air filters and dehumidifiers
- Sensors
- Explosion suppression mechanisms
- Bigbag reshaper
- Rotary valves
- AGVs

Most of the costs will be approximated and verified afterwards by Nestlé experts. To start of most approximations are based on the DACE price booklet [15], supplied by Nestlé. DACE offers price indications for the Dutch process industry based on prices given by connected suppliers within the industry. All approximations and calculations will be explained below.

Silos

DACE offers a price indication for AINSI 304 silos based on their sizes. This material is suitable for hygienic environments. These silos range from 10 to 500 cubic meters. The prices include everything that is needed for the silos, excepts for the foundation costs, the structural costs and the transportation costs. Also the silos each have a standard corresponding height and diameter that will be used as well. As the maximum size of the current silos at Nestlé is 100 m3, this size will be assumed as a maximum for the other silos too.

Silo insulation

As the powders cannot be stored at to low temperatures, the silos have to be insulated as these are built outside. The costs of insulating a silo are based on its surface area. Depending on the shape of the silo part, a factor comes on top of the already calculated surface area as it is harder to insulate.

Therefore for every silo size, the insulated area has been calculated and the extra insulation costs have been added to the silo costs. The chosen insulation is winter insulation as, this is compliant to the needed insulation mentioned in chapter 4.

Piping

Pipes have a certain cost per meter also found on DACE. For these calculations an inner diameter of 10 mm has been taken as good enough approximation after talking to experts within Nestlé. As the pipes are sold per inches, the diameter of 4 inches will be taken. The pipes are also made of AINSI 304 steel and have to be grounded.

When calculating the length of the pipes that is needed, the amount of bends are an important factor as well as the height difference. For these, the lengths have been calculated and the bends and height differences have been factored in. For the pipes, the following would be needed. To Egron: 1 pipe for lactose, 1 pipe for maltodextrines. For EHP: 1 pipe for lactose, 1 pipe for glucose and maltodextrines. This is the best case scenario. In the worst case scenario, every powder would have its own pipes excpet for maltodextrin 11 - 1 & 11 - 2 and maltodextrin 12 - 1 & 12 -2 as these powders are the same. In case of not having the powders being delivered in bulk, the same piping is also needed in the other direction. However, in this case it would make sense to have the lactose tipped in the EHP and then moved to the silo as it guarantees a peptide free environment for the lactose.

Blowers

After talking to experts, rootblowers have been recommended for the blowers. For these, some calculations have to be done, as only a certain pressure drop is allowed to be over the whole piping when material is being transported. Also the blowers can only transport so much powder at the same time. This has to be sufficient to keep the production going 24/7. Otherwise it is not an option to install silos within Nestlé. The costs are thus related to the amount of material that has to be transported at the same time and by how much powder one root blower can transport per day.

As the blowers need suitable clean air, an dehumidifier system and aftercoolers are needed too as can be seen in figure B.1. For this the assumption will be made that these will be placed together with the root blowers and that only one of these systems is needed per 3 root blowers. As these depend on the amount of material they have to handle, the calculations can be made without running the model.

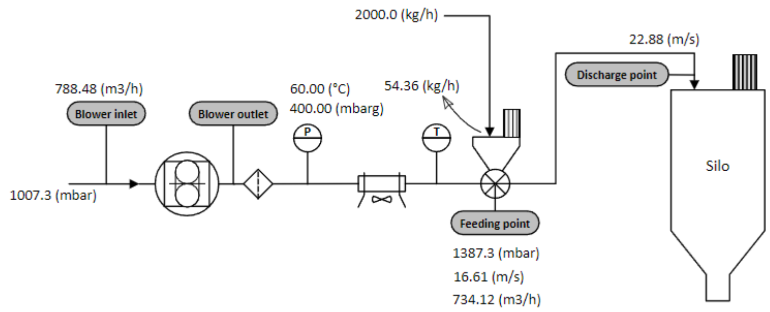


Figure B.1: Output of the pump calculation tool from Nestlé

This rootblower configuration is feasible for the needed distance, allowing one rootblower to transport 2000 kg of powder per hour. When looking at the powder consumption and arrival data, 2 blowers would be sufficient for handling the outgoing powder and 3 would be needed for handling the incoming powder.

Extra silo equipment
Each silo will have some sensors such as pressure sensors, humidity sensors and temperature sensors. These sensors are needed in order for the system to work. Additionally, flow sensors and pressure sensors are needed within the piping as to make sure that the right amount of powder is being transported at the right temperature. Each silo will need a rotary valve in order to unload it. Explosion surpression mechanisms can also be found on the DACE website and these have been incorporated in the costs of building one silo together with the sensors, rotary valves and control systems to operate a single silo.

Bigbag reshaper
If the bigbags will be reshaped, these have to move through the bigbag reshaper before entering the facility. Only one of these will be bought and the total costs of this machine will be added as a constant to the models.

B.2. Operational costs
When looking at the operational costs, these depend on the following:

- Man hours
- Electricity usage
- Pallet storage costs
- Cleaning costs
- Powder storage costs
- Transportation costs

Man hours
A certain amount of Nestlé employees will be needed to handle the powders within the facility. Employees would help on the following processes: unloading trucks with forklifts. Transporting bigbags to the Egron tipping station. Tipping the bigbags at the tipping stations. Depending on how many bigbags will arrive per truck, more or less employees are needed at Nestlé.

Electricity usage
Electricity is needed to power the rootblowers and to transport the powders. Depending on the amounts, more or less is needed.

Pallet storage costs
The costs for storing pallets are dependant on factors such as building costs, handling costs and energy costs. These will be combined in a cost per pallet per day of storage. In the case of storing pallets at the third party warehouse, these can be defined clearly. At Nestlé these are so low, that they can be assumed zero

Cleaning costs
When silos and pipes are not operational, these can be cleaned. Otherwise silos have to be cleaned periodically. Within Nestlé this is done once every 2 years for their internal silos. As the cleaning of a silo is a three man job and takes about one day, this can be approximated and added to the model.

Powder storage costs
Energy is needed to make sure that the environment of the powders within the silos is correct, for this costs are also made. However, these can also be assumed negligible

Transportation costs
When transporting powders via road or via pipes, costs are made. These costs will be calculated too. These are based on the amount of air that needs to be prepared for the root blowers as well as the amount of energy each root blower consumes.

For the transportation costs between the third party warehouse and the Nestlé warehouse, a price booklet has been supplied. This has been used as the basis for the driver costs, transportation costs, administrative costs and loading costs.

B.3. Input parameters

The input parameters have been validated by Nestlé experts and are good enough for usage.

PMM parameters

In the table B.1 below, the cost inputs for the PMM can be found.

Table B.1: Parameters PMM

Parameter	Value
ci	€ 1,27
cs	€ 1,60
co	€16,69
cp	0
ca	€ 70,13
ct	€ 10,08
cldm	€ 113,27

SM parameters

The parameters for the silo model can be found in table B.2 below and these are applicable for models including silos. Note that the blower capacity is very high as it is expressed in m3 per day instead of tons per hour. As this value depends on the amount of powder used, it can can be adjusted according to the maximum of powder handled. The $csilo$ is double for lactose silos as these have to be connected to two production lines.

Table B.2: Parameters for SM

Parameter	Value
ccl (cleaning costs)	€ 5.000
c (running costs of bin)	€ 0
co (piping costs EHP)	€ 12.173
co (piping costs Egron)	€ 15.365
co (costs per blower)	€ 22.030
co (blower energy costs)	€ 12,10 per ton
$mrem$	72 m3
csilo	€ 8.034

Silo sizes and costs

For the parameters W_k aqnd C_k, the silo sizes and their costs are needed. The available silo sizes and their costs are found in table B.3 below:

Table B.3: Silo sizes and their costs

Silo size	Silo costs
10 m3	€ 40.252
20 m3	€ 57.957
40 m3	€ 80.147
60 m3	€ 106.924
100 m3	€ 145.824

Extra parameters SPM

In case of the SPM, the piping costs double. As more pipes are needed. Only for Lactose the costs only grow with the piping costs to the EHP, as this is where it will be tipped. The cleaning costs stay the same, but the $csilo$ is doubled once more. Finally, co has an additional €23,43 per pallet in handling costs. $madd$ is changed to 216, due to the amount of blowers. Finally the values for ap_i can be found in table B.4 below:

Table B.4: Pallets per cubic meter

Powder	Pallets per m3 (api)
Glucose	0.5
Lactose	0.9
Maltodextrin 12 - 1	0.5
Maltodextrin 12 - 2	0.45
Maltodextrin 11 - 1	0.6429
Maltodextrin 11 - 2	0.6429
Maltodextrin 17	0.6667

CSPM parameters

The parameters for the CPSM are based on all the parameters above and are thus the same.

C

Detailed data analysis and preparation

In order to forecast how many silos will be needed or how much warehouse space should be rented, the data should be cleaned and prepared, such that it can be used effectively to forecast the powder arrivals and consumption. The way this is commonly done is by starting with the cleaning of the data [74]. Analysing the cleaned data and identifying trends. Finally this can be used for data generation. The data that has been provided by Nestlé is powder consumption data and powder arrival data from its SAP system.

Before doing any of this, it is important to understand the changes that will happen within the factory and to understand what data insights are important. For the Egron production line, growth in output will happen with the same machines as the line will stay the same. This means that probably more days will be used to produce and that some batches will be bigger. For the EHP a new production line will be built, but the output of the line itself will stay more or less the same. Thus the EHP consumption will be more or less the same, and that only the extra production line will double the consumption with more or less the same amount of consumption per day and number of consumption days.

Keeping this in mind, it is important to know how the growth of production will happen within the Egron line in more detail, as consumption data will have a bigger impact on the type of growth. While for the EHP, the overall trends are more important to mimic the consumption.

For the incoming data, it is important to understand how many trucks are used by each production line and how often these arrive to mimic the growth. Finally a choice has to be made on the storage strategy. Will it stay the same or will less material be stored? In this case the assumption is made that the storage strategy will stay the same and that the incoming and outgoing material amounts will both grow with the same factor.

C.1. Data cleaning

First of all the data has to be cleaned. This means that it has to be checked for outliers and that these have to be removed. The outliers include waste, sending trucks back to the supplier, inventory differences and small mistakes within the data.

After talking to experts within the demand planning department of Nestlé, most of the special cases can be solved. When a bigbag is being scrapped, this can be seen as material consumption and thus these actions can be added to the consumption data. The inventory differences at the end of the year are mostly due to small spillages when the bigbags are handled. As it is almost impossible for an operator to fully empty a bigbag without any spillage. The sum of these spillages results in the inventory differences at the end of the year. Since there is no data on the daily stock available, these differences will be averaged out over all consumption values, since this is where these spillages happen.

When looking at small mistakes, these include negative incoming goods or powder consumption of 1 kg. These are either corrections when powder is rejected or when a small sample is being taken. Negative incoming material has been removed and added as extra consumption that day or removed from an earlier shipment. Very small consumption has been removed from the data as these make no impact on the total production, but do impact averages quite much.

In 2022, 1 truck of goods has been rejected in the end of May. The most logical solution would be to just remove an earlier truck from the incoming values. However, this could not be done due to the fact that this would result in a negative stock of the material. Therefore the truck has been removed from other incoming trucks. Note that 1 truck is about 0.08% of the total incoming goods, but not changing the data would result in a difference of 17 extra pallets at the end of the year on a storage of 74 pallets. Which is about 22% of the total storage and thus has a bigger impact. To conclude 24 pallets have been removed from all incoming trucks, where most has been removed after august, since this is where the lowest inventory point was and the stock cannot become negative.

In 2023, a big amount of the maltodextrin 12 - 1 powder is suddenly turned into maltodextrin 12 - 2 in week 47. Since the amount is equivalent to about 69 bigbags, it has to be taken into account. Therefore new incoming shipments will be created for maltodextrin 12 - 2, while shipments of maltodextrin 12 - 1 will be made smaller or removed. All of this is done while making sure that the stock of a material never reaches zero. Now that the data is clean, it can be used for analysis.

