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Integrated scheduling of ice cream production with rework via mixing

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Integrated Scheduling of Ice Cream Production with Rework via Mixing

by

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I. Preface

This report presents the results of my research project in order to receive the Master's degree in Operations Management and Logistics at Eindhoven University of Technology, The Netherlands. This research project has been carried out at Unilever. The past year I have conducted a challenging project from which I have learnt a lot. For this experience I would like to thank several people who supported me during the project.

From TU Eindhoven I would like to thank my first supervisor, Ir. Dr. S.D.P. Flapper. I very much appreciate for all the critical remarks, helpful comments and advices which supported me during the project. Your guidance and endless enthusiasm for my project motivated me to strive for good results, which also made our meetings very enjoyable for me. I also would like to thank my second supervisor Dr. Ir. N.P. Dellaert for looking at the project from a broader perspective and asking critical questions which supported me to improve this report.

From Unilever I owe thanks to Prof. dr. Peter Bongers for initiating the project and for answering the questions I had in his valuable time. I would also like to thank Hans Hoogland at Unilever, Vlaardingen for his time to arrange my internship in a new company environment. Also I had useful inspirations and ideas from him during our discussions in Vlaardingen.

From Ben & Jerry's Sourcing Units in Hellendoorn, I would like to thank Joris Engelen who helped me to get a clear view on the processes. I would also like to thank Wilco Oldemaat for trying to give me all relevant data of the SU Hellendoorn and made time to answer my questions related to the scheduling department. I enjoyed very much the cheerful environment of Ben & Jerry's thanks to their hospitality in my visits.

Last, but certainly not least, I would like to thank my family and friends for showing their interests and support during my study period. Especially I want to thank my family for their support and endless believe in me during my entire study. I am very grateful that they made it possible for me to finish my master education. I would also like to thank my housemate Joske for the flowers and tea during my study sessions at home. And finally special thanks to Andres for his great support and encouragement at all times.

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II. Abstract

In the ice cream production of SU Hellendoorn, a considerable amount of intermediate products exits the processes as waste due to start-ups, machine failures and human mistakes in the production. The waste material can be reworked via mixing the waste with a new batch. Reworking results in gain since it replaces the material for the new ice cream batch. However, reworking a perishable material via mixing has its two specific limitations: Storage time and mixing restrictions in terms of ice cream types that can be mixed together in allowed percentages. The rework decisions should be made in an integrated way with regular production where the rework limitations are considered and total relevant cost minimization is achieved. The detailed scheduling has to satisfy the production targets that are set by medium-level planning. The waste source generates waste unexpectedly, therefore a reactive scheduling approach is adopted. The developed reactive scheduling model with rework updates the previously confirmed schedule at the time of waste generation for the remaining time horizon. The model takes the waste amount, the location and the timing of the waste generation and the rest of the week's production target quantities as input parameters, and gives a new schedule (the line allocation, the sequence/timing and batch sizing) in which the rework option is included. The scheduling tool is implemented in AIMMS accompanied with a user interface. Excel connection is also provided for the user to easily enter the input to the model. The results show that it is possible to gain savings by reworking which depends on the type of the mixing limitations that are used.

III. Management Summary

The Sourcing Unit (SU) Hellendoorn is one of the factories in the European supply chain of Unilever for the ice cream category and is producing Ben & Jerry's ice cream for Europe. In the ice cream production of SU Hellendoorn, a considerable amount of intermediate (non-finished) products exits the processes as waste. The reason of the waste can be start-up, machine failures or human mistakes in the production. There are two main types of waste: (1) defective product that does not fulfil the preset specifications set by the company and (2) the material that is kept in side storage in case of a blockage in the production line. Examples to the first type of waste are the ice cream that does not include the right amount of inclusion due to a failure in the machine that adds inclusions to the ice cream (fruit feeder) or wrong label/package. Second type of waste stems from the continuous production environment in the production lines, which do not have any buffer within the line. If a line stops for a reason, the material that is already in the line before the blockage point has to be kept in a separate storage tank. This waste cannot be put back in the line. Both types of waste can be transformed to the products that fulfil the preset specification by reworking the waste via mixing with a new batch of ice cream.