C.2. Data analysis

When analysing the data, it is very important to get an overview of how production works as well as the incoming data. These will in turn affect the generated data as some things must stay the same in the new situation. An example of this is that only full trucks arrive at Nestlé and that half trucks cannot arrive in the generated data.

For the data different things have been analysed. These include monthly trends, weekly trends, average daily consumption and incoming amounts of material as well as pallet sizes and their distributions. Order sizes have been compared as well as days of consumption per month. Furthermore some materials can be analysed separately from each other as these are used in different production lines. Where chapter 2 only analysed the data briefly, the data will now be studied in more detail.

C.2.1. Yearly analysis

When looking at the incoming materials when summed on a weekly basis. It can be seen very clearly that in 2022, there was a stop in week 42. There was no incoming material in week 40 and almost no incoming material in week 41. There was almost no production in weeks 41 and 43, while there was no production in week 42. Furthermore, production in 2022 uses about 110.000 kg of material on average, except for a few weeks. For 2023 , this was more or less the same with more days where significantly less production happened. This can be seen clearly in figure C.1 and figure C.2.

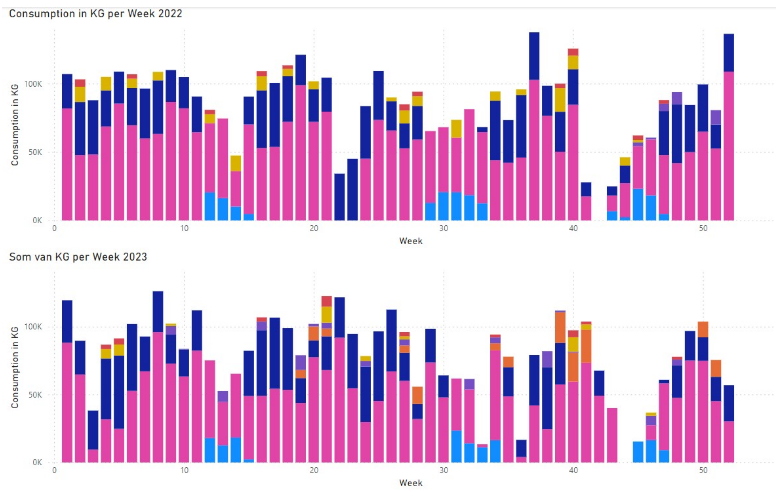


Figure C.1: Weekly powder consumption in 2022 (top) and 2023 (bottom)

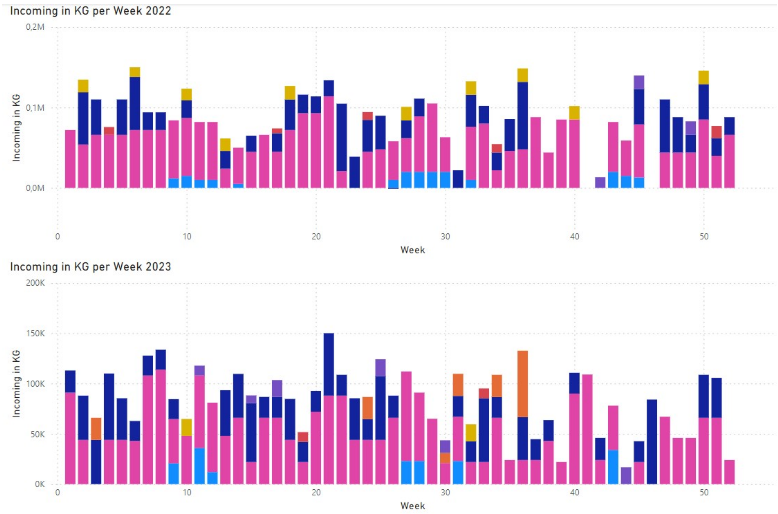


Figure C.2: Weekly powder arrivals in 2022 (top) and 2023 (bottom)

The maltodextrins 11 - 1, 11 - 2 and 17 are used more or less in the same way over the 2 years. The only big difference is that, maltodextrin 11 - 1 is used more in 2023 and less in 2022. In case of arrivals, there are fewer amounts of powder arriving in 2023.

For lactose, the consumption is more equally distributed in 2022 and less in 2023. Both years had a couple of moments that production was either zero or almost zero.

Maltodextrin 12 - 1, 12 - 2 and glucose show an interesting pattern, where glucose is used for production about 3 times per year for about 4 weeks. Maltodextrin 12 - 2 is only used in the year 2023 and not in 2022. Furthermore glucose arrives about 3 weeks before it is used, so this gives an indication of how long materials have to be stored. Furthermore the combined maltodextrin 12 - 1 and 12 - 2 consumption, shows about 4 peaks within 2023.

C.2.2. Powder usage

One of the things that needs to be analysed is the minimum usage of powders, this will in turn help predict how much the output can grow on a daily basis. If this is the size of a bigbag, this has to be noted. However, only maltodextrin 17 has a clear bigbag consumption size. When analysing the production orders, the following was found:

Egron line

The Egron production line uses the following powders: lactose, maltodextrin 11 - 1, maltodextrin 11 - 2 and maltodextrin 17. The expected growth of this line for when the AGVs will be implemented is about 17% and this number will be kept in mind when analysing this data. Since lactose is used by both lines, it will be treated separately.

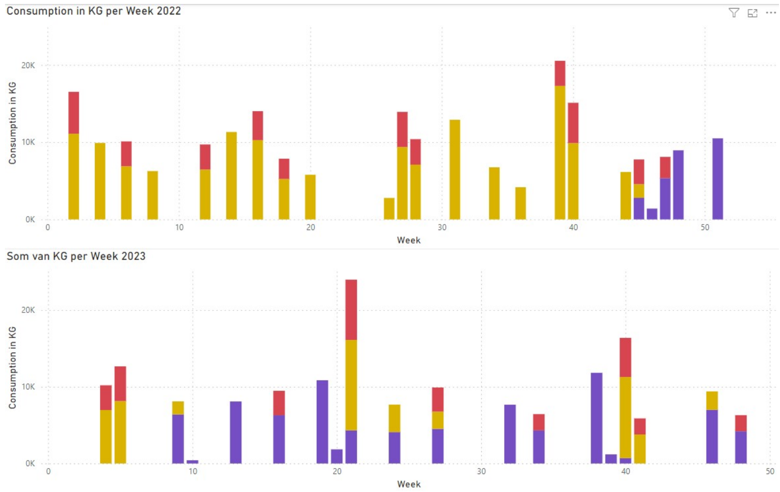
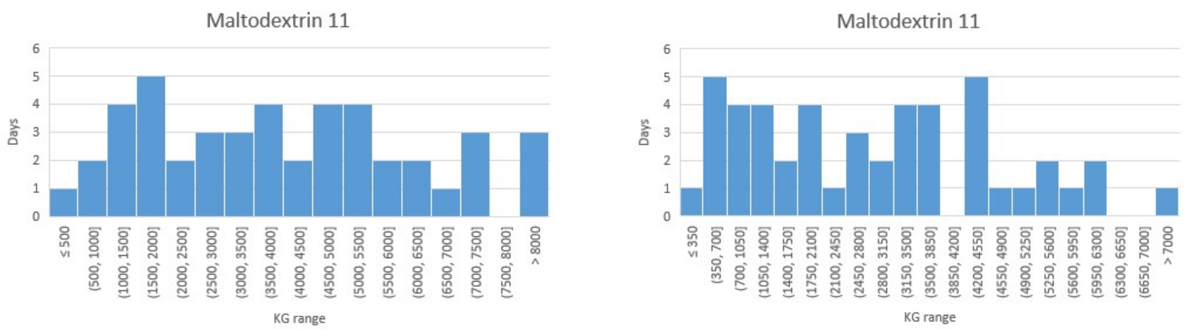


Figure C.3: Weekly powder consumption of maltodextrin 11 - 1 (yellow), 11 - 2 (purple) & maltodextrin 17 (red)

Maltodextrins:
As there are only 45 datapoints in 2022 and 57 in 2023, it is difficult to notice any clear trends. These few datapoints will also make forecasting more difficult. The maltodextrins are used about every other week in 2022, except for when there is no production within the Egron, which happens once or twice a year at the Egron as can be seen in figure C.3. In 2023 the maltodextrins are used about once every 3 weeks, also with the exception of a few stops. When looking at the total amount that is used daily, it is fairly evenly distributed as can be seen in figure C.4.

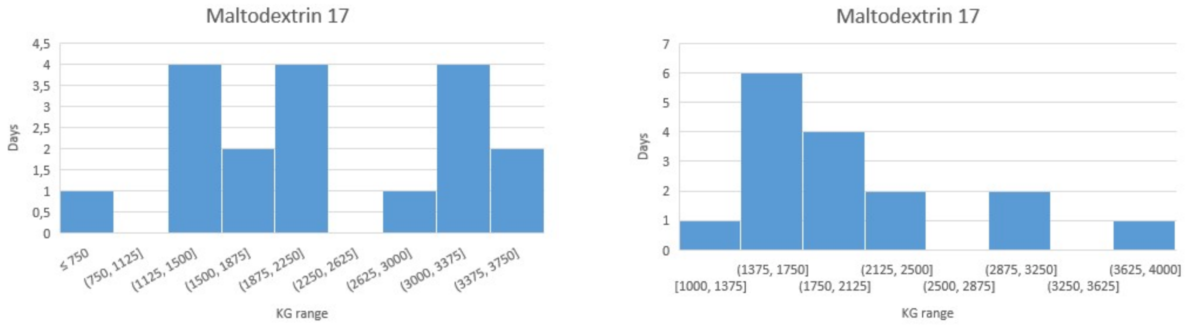


(a) Maltodextrin 11 consumption in 2022

(b) Maltodextrin 11 consumption in 2023

Figure C.4: Histograms of maltodextrin 11 consumption

For maltodextrin 17, a clear observation is that it is always used within the same week that the maltodextrin 11 - 1 and 11 - 2 are used, but then only about half of the time. Maltodextrin 17 is most often used per 2, 3, or 4 bags in 2022 and per 2 or 3 bags in 2023. All bags have the size of 750 kg. Once again, there are very few data points, meaning that the forecasting will be difficult.



(a) Maltodextrin 17 consumption in 2022

(b) Maltodextrin 17 consumption in 2023

Figure C.5: Histograms of maltodextrin 17 consumption

EHP line

As the consumption of the EHP will double, it is best to look at the overall consumption over the 2 years to see anything specific. Most clear is that the consumption of glucose happens for about 3 months a year in 2022, starting week 12, 29 and 43. Where in 2023 this happens in weeks 12, 31 and 45.