If waste cannot be reworked, it has to be disposed which requires high disposal cost (approx. 1 euro/kg) or it has to go under other methods of waste treatment (pig farms, bio-digester). Currently no ice cream waste is disposed in Hellendoorn factory. Instead, the waste is treated in a methane bio-digester which generates energy as a by-product. However, the profit that can be gained from bio-digester is still low compared to the profit that can be gained from reworking the ice cream.

Reworking results in gain since it replaces the new material for the new ice cream batch. The material cost for the ice cream is high. This creates potential for profitability of the rework. However, reworking a perishable material via mixing has its two specific limitations. First, the perishability of the ice cream brings about the limited storage time for the product to be reworked and necessary conditions of the storage facilities. In addition, as reworking is done via mixing with a new ice cream batch, there are mixing restrictions in terms of ice cream types that can be mixed together with allowed mixing percentages.

Currently in the SU Hellendoorn, only a small portion of the waste is reworked and the rework decisions are based on the experience of the workers. When the initial scheduling is made, reworking of wastes is not taken into account. However, when the rework limitations are considered, the reworking of a waste can be enabled via the scheduling of regular production. Therefore, the rework decisions should be made in an integrated way with regular production where the rework limitations are considered and total relevant cost minimization is achieved. In addition, the detailed scheduling has to satisfy the production targets that are set by medium-level planning. The need for a scheduling tool which defines the optimal schedule considering rework led to the following research assignment:

"*Design a scheduling tool for integral planning of ice cream production with rework which satisfies the required production targets and minimizes the total relevant cost.*"

Although the SU Hellendoorn has been used as a case study to develop and test the model, the intention of the research was to develop a model that is generally applicable. Therefore the scheduling tool is aimed to be as general as possible so that it can be applied to other comparable ice cream factories of Unilever with only minor changes in the tool.

The production environment in SU Hellendoorn is defined as a two-stage manufacturing process with limited intermediate storage. The batch production is employed due to changeover times in the production lines. Production characteristics also require lot streaming resulting in sublot formation in the first stage. Detailed scheduling of the stages is done per week and fixed one week before.

An investigation of the rework limitations showed that the freezer storage option has the disadvantages of high storage cost and does not require scheduling due to long storage time (months). Therefore, only -5/+5°C storage with maximum 72 hours storage time is considered under the scope of this research.

SU Hellendoorn uses reworking based on strict mixing restriction in which only same recipes of ice cream can be mixed with each other. However, the other ice cream factories of Unilever use a general rework matrix in which different recipes are allowed to be mixed each other. As a result, two types rework matrix are concluded:

1. Limited rework matrix: only mixing between same recipes allowed
2. General rework matrix: mixing between different recipes allowed

In the SU Hellendoorn, three waste sources are observed which have different characteristics. An analysis of each waste source is conducted to find out the potential benefit that can be gained by scheduling the rework. The results are given in Table III.1.

Waste sources	Occurrence (Timing)	Waste type	Scheduling required	Percentage Amount Waste (%)
#1: Breakdown/mistake in mixer	Unexpected	Base mix		3 %
#2: Freezer start-up	Deterministic	W/ flavour		10 %
#3: Breakdown/mistake in production lines	Unexpected	W/ flavour and/or inclusion and/or package	√	**87 %**

Table III-1: Characteristics of the waste sources

Based on this analysis, it was decided to focus on the waste source which requires scheduling for reworking (due to main rework limitations of storage time and mixing restrictions) and offers the highest expected potential savings by reworking. Therefore, the third waste source that is generated by a breakdown/mistake in the production lines is considered further in the scheduling problem.

The waste generated by the third waste source is with inclusions and/or with packages which have to removed before reworking. Moreover, before and after these removal operations, the waste has to be stored. The equipment for the inclusion/package removal process and the waste storage tanks require an initial investment at the moment that this type waste is decided to be reworked.

Under the 72 hours storage limit for the waste, four rework opportunities by mixing are concluded. Under the limited rework matrix scenario, one of these rework opportunities cannot be used (see Table III. 2).

Rework opportunities (under 72 hours storage limit)			Rework Matrix	
			Limited	General
Same week	1	Mixing within the same production batch	√	√
	2	Mixing with same recipe different size product	√	√
Different weeks	3	Mixing with same recipe (from Friday to Monday)	√	√
Same & Different week	4	Mixing with different recipe		√

Table III-2: Reworking opportunities under two rework matrix scenarios

The model is developed such a way that these rework opportunities are included. The characteristic of the selected waste source (unexpected occurrence) and the waste storage option under the scope selected (max. 72 hours) led to the adoption of a reactive scheduling approach.