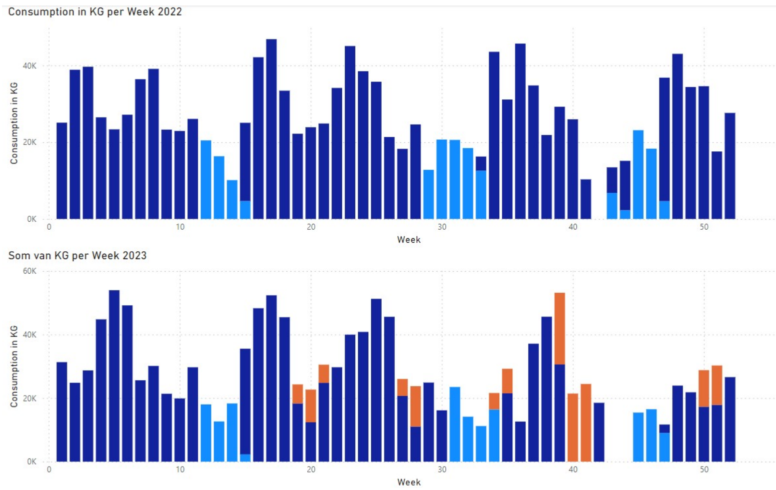
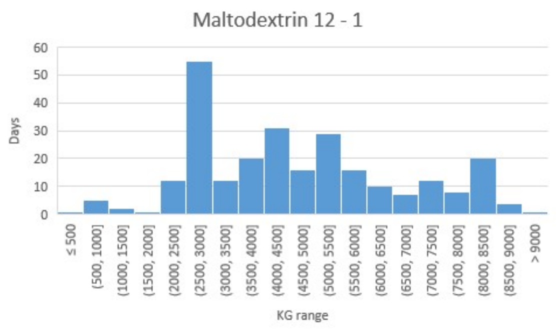
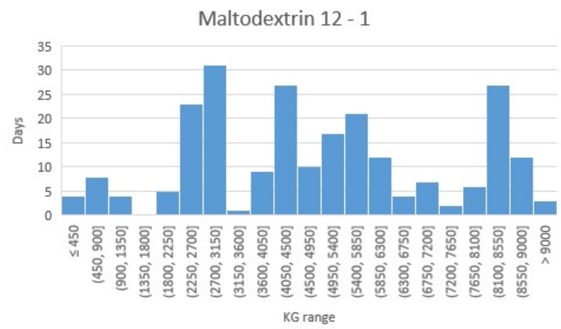


Figure C.6: Weekly powder consumption of maltodextrin 12 - 1 (dark blue), 12 - 2 (orange) & Glucose (light blue)

In 2023 maltodextrin 12 - 2 is introduced and this takes over some of the maltodextrin 12 - 1 consumption, as it is practically the same material. Furthermore maltodextrin 12 - 1 and 12 - 2 combined has a couple of usage peaks around week 5, 17, 24, 36 and 48. In 2022 production often uses 3 bigbags of maltodextrin 12 - 1 per day, and sometimes 4 or 5. While in 2023 it is most often 2, 3, 5 or 9 bigbags. For maltodextrin 12 - 2 it is most often 3 bigbags. The bigbags have sizes of either 900 or 1000 kg.

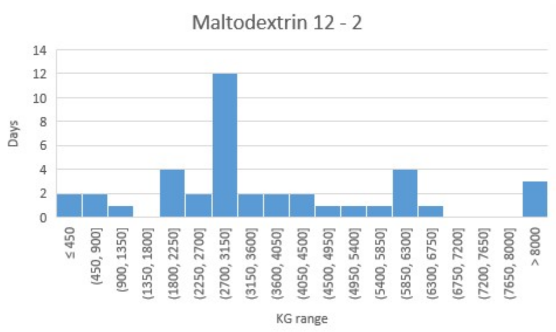


(a) Maltodextrin 12 - 1 consumption in 2022

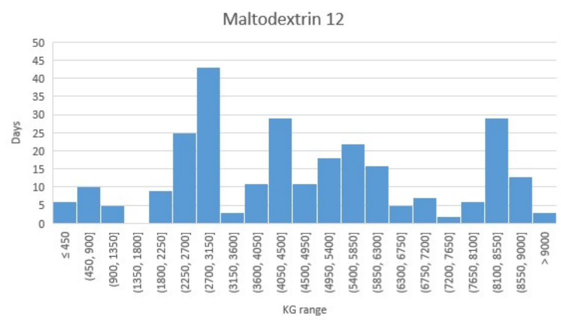


(b) Maltodextrin 12 - 1 consumption in 2023

Figure C.7: Histograms of maltodextrin 12 - 1 consumption



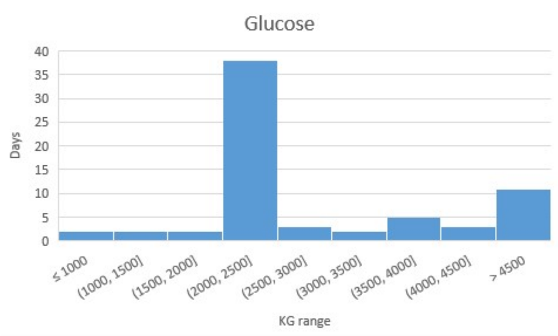
(a) Maltodextrin 12 - 2 consumption in 2023



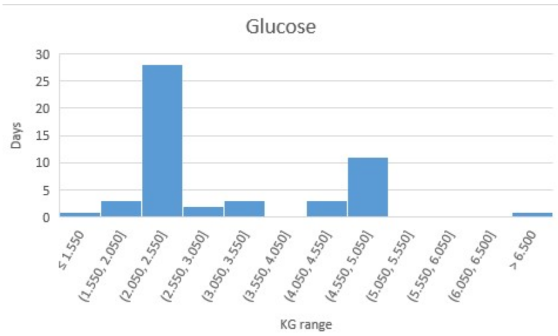
(b) Maltodextrin 12 consumption in 2023

Figure C.8: Histograms of maltodextrin 12 - 2 and maltodextrin 12 consumption

In 2023, glucose is most often used per 2 or per 5 bigbags, while the production orders go per 200 kg. In 2022, it is also most often done per 2 or 4 bigbags. It is used 3 times a year for about a month.



(a) Glucose consumption in 2022



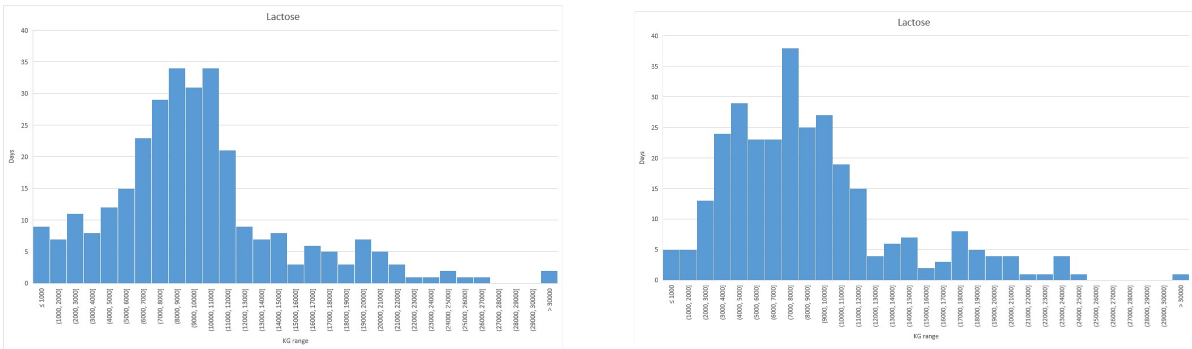
(b) Glucose consumption in 2023

Figure C.9: Histograms of glucose consumption

Lactose

As lactose is used by both the EHP and Egron production lines it has to be treated differently. According to Nestlé, lactose has been used for 23,5% by the EHP and for 76,5% by the Egron. This division will also be used to further estimate the total consumption of lactose. As lactose is used for 298 and 297 days in each year (see figure C.10), it is the material with highest number of days of consumption at Nestlé. Its daily consumption is similar to a skewed normal distribution, as can be seen in figure C.11. With a peak around the 9000 kg per day, which is equal to 9 bigbags on average.

Figure C.10: Weekly powder consumption of lactose



(a) Lactose consumption in 2022

(b) Lactose consumption in 2023

Figure C.11: Histograms of lactose consumption

C.2.3. Powder arrivals

Besides the usage of powders, the arrivals of powders also has to be analysed in order to find trends that could impact the data generation for when the AGVs will be implemented. Once again, the EHP, Egron and lactose will be covered. An important trend within the arrivals is that these never arrive during weekends and only on weekdays.

A problem encountered in the data, are the small inconsistencies found in the bigbag weights. Some suppliers of the same material have different bigbag sizes, meaning that a bigbag could weigh 1000 kg or 900 kg for example. This is not a problem for the models with silos, but it is for the pallet movement model (PMM). This is because it is unclear how much weight is available per pallet and the model is built in such a way that it can only accommodate one size. Furthermore a bigbag might be 2kg lighter or heavier than expected due to small deviations in the filling process at the supplier. Finally, production does not use an exact amount of bigbags, but just the quantity of powder that is needed. In this case half a bigbag could be used, resulting in half a bigbag of storage. In practice, this half bigbag would be tipped, and not returned to the warehouse. However, in the PMM this will be modelled as a stored half bigbag.

Egron line

The maltodextrin 11 powders have about one truck arriving each month in 2022 and only 8 arriving in 2023. These trucks also carry 24 pallets on average. For maltodextrin 17, only 4 trucks arrived in 2022 and 3 arrived in 2023. Making this a material that is used very sparingly. In 2022 the maltodextrin 11 - 1 and 11 - 2 would come mostly in 700 kg bags and sometimes in 800kg or 650 kg bags as well. In 2023 all received bags where of 700kg.

Figure C.12: Weekly powder arrivals of MD 11 - 1, MD 11 - 2 & MD 17

EHP line

Just as for the consumption, there is little overlap between the incoming amounts of maltodextrin 12 - 1 and maltodextrin 12 - 2 with glucose. What is interesting is that glucose is ordered about 3 weeks in advance to when it is used. In 2022, there was a clear gap of no maltodextrin arrivals between week 36 and 45, while in 2023 there weren't such gaps. Up to 4 trucks of maltodextrin can arrive per week, but often only 1 truck arrives each week. In 2023 there are more weeks that see 2 trucks arrive than 2022. In 2022 there are more shipments of glucose, but these contain more half filled trucks. In 2023 only full trucks arrive, while sometimes there are even 2 trucks arriving.

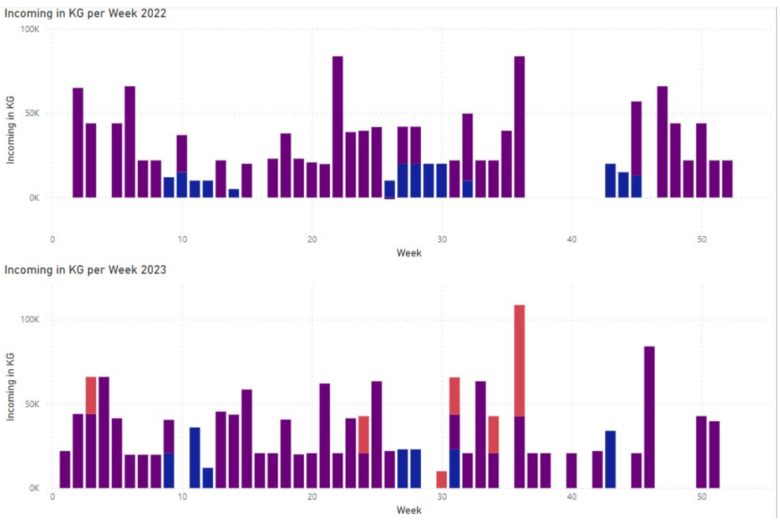


Figure C.13: Weekly powder arrivals of MD 12 - 1, MD 12 - 2 & glucose

Lactose

The sizes of the lactose trucks have changed in 2023 compared to 2022. In 2022, most trucks had a size of 24.000 kg, while in 2023 these were most often 22.000 kg. On average 2 trucks arrive per week, but this can be 1 or even 5 trucks per week. A couple of times per year, there are no deliveries.

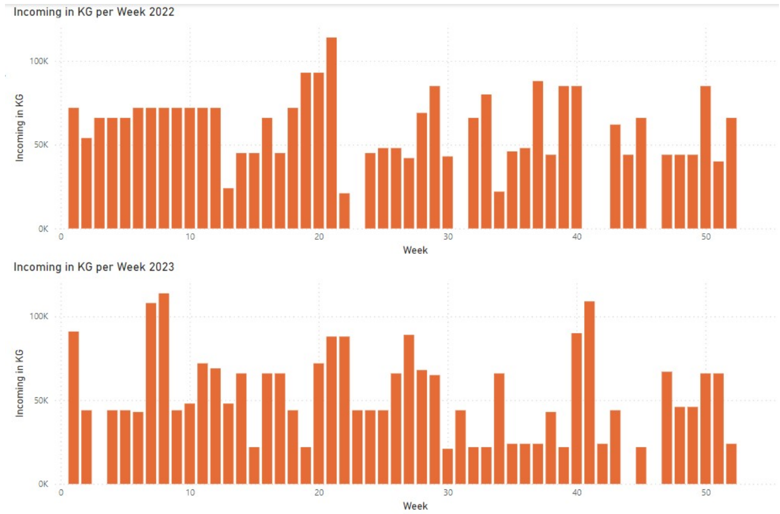


Figure C.14: Weekly powder arrivals of lactose

C.3. Data generation

When generating data, two incoming datasets have to be generated and only one consumption dataset has to be generated. This is because for the incoming data, bulk trucks and normal trucks have to be modelled.

For the data generation, the 'worst case' will be taken into account as this results in the highest amount of bigbags present within the system as well as the highest amount of powders within the system. If for example bigbags can be delivered in 900 or 1000 kg, 900 kg will be used for the data generation as it results in more incoming trucks and more storage of powders.

For the new production line, it is assumed that it will produce out of sync with the other production line, resulting in lower consumption peaks of glucose and maltodextrin 12.

C.3.1. Generation of consumption data

The data that will be generated first is the consumption data, as this is has the highest variability. Also input data is often output data dependant as stock levels cannot be lower than a certain value. Therefore generating input data will be done after generating output data. The steps of doing this are presented below, and each step will be discussed in more detail after. The output data will be generated in the following way:

1. Determine how many days of extra production will likely happen.
2. Change histograms of powders such that these have a higher mean. Changes should be in line with the pallet sizes, if applicable.
3. Take average days of consumption per week based on the 2 historical years. This will be the expected days of consumption of this week.
4. Using a random number generator assign a value to a day of the week. Do this for each week.
5. Check if outputs make sense and change these manually if necessary.

Step 1
As the output will be assumed to grow by a certain factor, this can be done by either producing more days per year or by producing more per day. As there are only 365 days in a year, a line cannot produce more than these days. Furthermore machines need to be cleaned and therefore continuous production is not possible. When determining these numbers it is important to take the factory in mind.

For the Egron line, no extra machines will be built or placed, therefore most of the growth will come from producing more days per year. For the maltodextrins, a couple of extra production days will take place, while a few days will see more production. However as there is very little data on maltodextrins, this is just an assumption that has been made.

For the EHP a second line will be built. When looking at the growth factor of 2,086 it is assumed that this consists of 2 lines that produce 1,043 as much as in 2023 and these will produce identically. Therefore only few extra days are needed while the production amounts can stay more or less the same. The same goes for glucose. This means that no new histogram has to be made and that the current one can be used.

Lactose will see a some increase in days used by production as it is being used by both factory lines, one of which will grow by 2. However lactose is already used almost 300 days a year, therefore not many extra days are left. Thus about 20 extra days of production are assumed.

Step 2
For every powder, the distribution type has been analysed. After this, the mean has been shifted upwards. The maximum value has been kept, as this is machine dependant, while the minimum value has been brought upwards. Therefore, the variance of the new distribution has become smaller. The generated data should have the same bin sizes if the bin size is based on pallet sizes.

When looking at the histograms of all consumption data, most often there are a few consumption sizes that are standard and used most (for example for glucose). For maltodextrin 17 there are also multiples of the bigbag sizes to be found within the data. Therefore the size of 1 or more bigbags has been added to most values and the same distribution has been used to generate values for the new dataset, that still has a similar distribution. However, the maximums have been left intact as these are determined by the factory equipment.

Step 3
For every week within the year a new expected total output is needed, that is similar to the trends seen within 2022 and 2023. As not all trends align, this is not a must for the weekly output that should be perfectly met, but more or less reached. For some materials that had a clear trend difference between 2022 and 2023, 2023 has been factored in stronger or taken as the only reference. The number of days without production is then averaged over the two years, factoring in the trends from the yearly analysis and a week without production. Also these days have been reduced a little bit as has been mentioned before. The days of production per week will then be used in the next step.

Step 4
Using a random generator in excel, a value is generated according to the new mean and standard deviation and added to the new data. The day the value is assigned to in the week is also determined using a random number generator, while making sure that this is not twice on the same day.

Step 5
Now that the data has been generated it has to be checked. The total consumption should be right. The amount of days of production has to be right. The number of days of production before stoppage should be right. The days of no production should be right. Furthermore the trend should also be right, when looking at the yearly consumption. If any change was needed, this has been done manually.

C.3.2. Generation of incoming data

When looking into generating the incoming data, the generation becomes more complex and needs more manual input. This is because the stock can never be negative.

For the Egron maltodextrins, there are very little deliveries. That's why for these powders a manual approach has been taken. The incoming data has been compared to 2023 as this is the most up to date and the deliveries have been done in such a way that the stock jumps up at around the same values as can be seen in 2023, with the different production peaks taken into account. This simulates a reorder point.

For Lactose, there was very little trend in the incoming data. Therefore the average number of trucks per week have been matched and random data has been created using excel to pick the delivery days and amount of deliveries per week.

For glucose the deliveries are very closely linked to the consumption. As deliveries start 2 to 3 weeks before production, this will be replicated in the data. Again random delivery values have been assigned to random days, while making sure that there is no negative stock. The same has also been applied to maltodextrin 12 - 1 and maltodextin 12 - 2. As there is no delivery when glucose is consumed and a peak in deliveries about 2 weeks before consumption deliveries.

Initial stock
As not only the incoming values have to be generated, but the initial stock as well, the initial stock has also been generated. This has been done by taking the average stock of each material over the two years and by multiplying this with the growth the material is expecting.

C.3.3. Bulk data

Bulk trucks have different sizes than normal trucks, The approximate volume of bulk trucks depends on its volume and empty weight. In the biggest part of Europe a maximum total tonnage of 40 tons per truck is allowed [66] meaning that this would change the amount of kg brought per material. Based on info of suppliers [1] the following materials have the following bulk densities and bulk truck sizes:

Material	Bulk density (1000 kg/m3)	Bulk truck size	Powder weight
Lactose	0.9	38 m3	34.200 kg
Glucose	0.50	66 m3	33.000 kg
Maltodextrin 12	0.45	66 m3	29.700 kg
Maltodextrin 11	0.45	66 m3	29.700 kg
Maltodextrin 17	0.50	66 m3	33.000 kg

Table C.1: Powders and their approximate bulk densities

These size are actually bigger than the normal shipment size for most materials. This means that less trucks will be needed on a weekly basis. Smaller amounts could also be ordered, but this will not be taken into account for this study. Using this information, the weekly incoming amount of powder has been replicated as closely as possible.

C.4. Data validation

Finally the data has to be validated, to make sure it is a good representation of a possible future scenario. This is done in 2 ways, by comparing averages, trends and histograms from the generated data with the historical data and by presenting it to experts and by collecting their feedback.

C.4.1. EHP data validation

For the EHP, the current dataset has been used to generate random values, therefore it does not make sense to compare the histograms of the consumption data. When looking at the yearly consumption, the offset of the second production line can be clearly seen in figure C.15. The glucose values have clearly been generated once and added with a couple of weeks in between. This is however fine for the needed level of detail.

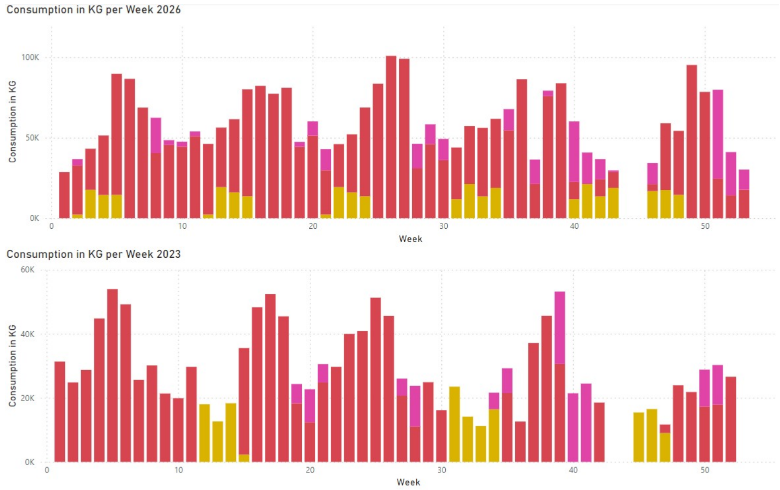


Figure C.15: Weekly consumption of maltodextrin 12 - 1 (red), 12 - 2 (pink) and glucose (yellow)

When looking at the total generated stock, this is quite a lot as can be seen in fig C.16. This can be explained due to the fact that maltodextrin 12 - 2 is newly introduced and grows a lot in 2023. When extrapolating this, the stock becomes even bigger. When this was discussed with experts, the suggestion was to leave it as it shows the necessity of Nestlé reducing its stock.

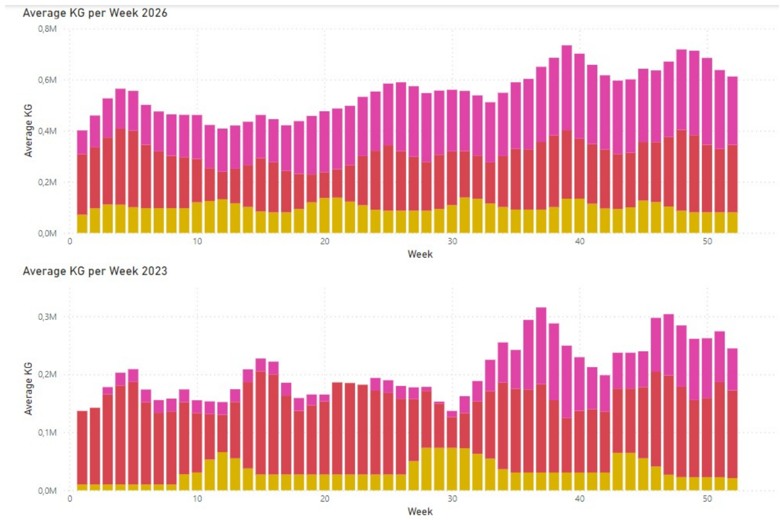


Figure C.16: Weekly stock of maltodextrin 12 - 1 (red), 12 - 2 (pink) and glucose (yellow)

This will have an impact on the outcome of the models, but as more material arrives at Nestlé than leaves the facility it makes sense. This also shows that when a second production line is needed this will impact the needed safety stock. Apart from this, the stock curve does make sense.

C.4.2. Egron data validation

When looking at the consumption of maltodextrin 11 - 1, 11 - 2 and 17, the consumption data shows little difference in amounts and most variation is within the weeks of production. The amounts are fairly the same due to the growth of just 17%, as can be seen in figure C.17.

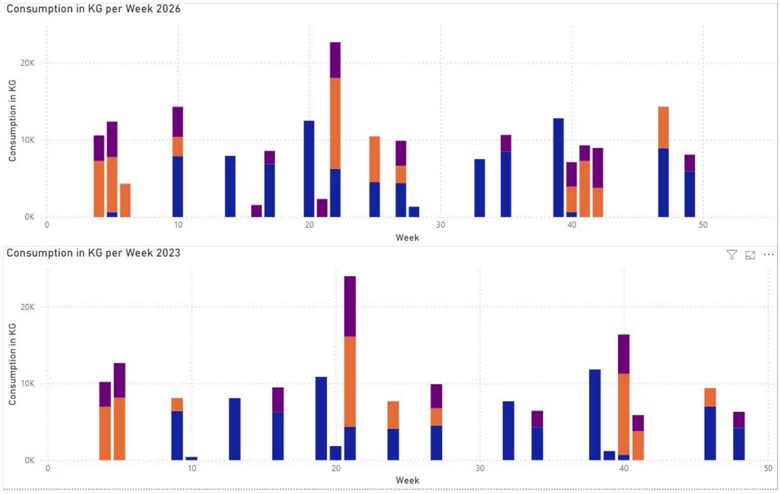


Figure C.17: Weekly consumption of maltodextrin 11 - 1 (orange), 11 - 2 (blue) and 17 (purple)

When looking at the stock of these powders, the averages are very similar as there is little product that is ordered too much on a yearly basis. However, there is little certainty in this data due to the fact that it has few data points.