When information regarding a breakdown or worker mistake leading to waste generation is received from the production lines, the schedule that is previously confirmed is updated for the remaining time horizon. The new schedule takes the waste amount, the location and the timing of the waste generation and the rest of the week's production target quantities as input parameters, and gives a new schedule in which the rework option is included. The output gives the line allocation of each product, the sequence/timing of their production in both stages, the sizes of the production batches for each product in Stage 2 and the number and size of the sublots of each production batch in Stage 1. The rework limitations of storage time and rework matrix determines the possibility of the rework which depends on the products that are produced in the rest of the week. The model also decides if it is profitable to change the sequence of the production or line allocation leading to more changeover or production cost but creating rework opportunity that will result in material saving.

The developed reactive scheduling model has been implemented in AIMMS accompanied with a user interface. Excel connection is also provided for the user to easily enter the input to the model.

The output of the model depends on many input factors such as the exact timing of waste generation, product types to be produced in the rest of the week and the allowed mixing percentages (rework matrix) with the other batches. The effect of the rework matrix on the solution is analyzed via a scenario analysis. Using less restricted mixing limitations (general rework matrix) resulted in higher rework opportunities, so higher saving via rework. The potential savings amount via reworking also depends on the location of the waste generation which affects the rework cost.

The potential gain from reworking is estimated by running the model with real waste data. Results are given in Table III.3.

Rework matrix scenario	Percentage reworked	Payback Period (weeks)
Limited rework matrix	69 %	16
General rework matrix	83 %	13

Table III-3: Result of the model runs with real waste data

It is concluded that not all the waste could be reworked due to rework limitations (mainly mixing limitations determined by the week's production portfolio). Whereas 69% of the waste is reworked under the limited rework matrix scenario, it increases to 83% under the general rework matrix scenario. The yearly potential savings are estimated for the limited and general rework matrix respectively. It is found out that using general rework matrix increases the potential savings by 22%. The payback periods required for the initial investments are 16 weeks when limited rework matrix is used and 13 weeks when general rework matrix is used.

Taken the conclusions into account, the recommendations for the SU Hellendoorn are:

1. Since not all the waste can be reworked due to rework limitations (mainly mixing limitations determined by the week's production portfolio), the rework percentages can be increased by planning the production of compatible products (i.e. the products between which mixing is allowed) in the same week. This can be done in the medium level of planning when the weekly production portfolio is decided. Since the higher planning level has also other concerns such as inventory cost and capacity restrictions, it is recommended to consider the reworking possibilities integrated with other decision factors in the mid-term planning.
2. The potential savings estimations are done by making several assumptions to the existing waste data in SU Hellendoorn since there was no data including exact timing of the waste generations. In addition, the rework costs are estimated for each waste generation location. For a more precise estimation of potential savings by reworking, it is recommended to collect waste generation data with exact timings, and analyze the rework cost factors further.
3. The SU Hellendoorn, differently from other ice cream factories of Unilever, does not rework by mixing different recipes. It can be worth to investigate the reasons of this difference in applications.

IV. Table of Contents

I. Preface II

II. Abstract III

III. Management Summary IV

IV. Table of Contents VII

V. Introduction 9

VI. Report Outline 10

Chapter 1. Company Description 11

1.1. Unilever General 11
1.2. Unilever Supply Chain Company (USCC) 11
1.3. Sourcing Unit (SU) Hellendoorn 11

Chapter 2. Research Project 12

2.1. Problem background 12
2.2. Research Assignment 12

Chapter 3. Sourcing Unit Hellendoorn 14

3.1. General production 14
3.2. Characteristics of the production 14
3.3. Stock Keeping Units (SKUs) 17
3.4. Decision Hierarchy 17
3.5. Current scheduling 19

Chapter 4. Rework in SU Hellendoorn 20

4.1. Main rework limitations 20
4.2. Waste sources 21
4.3. Waste source scope selection 23

Chapter 5. Rework opportunity analysis 26

5.1. The limited rework matrix 26
5.2. General rework matrix 28
5.3. Conclusion rework opportunity analysis 28

Chapter 6. Model Development 29

6.1. Scheduling approaches 29
6.2. Model Requirements 31
6.3. Literature Review 34

Chapter 7. Reactive scheduling model with rework 36

7.1. Conceptual Model 36
7.2. Assumptions regarding the conceptual model 40
7.3. Mathematical model 41
7.4. Problem Size Reduction 48