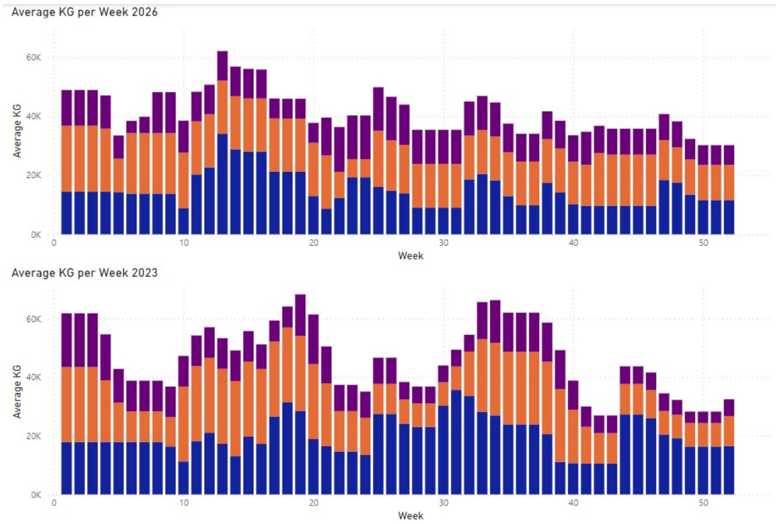
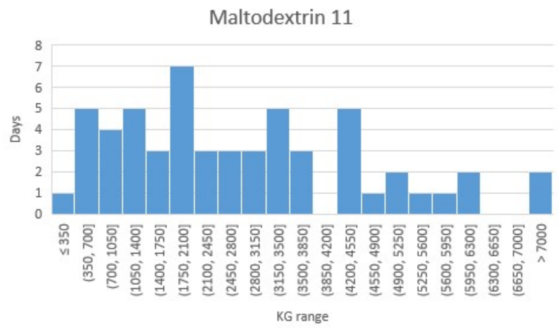
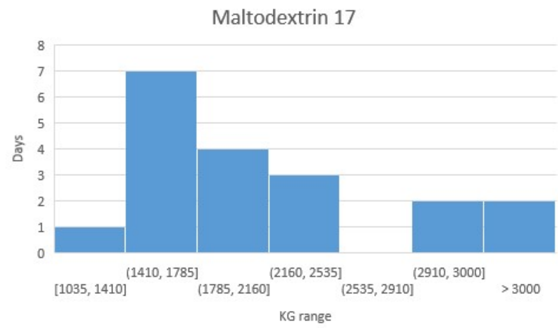


Figure C.18: Weekly stock of maltodextrin 11 - 1 (orange), 11 - 2 (blue) and 17 (purple)

The histograms in figure C.19 below, show some overlap with the histograms from 2022 and 2023 in figures C.4 and C.5. But as there is little available data, this can be expected.



(a) Histogram of maltodextrin 11 consumption



(b) Histogram of maltodextrin 17 consumption

Figure C.19: Histograms of maltodextrin 11 and maltodextrin 17 consumption in 2026

C.4.3. Lactose data validation

The lactose consumption data in 2026 has fewer weeks where almost nothing has been consumed. This can be explained by the fact that it is used more often and by more production lines. Meaning that if one of the production lines stops, the impact on the consumption is smaller, as can be seen in figure C.22. Apart from this the lactose consumption looks plausible with the clear stopping week.

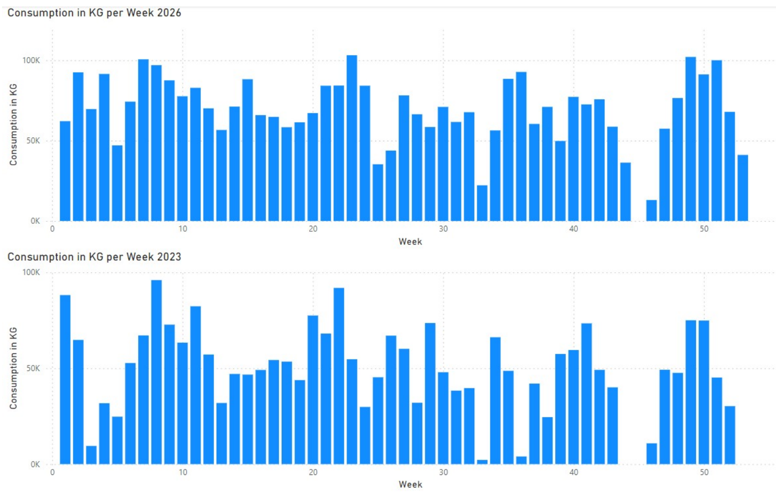


Figure C.20: Weekly consumption of lactose

The stock of lactose is also much higher than the stock in 2023. This is again due to the fact that Nestlé order more than it needs and this gets extrapolated in 2026. Besides this, the data has been validated by Nestlé experts.

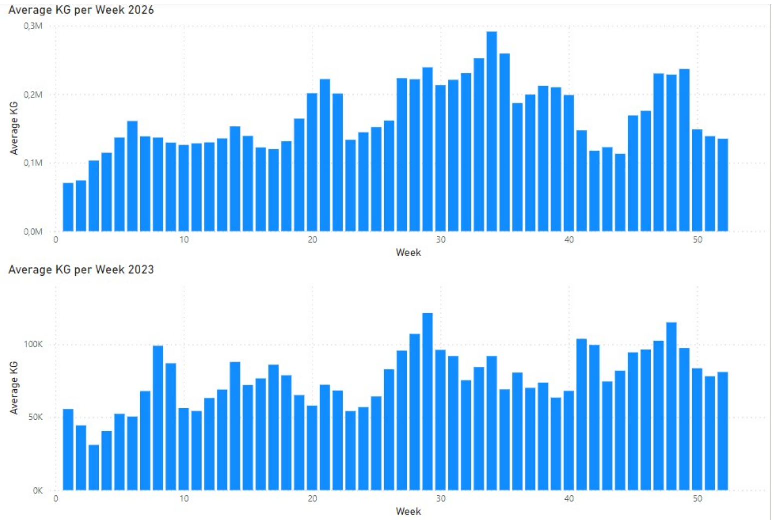


Figure C.21: Weekly stock of lactose

As the data generated for lactose has been done using a random number generator, the data can be put in a histogram to be checked. As can be seen in figure C.22, the histogram has a higher mean and smaller standard deviation, thus making it correct.

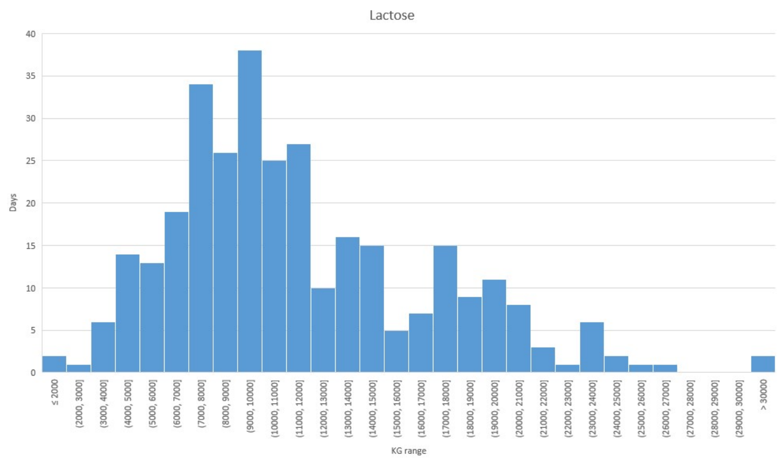


Figure C.22: Histogram of lactose consumption

C.4.4. Conclusion

The data has been generated and except for the high stock, no anomalies have been found. The data can thus be used for the case study. The tables with the respected values can be found in Appendix D.

D Tables

	Hygiene	Implementation complexity	Integration with current workflow	Safety and compliance	Profitability
Hygiene	1	9	9	1	9
Implementation complexity	1/9	1	3	1/9	5
Integration with current workflow	1/9	1/3	1	1/9	3
Safety and compliance	1	9	9	1	9
Profitability	1/9	1/5	1/3	1/9	1

Figure D.1: Comparison matrix M

Table D.1: Sample incoming and outgoing data of 3 powders

Time	In 1	In 2	In 3	Out 1	Out 2	Out 3	Total stock 1	Total stock 2	Total Stock 3
0	18	14	26	7	9	22	11	5	4
1	25	24	33	1	23	1	35	6	36
2	18	28	12	1	4	8	51	30	41
3	0	5	37	0	5	9	51	30	69
4	8	21	21	7	15	24	52	36	66
5	4	11	10	1	12	5	55	35	71
6	5	5	6	7	13	8	52	27	69
7	3	16	25	9	10	11	47	33	83
8	2	20	24	3	2	6	46	51	101
9	10	20	21	6	17	4	50	54	118
10	2	10	21	4	16	3	48	48	135
11	8	9	25	2	20	10	54	37	150
12	4	9	28	7	15	16	52	31	162
13	3	20	20	3	22	10	52	28	172
14	0	24	6	7	23	23	46	29	154
15	10	12	12	0	12	9	56	29	158
16	10	15	9	3	23	11	63	21	156
17	4	11	24	1	12	20	65	20	159
18	2	21	28	5	23	4	63	18	183
19	1	21	3	6	6	1	58	33	185
20	4	20	6	5	0	11	56	53	180
21	7	17	9	4	20	14	59	50	174
22	3	6	15	6	13	2	56	43	188
23	1	15	19	0	15	5	57	43	202
24	8	13	29	1	19	10	64	37	221
25	3	21	21	2	4	4	65	53	239
26	1	1	12	4	18	22	62	37	229
27	3	20	29	5	1	19	60	56	239
28	10	14	29	1	23	23	69	47	245
29	3	11	4	6	9	3	65	48	247
30	1	10	16	2	11	6	64	47	257

Table D.2: Sample silo sizes and costs

Size	Cost
25	25
50	50
75	75
100	100
10	10
200	200
40	40

Table D.3: Verification tests

MODEL	PARAMETERS TO CHANGE	HYPOTHESIS	RESULT	HYPOTHESES CORRECT?
SILO	max silo size 50	Model becomes infeasible	Model is infeasible	Yes
SILO	max out per silo = 15	More silos needed	Extra silo of 10	Yes
SILO	max out per silo = 15, cleaning cost = 10	Costs go down, more silos cleaned	Extra silo of 10 and cleaning used	Yes, cleaning is cheaper than holding multiple silos
SILO	costs silo size 100 becomes 50	Costs go down, more size 100 silos used	sizes 200, and 100	Yes, still 200 due to holding costs
SILO & PALLETS	max in per silo = 20	More silos are used and cleaning is needed	6 silos used, 200 75,75,50,10,10	Yes, 4 times cleaning
SILO & PALLETS	max in =20 & out per silo = 15	More silos needed and more cleaning	6 silos used, 200 75,75,50,10,10	Yes, 2 times extra cleaning
SILO & PALLETS	max in =20 & out per silo = 15, cleaning = 1000	No cleaning at all	No cleaning, very small amounts of powder left in every silo	Yes, might be a problem, but this can be solved with changing storage costs. It is cheaper to store a minimum amount of material, than to clean the silo.
PALLETS	storage third party warehouse cs=100	Most stock goes to warehouse, until max	Drops at 25, but at the end of time period growth due to transport costs	Yes
PALLETS	pallet handling costs cp=0	More stock to company warehouse	40 more pallets used, but still low amount at warehouse due to truck costs	Yes
PALLETS	Truck size = 10	More trucks driving, higher costs	Higher average of daily trucks, more days with trucks, higher costs	Yes
PALLETS	max daily trucks = 2	Almost every day 2 trucks, higher costs	Almost 2 trucks per day every day, more deliveries	Yes
PALLETS	max pallets warehouse	More storage at third party, until infeasible	Infeasible for less than 73 pallets storage (needed for weekends), never more than 250, due to transportation costs	Yes
PALLETS	Transport costs to 1000	All trucks are filled to the max and the least amount of trucks drive	Fewer trucks drive, costs go up	Yes
COMBINED	Materials are not compatible	More materials stored as pallets	Silo costs become more expensive, less material stored in silos	Yes