Chapter 8. Software Implementation 49

Chapter 9. Validation and Verification 50

9.1. Model Verification 50
9.2. Model Validation 52

Chapter 10. Some Extensions to the Model 58

10.1. Waste generation more than one location 58
10.2. Calculation of the filling time of an aging time 58

Chapter 11. Investment Analysis 60

Chapter 12. Insights for SU Hellendoorn 61

12.1. Waste analysis 61
12.2. Potential Savings 61
12.3. Investment Analysis 63

Chapter 13. Conclusions and Recommendations 65

13.1. Conclusions 65
13.2. Recommendations 66

References 68

List of Figures & Tables 70

List of Figures 70
List of Tables 70

Definition of Concepts 71

List of Abbreviations 71

Appendix L: Extensions to the model 72

V. Introduction

This report presents the master thesis research for the thesis project “Integrated scheduling of ice cream production with rework via mixing” which is carried out at Unilever.

The planning and control of rework in the process industries is an important issue that requires operational strategies to deal with (Flapper et al., 2002). In the ice cream production of SU Hellendoorn, a considerable amount of intermediate (non-finished) products exits the processes as waste. The waste generation can occur due to start-ups, machine failures and human mistakes in the production. The waste material can be transformed to the products that fulfil the preset specifications set by the company by reworking via mixing the waste with a new batch.

If waste cannot be reworked, it has to be disposed which requires high disposal cost. Currently no ice cream waste is disposed in Hellendoorn factory. Hellendoorn started using methane bio-digester as a waste treatment method, in which energy is generated as a by-product. However, the profit that can be gained from bio-digester is still low compared to profit that can be gained from reworking the ice cream. Reworked ice cream waste replaces the new material for the new ice cream batch. The material cost for the ice cream is high. This creates potential for profitability of the rework. However, there are certain limitations in reworking of ice cream. These limitations are specific to food process industry that produces perishable products. The main limitations are two-fold: (1) since the waste is deteriorating by time, there is storage time limit for the waste when kept in the right storage conditions and (2) since rework is done by mixing with a new batch of product, there is mixing restriction in terms of percentages depending on the product type of the new batch.

Currently in the SU Hellendoorn only a small portion of the waste is reworked and the scheduling decisions related to rework are based on the experience of the workers. A scheduling tool, with which more reliable decisions can be made based on the total cost minimization considering the constraints, is required. The model that has been developed in this research concerns the scheduling of the rework in a short-term period by focusing on detail scheduling, where it has to satisfy the production targets committed by medium level planning.

VI. Report Outline

The outline of the remaining of this report is given in Figure VI.1.

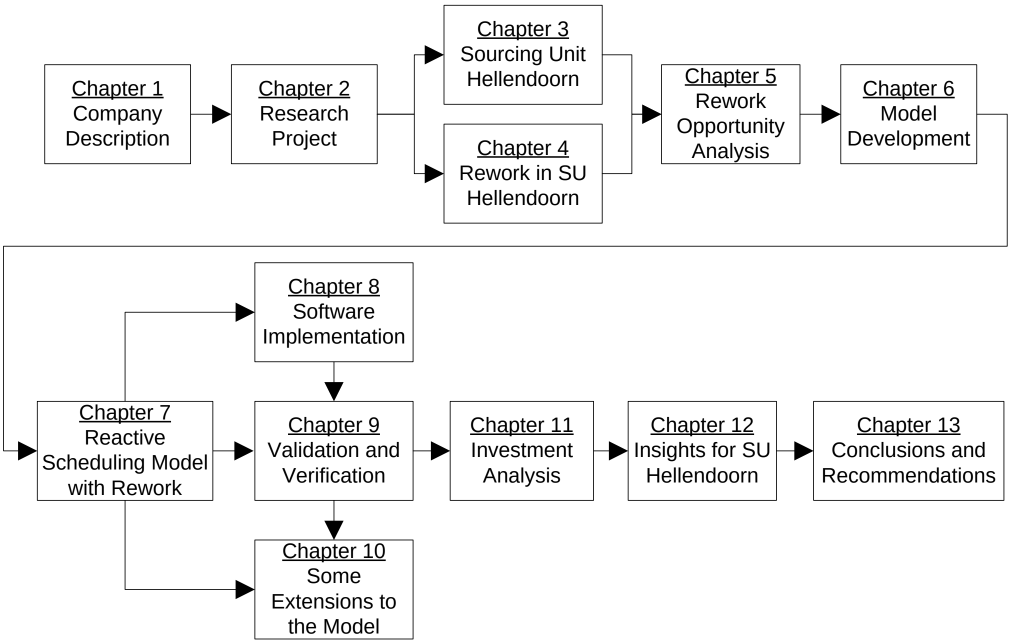


Figure VI-1: Characteristics of the waste sources

In chapter 1 a short description of Unilever, the Unilever Supply Chain Company (USSC) and the SU Hellendoorn will be given. Chapter 2 presents the research project by providing the problem background and the research assignment together with the defined sub-questions. In chapter 3 and 4, the characteristics of the production, scheduling and rework in the SU Hellendoorn will be analyzed under the scope of the research assignment. Based on these analyses, chapter 5 discusses the rework opportunities by mixing.

After the system is analyzed, the model development phase is started in chapter 6. The scheduling approaches, the model requirements and the literature review are given in this chapter. Chapter 7 discusses the reactive scheduling model created to solve the problem. This chapter starts with the conceptual model then the model assumptions will be explained. After this the mathematical model will be given.

After the model had been developed, it has been implemented in the software package AIMMS. The description of the implementation can be found in chapter 8. In chapter 9 the validation and the verification of the model will be provided in where the justification of the assumptions is made and the scenario analysis is performed. Based on the justification of the assumptions, chapter 10 explains possible extensions on the mathematical model which can release the two of the assumptions.

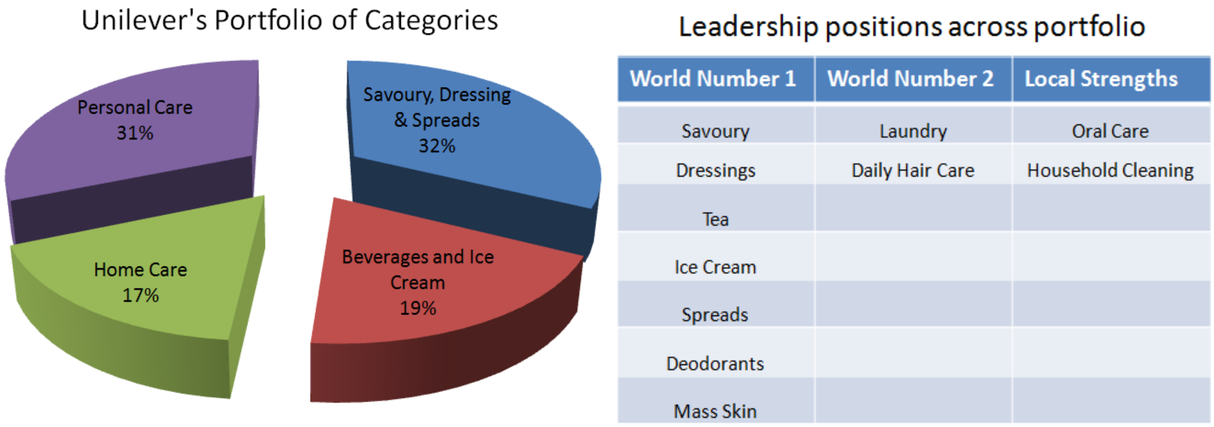
Chapter 11 discusses an investment analysis technique to evaluate the profitability of the reworking since rework requires initial investments. Chapter 12 provides insights for the SU Hellendoorn based on the waste analysis, reactive scheduling model and the investment analysis. Finally in chapter 13 the conclusions and recommendations are discussed. In the first part the conclusions of this research project will be explained. The second part will give recommendations for the SU Hellendoorn and for academics.

Chapter 1. Company Description

This master thesis has been executed at Unilever Research and Development in Vlaardingen. The Sourcing Unit (SU) Hellendoorn has been used as a case study to develop and implement the model. This chapter provides a short introduction to Unilever, the Unilever Supply Chain Company (USCC) and the SU Hellendoorn.