Table D.4: Complexity experiment SM

MATERIALS	SILOS	SILO TYPES	TIME PERIODS	CALCULATION TIME	OPTIMALITY GAP
2	6	6	10	1,21	0
2	8	6	10	4,97	0
2	10	6	10	3,17	0
2	6	8	10	1,61	0
2	6	10	10	2,92	0
2	6	6	20	5,72	0
2	6	6	30	5,98	0
3	6	6	10	6,83	0
3	8	6	10	40,29	0
3	10	6	10	176,68	0
3	6	8	10	17,28	0
3	6	10	10	7,68	0
3	6	6	20	82,39	0
3	6	6	30	32,97	0
4	6	6	10	54,61	0
5	6	6	10	31,5	0

Table D.5: Complexity experiment PMM

MATERIALS	TIME	CALCULATION TIME	OPTIMALITY GAP
2	10	0,04	0
2	20	0,16	0
2	30	0,38	0
3	10	0,06	0
3	20	0,16	0
3	30	0,3	0
4	10	0,13	0
4	20	0,14	0
4	30	2,62	0
5	10	0,1	0
5	20	0,28	0
5	30	1,63	0
6	10	0,05	0
6	20	1	0
6	30	1,6	0

Table D.6: Complexity experiment CSPMM

MATERIALS	SILOS	SILO TYPES	TIME PERIODS	CALCULATION TIME	OPTIMALITY GAP
2	6	6	10	1,99	0
2	8	6	10	3,78	0
2	10	6	10	3,26	0
2	6	8	10	1,33	0
2	6	10	10	2,21	0
2	6	6	20	7,33	0
2	6	6	30	10,3	0
3	6	6	10	11,5	0
3	8	6	10	74,48	0
3	10	6	10	109,42	0
3	6	8	10	5,01	0
3	6	10	10	20,8	0
3	6	6	20	24,05	0
3	6	6	30	84,54	0
4	6	6	10	53,41	0
5	6	6	10	52,39	0

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
108.00	104.26	559.67	208.43	32.08	49.86	24.10

Table D.7: Initial stock in m3

Table D.8: Initial stock pallets 3PL

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
54	94	183	94	21	32	16

Table D.9: Pallets per m3 of material

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0.5	0.9	0.5	0.45	0.6429	0.6429	0.6667

Table D.10: Bulk powder arrivals in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0.00	0.00	0.00	0.00	0.00	0.00	0.00
66.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	66.00	0.00	0.00	0.00
66.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	66.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	66.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table D.10: Bulk powder arrivals in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
66.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	66.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	66.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	66.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
66.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00

Table D.10: Bulk powder arrivals in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	66.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	66.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	66.00	0.00	0.00	0.00
66.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table D.10: Bulk powder arrivals in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
66.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	66.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	66.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	66.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	66.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table D.10: Bulk powder arrivals in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
66.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
66.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00

Table D.10: Bulk powder arrivals in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	66.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	66.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	66.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	66.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
66.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
66.00	0.00	0.00	66.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	66.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	66.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	66.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table D.10: Bulk powder arrivals in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
66.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	66.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00

Table D.10: Bulk powder arrivals in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	66.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	66.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	36.67	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table D.11: Powder arrivals in pallets

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0	0	0	0	0	0	0
23	24	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	24	0	22	0	0	0
23	22	24	0	0	0	0
0	24	24	0	0	0	0
0	0	0	22	0	0	0
0	24	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
23	24	0	0	0	0	0
0	22	24	22	0	0	0
0	44	0	0	0	0	0
0	22	24	0	0	0	0
0	24	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

Table D.11: Powder arrivals in pallets

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0	0	0	0	0	0	0
0	22	24	0	0	0	0
23	24	0	0	0	0	0
0	0	24	0	0	0	0
0	24	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	22	0	0	0	0	0
0	21	24	0	0	0	0
0	22	24	0	0	0	0
0	0	0	0	0	0	0
0	22	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	24	0	0	0	24	0
0	24	24	0	0	0	0
0	0	0	0	0	0	0
0	0	24	0	0	0	0
0	24	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	24	24	0	0	0	0
0	0	0	0	0	0	0
0	24	24	0	0	0	0
0	22	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	13
0	22	0	0	0	0	0
0	0	0	22	0	0	0
0	22	24	0	0	0	0
0	44	0	0	0	0	0
0	24	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	24	0	0	0	0	0
0	0	24	0	0	0	0
0	24	0	0	0	0	0
0	0	0	22	0	0	0
0	24	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
23	22	0	0	0	0	0
0	21	0	0	0	0	0
0	22	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	22	0	0	0	0	0
0	0	0	0	24	0	0
0	24	0	0	0	0	0
0	66	0	0	0	0	0

Table D.11: Powder arrivals in pallets

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
12	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	22	0	0	0	0	0
0	0	24	0	0	0	0
0	22	0	0	0	0	0
0	0	0	0	0	0	0
0	22	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	24	0	0	0	0	0
0	0	24	0	19	0	0
0	0	24	0	0	0	0
0	22	24	0	0	0	0
0	24	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	22	0	0	0	0	0
0	0	24	0	0	0	0
0	22	24	0	0	0	0
0	21	24	0	0	0	0
0	0	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	24	24	0	0	0	0
0	0	24	0	0	0	0
0	24	24	0	0	0	0
0	0	24	0	0	0	0
0	24	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	21	24	0	0	0	0
0	21	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	22	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	24	0	0	0	0	0
0	0	0	0	0	0	0
0	24	24	0	0	0	0
0	0	24	0	0	0	0
0	0	0	22	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	21	24	0	0	0	0
0	43	24	0	0	0	0
0	0	0	22	0	0	0
23	21	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	22	24	0	0	0	0

Table D.11: Powder arrivals in pallets

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0	22	0	22	0	0	0
23	21	0	0	0	0	0
0	44	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	22	0	0	0	0	0
12	22	0	0	0	0	0
0	24	24	0	0	0	0
0	0	0	22	0	0	0
0	22	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	24	0	0	0	0	0
0	22	24	0	0	0	0
0	22	0	0	0	0	0
0	21	24	0	0	0	0
0	24	0	0	0	0	20
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	24	0	0	0	0
0	0	24	0	0	0	0
0	21	24	0	24	0	0
0	21	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	24	0	0	0	0
0	0	48	0	0	0	0
0	22	24	0	0	0	0
0	22	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	24	0	0	0	0	0
0	24	24	0	0	0	0
0	24	24	0	0	0	0
0	21	24	0	0	0	0
0	0	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	24	24	0	0	24	0
0	22	24	0	0	0	0
0	0	24	0	0	0	0
0	0	24	0	0	0	0
0	0	0	22	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	24	24	0	0	0	0
0	22	24	22	0	0	0
0	24	24	0	0	0	0
0	0	24	0	0	0	0

Table D.11: Powder arrivals in pallets

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	24	24	0	0	0	0
0	69	0	0	0	0	0
0	24	24	0	0	0	0
0	0	24	0	0	0	0
0	22	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	21	0	0	0	0	0
0	21	0	0	0	0	0
0	0	24	0	0	0	0
0	0	24	0	0	0	0
0	21	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	22	24	0	0	0	0
0	0	0	0	0	0	0
0	22	24	0	0	0	0
12	0	0	0	0	0	0
0	22	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	24	0	0	0	0
0	21	0	0	0	0	0
0	0	0	0	0	0	0
0	0	24	0	0	0	0
23	22	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	22	0	0	0	0	0
23	22	0	0	0	0	0
0	21	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
12	0	0	0	0	0	0
0	45	24	0	0	0	0
0	22	0	0	0	0	0
0	22	0	0	24	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	22	0	0	0	0	0
0	0	24	0	0	0	0
0	22	0	0	0	0	0
0	0	0	0	0	0	0
0	22	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	24	0	0	0	0
0	22	24	0	0	0	0

Table D.11: Powder arrivals in pallets

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0	21	24	0	0	0	0
0	0	0	22	0	0	0
0	21	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	21	24	0	0	0	0
0	21	24	0	0	0	0
0	0	24	0	0	0	0
0	0	24	0	0	0	0
0	0	0	22	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	21	24	0	0	0	0
0	0	48	0	0	0	0
0	0	0	0	0	0	0
0	0	24	22	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	44	0	0	0	0	0
0	0	24	0	0	0	0
0	22	24	0	0	0	0
0	22	24	22	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	21	0	0	0	0	0
0	0	24	0	0	0	0
0	48	24	0	0	0	0
0	21	24	22	19	0	0
23	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	24	0	0	0	0
23	0	0	22	0	0	0
0	22	24	0	0	0	0
0	0	24	0	0	0	0
0	22	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	22	0	22	0	0	0
0	0	0	0	0	0	0
0	21	0	0	0	0	0
0	22	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	13
0	0	0	0	0	24	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

Table D.11: Powder arrivals in pallets

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0	0	0	0	0	0	0
0	21	0	0	0	0	0
0	0	0	0	0	0	0
0	21	0	0	0	0	0
0	0	0	0	0	0	0
0	21	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
12	0	0	0	0	0	0
0	21	0	0	0	0	0
0	22	0	0	0	0	0
0	21	0	0	0	0	0
0	21	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
23	21	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	22	0	0	0	0	0
23	22	0	0	0	0	0
0	22	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	24	24	22	0	0	0
0	0	24	0	24	0	0
0	24	24	0	0	0	0
0	69	24	0	0	0	0
0	24	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	24	24	0	0	0	0
0	0	0	22	0	0	0
0	0	24	0	0	0	0
0	0	24	0	0	0	0
0	24	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	22	0	0	0	0	0
0	21	24	0	0	0	0
0	22	24	0	0	0	0

Table D.11: Powder arrivals in pallets

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0	0	0	22	0	0	0
0	22	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	24	0	0	0	0
0	0	24	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	24	0	0	0	0	0
0	0	0	0	0	0	0
0	24	24	0	0	0	0
0	48	24	0	0	0	0
0	22	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	22	24	0	0	0	0
0	22	0	0	0	0	0
0	24	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	24	0	0	0	0
0	21	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

Table D.12: Powder consumption in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0.00	20.98	5.87	0.00	0.00	0.00	0.00
0.00	22.44	21.83	0.00	0.00	0.00	0.00
0.00	7.33	11.48	0.00	0.00	0.00	0.00
0.00	18.25	24.57	0.00	0.00	0.00	0.00
0.00	11.56	12.27	6.51	0.00	0.00	0.00
0.00	21.56	12.69	0.00	0.00	0.00	0.00
0.00	9.09	4.22	2.22	0.00	0.00	0.00
0.00	12.26	12.78	0.00	0.00	0.00	0.00
0.00	19.46	6.49	0.00	0.00	0.00	0.00
0.00	11.68	13.00	0.00	0.00	0.00	0.00
4.57	17.18	6.40	0.00	0.00	0.00	0.00
4.58	22.59	6.28	0.00	0.00	0.00	0.00
4.60	19.34	5.63	0.00	0.00	0.00	0.00
3.64	15.34	11.69	0.00	0.00	0.00	0.00
5.49	9.22	5.81	0.00	0.00	0.00	0.00
4.72	0.00	0.00	0.00	0.00	0.00	0.00
6.18	0.00	13.92	0.00	0.00	0.00	0.00
6.17	10.92	13.31	0.00	0.00	0.00	0.00
0.00	12.17	0.00	0.00	0.00	0.00	0.00
6.18	20.01	9.22	0.00	0.00	0.00	0.00