1.1. Unilever General

Unilever has more than 400 brands, 12 of which generate sales in excess of €1 billion a year. Unilever products are sold in more than 180 countries More than 167,000 people work for Unilever. All the categories of Unilever from home, personal care through foods products have leading category positions. Their portfolio ranges from world-leading brands including Lipton, Knorr, Dove, Axe and Omo, to trusted local brands including Blue Band and Hertog [1]. Unilever's portfolio categories and their leadership positions are given in Figure 1.1.



World Number 1	World Number 2	Local Strengths
Savoury	Laundry	Oral Care
Dressings	Daily Hair Care	Household Cleaning
Tea		
Ice Cream		
Spreads		
Deodorants		
Mass Skin		

Figure 1-1: Unilever Categories and Positions [2]

Lipton's and Brooke Bond, Ben & Jerry's and Heartbrand are among the brands that have made Unilever global leaders in the ice cream and beverage markets, where volume grew 5.9% in 2010.

1.2. Unilever Supply Chain Company (USCC)

USCC is the centre of European Supply Chain organisation in Unilever. It is located in Switzerland since 2006 and responsible for the entire sourcing, production and logistics processes in Europe, i.e. from finding the raw materials to delivering Unilever end products. Supply of raw and packaging materials, the whole factory network including production planning, volume allocation and investments for the 62 European production facilities, and the transport and warehousing of finished products from the European manufacturing sites to the end-user markets are among the responsibilities of USCC. [3]

1.3. Sourcing Unit (SU) Hellendoorn

The SU Hellendoorn is one of the factories in the European supply chain for the ice cream category and produces Ben & Jerry's ice cream for Europe. The raw materials are supplied to the SU and SU satisfies the demand from the internal customers of the SU, which are the local marketing and sales units (MSUs). The MSUs sell the products to the local external customers, mostly retail companies.

Currently besides the Ben & Jerry's ice cream also Magnum After Dinner and Hertog ice cream variants are produced at the SU Hellendoorn. Currently there are three Ben & Jerry's production lines. It is expected that in the coming years the actual production capacity will be extended.

Chapter 2. Research Project

This chapter explains the research project "integrated scheduling of ice cream production with rework via mixing" which is carried out at Unilever. The problem that is briefly described in the introduction will be explained in more detail. First, the problem background and the motivation for investigating any improvement possibilities are explained. Second, the research assignment is given.

2.1. Problem background

In the ice cream production of SU Hellendoorn, a considerable amount of intermediate (non-finished) products exits the processes as waste. The reason of the waste can be start-up, machine failures or human mistakes in the production. There are two main types of waste: (1) defective product that does not fulfil the preset specifications set by the company and (2) the material that is kept in side storage in case of a blockage in the production line. Examples to the first type of waste are the ice cream that does not include the right amount of inclusion due to a failure in the machine that adds inclusions to the ice cream (fruit feeder) or wrong label/package. Second type of waste stems from the continuous production environment in the production lines, which do not have any buffer within the line. If a line stops for a reason, the material that is already in the line before the blockage point has to be kept in a separate storage tank. This waste cannot be put back in the line. Both types of waste can be transformed to the products that fulfil the preset specification by reworking via mixing it with a new batch of ice cream.

If waste cannot be reworked, it has to be disposed which requires high disposal cost (approx. 1 euro/kg) or goes under other methods of waste treatment (pig farms, bio-digester). Currently no ice cream waste is disposed in Hellendoorn factory. Hellendoorn started using methane bio-digester as a waste treatment method, in which energy is generated as a by-product. This generated energy is expected to cover a certain amount of Hellendoorn's energy consumption. Although bio-digester eliminates the dispose cost, even generates profit out of waste, profit that can be gained from bio-digester is still low compared to profit that can be gained from reworking the ice cream. Appendix A shows the detailed calculations.

Reworking of the ice cream waste results in gain since it replaces the new material for the new ice cream batch. The material cost for the ice cream is high. This creates potential for profitability of the rework. However, there are certain limitations in reworking of ice cream. These limitations are specific to food process industry that produces perishable products. First, the perishability of the ice cream brings about the limited storage time for the product to be reworked and necessary conditions of the storage facilities. In addition, as reworking is done via mixing with a new ice cream batch, there are mixing restrictions in terms of ice cream types that can be mixed together and allowed mixing percentages.