Table D.12: Powder consumption in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
9.11	17.15	9.23	0.00	0.00	0.00	0.00
4.57	14.97	18.26	0.00	0.00	0.00	0.00
4.55	15.59	18.35	0.00	0.00	0.00	0.00
4.53	11.48	8.35	0.00	0.00	0.00	4.52
0.00	10.32	18.71	0.00	0.00	16.17	2.07
5.42	8.89	9.21	0.00	0.00	7.38	0.00
4.57	12.37	21.88	0.00	0.00	0.00	0.00
9.11	1.43	24.38	0.00	0.00	0.00	0.00
8.17	12.31	21.94	0.00	0.00	0.00	0.00
1.80	10.18	29.23	0.00	0.00	0.00	0.00
0.00	7.10	29.47	0.00	0.00	0.00	3.27
0.00	0.00	30.99	0.00	1.41	8.49	5.92
0.00	5.35	30.74	0.00	0.00	9.58	0.00
0.00	5.56	28.22	0.00	0.00	0.00	0.00
0.00	7.70	30.59	0.00	0.00	0.00	0.00
0.00	16.24	38.24	0.00	0.00	0.00	0.00
0.00	19.36	27.09	0.00	0.00	0.00	0.00
0.00	20.01	19.00	0.00	0.00	0.00	0.00
0.00	8.32	18.53	0.00	0.00	0.00	0.00
0.00	14.38	24.38	0.00	0.00	0.00	0.00
0.00	11.70	24.91	0.00	0.00	0.00	0.00
0.00	18.27	21.09	0.00	0.00	0.00	0.00
0.00	6.87	29.56	0.00	0.00	0.00	0.00
0.00	25.76	14.68	0.00	0.00	0.00	0.00
0.00	25.94	24.11	0.00	0.00	0.00	0.00
0.00	8.89	13.99	0.00	0.00	0.00	0.00
0.00	11.31	12.26	6.19	0.00	0.00	0.00
0.00	12.69	7.16	13.23	0.00	0.00	0.00
0.00	9.86	5.88	6.69	0.00	0.00	0.00
0.00	1.32	16.97	1.24	0.00	0.00	0.00
0.00	23.07	18.44	2.38	0.00	0.00	0.00
0.00	26.24	23.09	9.45	0.00	0.00	0.00
0.00	23.27	6.26	9.47	0.00	0.00	0.00
0.00	3.62	8.35	6.72	0.00	0.00	0.00
0.00	13.44	11.01	0.00	0.00	0.00	0.00
0.00	19.56	19.94	0.00	0.00	0.00	0.00
0.00	13.53	12.98	0.00	0.00	0.00	0.00
0.00	21.31	10.07	0.00	0.00	0.00	0.00
0.00	11.77	18.26	0.00	0.00	0.00	0.00
0.00	14.01	20.50	0.00	0.00	0.00	0.00
0.00	10.47	14.92	6.84	0.00	0.00	0.00
0.00	12.91	15.57	0.00	0.00	0.00	4.48
0.00	0.00	15.74	0.00	9.71	3.76	3.30
0.00	14.83	10.15	0.00	4.27	1.78	0.00
0.00	14.97	18.19	0.00	3.58	0.00	0.00
0.00	10.76	11.53	0.00	0.00	0.00	0.00
0.00	22.29	12.74	0.00	0.00	0.00	0.00
0.00	9.77	18.46	6.51	0.00	0.00	0.00
0.00	11.40	19.01	0.00	0.00	0.00	0.00
0.00	15.09	5.85	0.00	0.00	0.00	0.00
0.00	10.91	18.81	0.00	0.00	0.00	0.00
0.00	16.68	18.14	0.00	0.00	0.00	0.00
0.00	12.42	19.80	0.00	0.00	0.00	0.00

Table D.12: Powder consumption in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0.00	15.82	13.24	0.00	0.00	0.00	0.00
0.00	12.42	13.05	0.00	0.00	0.00	0.00
0.00	15.92	12.47	0.00	0.00	0.00	0.00
0.00	9.38	25.47	0.00	0.00	0.00	0.00
0.00	10.20	19.31	0.00	0.00	0.00	0.00
0.00	10.67	0.00	0.00	0.00	0.00	0.00
0.00	10.43	13.92	0.00	0.00	0.00	0.00
4.61	8.86	13.31	0.00	0.00	0.00	0.00
13.15	4.64	0.00	0.00	0.00	0.00	0.00
4.59	12.36	9.22	0.00	0.00	0.00	0.00
4.68	8.57	9.23	0.00	0.00	0.00	0.00
9.14	12.04	18.26	0.00	0.00	0.00	0.00
0.00	10.05	18.35	0.00	0.00	0.00	0.00
3.12	9.23	8.35	0.00	0.00	0.00	0.00
4.03	6.06	18.71	0.00	0.00	0.00	0.00
0.00	0.00	9.21	0.00	6.10	0.00	0.00
4.58	0.00	17.47	0.00	10.99	0.00	0.00
9.13	6.63	18.49	0.00	0.51	0.00	0.00
4.58	20.81	9.15	0.00	0.00	0.00	0.00
4.59	29.71	15.59	0.00	0.00	0.00	0.00
4.73	13.96	14.19	0.00	0.00	0.00	0.00
4.59	7.98	16.82	0.00	0.00	0.00	0.00
9.14	0.00	18.26	0.00	0.00	0.00	0.00
0.00	6.84	18.39	0.00	0.00	0.00	0.00
9.17	10.52	18.30	0.00	0.00	0.00	0.00
4.58	20.98	18.54	0.00	0.00	0.00	0.00
4.58	27.02	14.73	0.00	0.00	0.00	0.00
0.00	23.57	21.87	0.00	0.00	0.00	0.00
0.00	9.09	37.37	0.00	0.00	0.00	0.00
0.00	10.88	26.66	0.00	0.00	0.00	0.00
0.00	7.78	28.17	0.00	0.00	0.00	0.00
0.00	10.20	27.95	0.00	0.00	0.00	0.00
0.00	12.70	26.82	0.00	0.00	0.00	0.00
0.00	15.71	19.26	0.00	0.00	0.00	0.00
0.00	8.62	36.82	0.00	0.00	0.00	0.00
0.00	7.30	17.06	0.00	0.00	0.00	3.12
0.00	0.00	25.42	0.00	13.84	0.00	3.42
0.00	10.87	24.76	0.00	1.41	0.00	0.00
0.00	7.98	16.28	0.00	0.00	0.00	0.00
0.00	7.98	28.12	0.00	0.00	0.00	0.00
0.00	25.74	19.84	0.00	0.00	0.00	0.00
0.00	10.33	31.27	0.00	0.00	0.00	0.00
0.00	9.09	26.16	0.00	0.00	0.00	0.00
0.00	7.98	25.02	0.00	0.00	0.00	0.00
0.00	11.59	24.49	0.00	0.00	0.00	0.00
0.00	6.59	30.18	0.00	0.00	0.00	0.00
0.00	6.06	26.72	0.00	0.00	0.00	0.00
0.00	9.57	18.44	0.00	0.00	0.00	0.00
0.00	12.69	28.53	0.00	0.00	0.00	0.00
0.00	10.36	26.73	0.00	0.00	0.00	0.00
0.00	8.82	18.24	6.84	0.00	0.00	0.00
0.00	19.26	22.87	0.00	0.00	0.00	0.00
0.00	10.20	23.80	0.00	0.00	0.00	0.00

Table D.12: Powder consumption in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0.00	8.79	10.15	0.00	0.00	0.00	0.00
0.00	0.00	8.02	0.00	0.00	0.00	0.00
0.00	0.00	6.07	0.00	0.00	0.00	0.00
0.00	21.18	9.43	0.00	0.00	0.00	0.00
0.00	15.17	13.44	8.46	0.00	0.00	0.00
0.00	7.91	9.07	4.87	6.52	0.00	0.00
0.00	0.00	19.51	0.00	7.55	0.00	0.00
0.00	12.91	19.64	0.00	9.69	0.00	0.00
0.00	5.55	18.35	0.00	3.98	0.00	0.00
0.00	5.86	20.51	0.00	0.00	0.00	0.00
0.00	27.22	13.56	6.29	0.00	0.00	0.00
0.00	12.08	7.24	0.00	0.00	0.00	0.00
0.00	19.90	6.83	4.44	0.00	0.00	0.00
0.00	9.09	13.78	5.84	0.00	0.00	0.00
0.00	9.09	13.50	6.28	0.00	0.00	0.00
0.00	19.99	1.30	12.71	0.00	0.00	0.00
0.00	12.98	6.17	0.00	0.00	0.00	0.00
4.61	10.40	12.22	0.00	0.00	0.00	4.67
13.15	10.25	11.85	0.00	9.49	0.00	3.37
4.59	0.00	6.05	0.00	4.39	12.19	5.90
4.68	6.43	5.82	0.00	0.00	13.99	0.00
9.14	18.79	11.83	0.00	0.00	0.00	0.00
0.00	20.68	5.84	0.00	0.00	0.00	0.00
3.12	25.74	5.93	0.00	0.00	0.00	0.00
4.03	11.75	11.99	0.00	0.00	0.00	0.00
0.00	22.47	12.42	0.00	0.00	0.00	0.00
4.58	18.47	6.18	0.00	0.00	0.00	0.00
9.13	17.93	11.71	0.00	0.00	0.00	0.00
4.58	14.14	12.10	0.00	0.00	0.00	0.00
4.59	21.18	12.81	0.00	0.00	0.00	0.00
4.73	10.67	6.04	0.00	0.00	0.00	0.00
4.59	9.77	18.82	0.00	0.00	0.00	0.00
9.14	7.03	9.16	0.00	0.00	0.00	0.00
0.00	10.88	4.93	0.00	0.00	0.00	0.00
9.17	13.81	19.60	0.00	0.00	0.00	0.00
4.58	22.68	17.64	0.00	0.00	0.00	0.00
4.58	21.21	14.13	0.00	0.00	0.00	0.00
0.00	9.97	24.72	0.00	0.00	0.00	0.00
0.00	7.98	32.14	0.00	0.00	0.00	0.00
0.00	10.57	25.08	0.00	0.00	0.00	0.00
0.00	0.00	11.48	0.00	1.99	4.04	0.00
0.00	0.00	28.24	0.00	5.41	1.78	0.00
0.00	3.83	29.21	0.00	2.63	7.38	0.00
0.00	6.30	19.79	0.00	0.00	0.00	0.00
0.00	9.01	38.35	0.00	0.00	0.00	0.00
0.00	9.52	33.57	0.00	0.00	0.00	0.00
0.00	4.25	33.19	0.00	0.00	0.00	0.00
0.00	11.47	38.08	0.00	0.00	0.00	0.00
0.00	5.47	20.17	0.00	0.00	0.00	0.00
0.00	7.98	38.39	0.00	0.00	0.00	0.00
0.00	7.98	22.55	0.00	0.00	0.00	0.00
0.00	6.69	32.48	0.00	0.00	0.00	0.00
0.00	4.84	39.29	0.00	0.00	0.00	0.00

Table D.12: Powder consumption in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0.00	5.48	38.26	0.00	0.00	0.00	0.00
0.00	9.43	32.03	0.00	0.00	0.00	0.00
0.00	34.63	28.60	0.00	0.00	0.00	0.00
0.00	20.01	24.83	0.00	0.00	0.00	0.00
0.00	10.41	36.69	0.00	0.00	0.00	3.07
0.00	0.00	31.96	0.00	3.99	4.98	3.37
0.00	6.89	27.71	0.00	5.81	0.00	0.00
0.00	20.00	15.54	4.62	2.96	0.00	0.00
0.00	19.26	19.92	0.00	0.00	0.00	0.00
0.00	8.65	17.79	0.00	0.00	0.00	0.00
0.00	15.54	6.40	7.61	0.00	0.00	0.00
0.00	10.37	0.00	5.95	0.00	0.00	0.00
0.00	0.00	0.00	1.34	0.00	0.00	0.00
0.00	0.00	9.43	14.17	0.00	0.00	0.00
0.00	12.90	1.38	15.29	0.00	0.00	0.00
0.00	0.00	8.99	5.71	0.00	0.00	0.00
0.00	12.89	19.93	0.00	0.00	0.00	0.00
0.00	0.00	25.72	0.00	0.00	0.00	0.00
0.00	3.10	13.19	0.00	0.00	0.00	0.00
0.00	23.20	20.12	0.00	0.00	0.00	0.00
0.00	12.89	13.08	6.29	0.00	0.00	0.00
0.00	15.79	12.54	0.00	0.00	0.00	0.00
0.00	7.98	5.92	4.44	0.00	0.00	0.00
0.00	16.30	12.27	5.84	0.00	0.00	0.00
0.00	5.74	5.95	6.28	0.00	0.00	0.00
0.00	7.34	6.89	12.71	0.00	0.00	0.00
0.00	20.21	18.11	0.00	0.00	0.00	0.00
0.00	5.54	18.52	0.00	0.00	0.00	0.00
0.00	5.04	18.21	0.00	0.00	0.00	0.00
0.00	8.89	11.85	0.00	0.00	0.00	0.00
0.00	17.94	5.82	0.00	0.00	0.00	0.00
0.00	6.92	11.83	0.00	0.00	0.00	0.00
4.74	14.97	5.84	0.00	0.00	0.00	0.00
9.39	8.01	5.93	0.00	0.00	0.00	0.00
9.45	6.73	11.99	0.00	0.00	0.00	0.00
4.70	16.24	12.42	0.00	0.00	0.00	0.00
4.75	10.06	6.18	0.00	0.00	0.00	0.00
9.43	4.64	11.71	0.00	0.00	0.00	0.00
4.74	8.38	12.10	0.00	0.00	0.00	0.00
4.74	16.44	12.81	0.00	0.00	0.00	0.00
4.74	10.36	6.04	0.00	0.00	0.00	0.00
9.46	9.09	18.82	0.00	0.00	0.00	0.00
0.00	9.09	9.16	0.00	0.00	0.00	0.00
9.44	11.17	4.93	0.00	2.84	0.00	0.00
4.73	4.43	19.60	0.00	10.38	0.00	0.00
4.73	0.00	17.64	0.00	3.46	0.00	0.00
4.73	0.00	14.13	0.00	0.00	0.00	0.00
3.65	0.00	15.79	0.00	0.00	0.00	0.00
0.00	0.00	13.30	0.00	0.00	0.00	0.00
0.00	0.00	16.64	0.00	0.00	0.00	0.00
4.75	0.00	1.82	0.00	0.00	0.00	0.00
4.68	5.56	9.61	0.00	0.00	0.00	0.00
9.45	10.02	19.63	0.00	0.00	0.00	0.00

Table D.12: Powder consumption in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
4.73	14.99	9.94	0.00	0.00	0.00	0.00
4.73	12.42	19.46	0.00	0.00	0.00	0.00
9.38	19.64	18.17	0.00	0.00	0.00	0.00
0.00	21.01	19.19	0.00	0.00	0.00	0.00
0.00	9.90	19.18	0.00	0.00	0.00	4.32
0.00	21.50	9.42	0.00	9.46	0.00	0.00
0.00	11.96	18.69	11.67	7.82	0.00	0.00
0.00	16.24	14.33	11.09	1.56	0.00	0.00
0.00	7.98	12.76	6.44	0.00	0.00	0.00
0.00	9.70	27.87	0.00	0.00	0.00	0.00
0.00	21.79	36.17	0.00	0.00	0.00	0.00
0.00	28.10	27.70	0.00	0.00	0.00	0.00
0.00	16.48	27.65	0.00	0.00	0.00	0.00
0.00	8.11	28.28	0.00	0.00	0.00	0.00
0.00	0.00	37.09	0.00	0.00	0.00	0.00
0.00	8.89	23.10	0.00	0.00	0.00	0.00
0.00	19.70	11.92	0.00	0.00	0.00	0.00
0.00	11.55	17.14	4.62	0.00	0.00	0.00
0.00	11.50	6.14	0.00	0.00	0.00	0.00
0.00	3.71	0.00	0.00	0.00	0.00	0.00
0.00	0.00	6.40	7.61	0.00	0.00	0.00
0.00	10.94	0.00	5.95	0.00	0.00	0.00
0.00	10.06	8.48	1.34	0.00	0.00	0.00
0.00	19.37	9.23	14.17	0.00	0.00	0.00
0.00	12.68	18.22	6.82	0.00	0.00	0.00
0.00	7.12	24.50	0.84	0.00	0.00	0.00
0.00	10.94	22.18	0.00	0.00	0.00	0.00
0.00	14.38	24.63	0.00	0.00	0.00	0.00
0.00	14.51	24.91	0.00	0.00	0.00	0.00
0.00	10.47	28.24	0.00	0.00	0.00	0.00
0.00	8.81	25.77	0.00	0.00	0.00	0.00
0.00	6.41	17.00	0.00	0.00	0.00	0.00
0.00	0.00	15.21	0.00	7.70	0.00	0.00
0.00	0.00	30.82	0.00	11.60	0.00	0.00
0.00	6.00	43.13	0.00	6.62	0.00	0.00
0.00	14.97	28.06	0.00	2.52	0.00	0.00
0.00	12.22	34.59	0.00	0.00	0.00	0.00
0.00	15.72	17.48	0.00	0.00	0.00	0.00
0.00	6.58	18.14	6.88	0.00	0.00	0.00
0.00	6.87	5.80	18.43	0.00	0.00	0.00
0.00	11.37	0.00	6.23	0.00	0.00	0.00
0.00	25.01	0.00	19.34	0.00	0.00	0.00
4.74	8.67	0.00	9.59	0.00	0.00	0.00
9.39	17.35	0.00	18.42	0.00	0.00	0.00
9.45	10.01	0.00	4.62	1.44	7.33	6.32
4.70	12.93	0.00	15.13	0.00	16.17	4.02
4.75	8.43	0.00	0.70	0.00	0.00	0.00
9.43	10.58	0.00	0.00	0.00	0.00	0.00
4.74	8.70	0.00	0.00	0.00	0.00	0.00
4.74	7.98	0.00	7.01	0.00	0.00	0.00
4.74	21.80	0.00	7.00	0.00	0.00	0.00
9.46	10.18	0.00	13.57	0.00	0.00	0.00
0.00	9.31	0.00	7.17	0.00	0.00	4.27

Table D.12: Powder consumption in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
9.44	13.00	0.00	13.83	0.00	8.40	6.06
4.73	4.82	0.00	0.00	0.00	0.00	0.00
4.73	19.56	0.00	6.81	0.00	0.00	0.00
4.73	18.05	5.87	0.00	0.00	0.00	0.00
3.65	4.70	11.67	0.00	0.00	0.00	0.00
0.00	14.71	6.01	0.00	0.00	0.00	0.00
0.00	12.51	11.83	0.00	0.00	0.00	0.00
4.75	9.11	5.87	0.00	0.00	0.00	0.00
4.68	3.78	0.00	0.00	0.00	0.00	0.00
9.45	8.23	4.22	2.22	0.00	0.00	0.00
4.73	11.35	0.00	0.00	0.00	0.00	0.00
4.73	12.16	0.00	0.00	0.00	0.00	0.00
9.38	8.07	0.00	0.00	0.00	0.00	0.00
0.00	10.38	0.00	0.00	0.00	0.00	0.00
0.00	13.50	0.00	0.00	0.00	0.00	0.00
0.00	11.14	0.00	0.00	0.00	0.00	0.00
0.00	5.32	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.57	0.00	0.00	0.00	0.00	0.00	0.00
4.58	0.00	0.00	0.00	0.00	0.00	0.00
4.60	0.00	0.00	0.00	0.00	0.00	0.00
3.64	0.00	0.00	11.67	0.00	0.00	0.00
5.49	0.00	1.14	11.09	0.00	0.00	0.00
4.72	6.05	0.00	6.44	0.00	0.00	0.00
6.18	8.43	8.48	0.00	0.00	0.00	0.00
6.17	12.70	17.45	0.00	0.00	0.00	0.00
0.00	5.35	9.15	0.00	1.44	2.89	0.00
6.18	0.00	18.22	0.00	5.93	4.98	0.00
9.11	0.00	18.84	0.00	12.47	4.10	0.00
4.57	7.10	18.84	0.00	0.00	0.00	0.00
4.55	21.21	9.58	0.00	0.00	0.00	0.00
4.53	17.47	0.00	0.00	0.00	0.00	0.00
0.00	15.51	14.41	0.00	0.00	0.00	0.00
5.42	26.56	4.12	0.00	0.00	0.00	0.00
4.57	16.13	4.42	0.00	0.00	0.00	0.00
9.11	10.13	5.89	0.00	0.00	0.00	0.00
8.17	9.40	12.79	0.00	0.00	0.00	0.00
1.80	0.00	22.12	0.00	0.00	0.00	0.00
0.00	7.29	24.51	0.00	0.00	0.00	0.00
0.00	14.58	32.39	0.00	0.00	0.00	0.00
0.00	11.27	30.74	0.00	2.10	0.00	4.27
0.00	14.16	25.74	0.00	6.99	0.00	0.00
0.00	6.95	24.82	0.00	4.11	0.00	0.00
0.00	12.49	38.12	0.00	0.00	0.00	0.00

Table D.12: Powder consumption in m3

Glucose	Lactose	MD 12.1	MD 12.2	MD 11.1	MD 11.2	MD 17
0.00	19.57	34.19	0.00	0.00	0.00	0.00
0.00	34.43	25.48	0.00	0.00	0.00	0.00
0.00	16.13	4.94	0.00	0.00	0.00	0.00
0.00	24.18	15.45	0.00	0.00	0.00	0.00
0.00	11.31	24.95	0.00	0.00	0.00	0.00
0.00	7.94	48.95	0.00	0.00	0.00	0.00
0.00	21.70	34.78	0.00	0.00	0.00	0.00
0.00	9.18	27.91	0.00	0.00	0.00	0.00
0.00	10.92	17.37	0.00	0.00	0.00	0.00
0.00	16.45	24.12	6.88	0.00	0.00	0.00
0.00	14.89	0.83	24.62	0.00	0.00	0.00
0.00	12.75	1.29	19.47	0.00	0.00	0.00
0.00	12.60	0.34	26.03	0.00	0.00	0.00
0.00	8.89	8.56	10.83	0.00	0.00	0.00
0.00	23.98	7.97	20.80	0.00	0.00	0.00
0.00	21.60	11.53	14.07	0.00	0.00	0.00
0.00	11.56	0.00	24.60	0.00	0.00	0.00
0.00	12.67	2.88	7.42	0.00	0.00	0.00
0.00	9.06	0.00	0.00	0.00	0.00	0.00
0.00	0.00	8.93	0.00	0.00	0.00	0.00
0.00	9.66	1.65	7.01	0.00	0.00	0.00
0.00	12.72	10.07	7.00	0.00	0.00	0.00
0.00	19.80	8.17	13.57	0.00	0.00	0.00
0.00	14.51	9.55	7.17	0.00	0.00	0.00
0.00	12.70	9.48	13.83	0.00	0.00	0.00
0.00	11.06	10.60	0.00	0.00	0.00	0.00
0.00	7.41	9.72	6.81	0.00	0.00	0.00