Currently in Hellendoorn only a small portion of the waste is reworked and the scheduling decisions related to rework are based on the experience of the workers. A scheduling tool, with which more reliable decisions can be made based on the total cost minimization considering the constraints, is required.

2.2. Research Assignment

Unilever wants to gain insight in reworking and know if rework adds extra value to the ice cream production. To evaluate this value, the rework has to be scheduled in an integrated way with regular production by taking into account the constraints associated with reworking. The detailed schedule should satisfy the weekly production targets that are determined by medium level planning. This leads to the following research assignment:

Design a scheduling tool for integral planning of ice cream production with rework which satisfies the required production target and rework constraints by minimizing the total relevant cost.

SU Hellendoorn has been used as a case study to solve the research assignment. However, for Unilever a model that is general applicable would be helpful in the development of production planning/scheduling models for other Unilever factories (with comparable characteristics to the SU

Hellendoorn). Therefore, the model should be general applicable and not tailor made for the SU Hellendoorn.

In order to solve the given research assignment, the following sub questions regarding SU Hellendoorn have to be answered:

1. What are the characteristics of the ice cream production and scheduling?
2. What are the limitations of reworking ice cream?
3. What are the waste sources and the characteristics of them?
4. What are the opportunities of reworking under the limitations of reworking and characteristics of the production, scheduling and waste sources?
5. How can the problem be mathematically formulated by considering the rework opportunities and limitations to find the cost-optimum schedule?

The goal of the first sub question is to get insight in the ice cream production and the scheduling in SU Hellendoorn. The answer to this sub question is provided in Chapter 3.

The second sub question aims to gain insight in rework in ice cream production by determining the limitations of rework. The third sub question concerns the waste sources and aims to gain insight in the characteristics and possible solution approaches to each characteristic waste source. The answers to these sub questions are provided in Chapter 4.

The answers to the first three sub questions provide information to the fourth sub question to determine the opportunities of reworking. The answer to fourth sub question is provided in Chapter 5.

The insights from the first four sub questions determine the base for the mathematical model for the scheduling tool. The goal of the fifth sub question is to provide the mathematical formulation that is based on the rework opportunities and rework limitations, considering the characteristics of the production and the waste generation. The answer to fifth sub question is provided in Chapter 7.

Contribution of this research to the company will be insight to the rework (i.e. limitations and potential savings) and a scheduling tool which helps the planners to generate weekly schedules that consider rework.

Chapter 3. Sourcing Unit Hellendoorn

This chapter provides information about the ice cream production and scheduling in SU Hellendoorn. First, the general production of ice cream is explained by providing a production flow diagram. The second section explains the characteristics of the production together with the detailed explanation of the production stages. In the third section, Stock Keeping Unit (SKU) that is under the scope of this research is defined. The fourth section gives the hierarchical levels regarding the planning decisions in SU Hellendoorn. Finally, the current scheduling in SU Hellendoorn is explained in the last section.

3.1. General production

SU Hellendoorn currently produces Ben & Jerry’s, Hertog and Magnum after dinner (MAD). There are five production lines, three for Ben & Jerry’s, one for Hertog and one for MAD. SU Hellendoorn will stop Hertog production in the close future. Moreover, MAD production corresponds to a small percentage of the total production volume. Thus, the focus is given to Ben & Jerry’s production in this project.

There are two departments in the factory: the mixing department and the production lines department. The mixing department is responsible for preparing the base mix required for the end product and sending them to the aging vessels for the aging process. Each production line has its own dedicated aging vessels. These vessels also act as a buffer between the departments and they have a maximum storage time due to perishability of the base mix. Within this time limit, the production line starts taking the base mix from the vessels for production. Production lines include the flavouring tanks, the continuous freezers, filling and packaging units.

Ben & Jerry’s has several recipes for its product, and each recipe has cup size options for the end product. There are three different sizes; Shorty (150 ml), Pint (500 ml) and Bulk (4500 ml). There are currently three Ben & Jerry’s production lines. Each production line has different capabilities for producing different sizes and recipes.

3.2. Characteristics of the production

The production environment can be defined as a two-stage manufacturing process with limited intermediate storage (Figure 3.1). Stage 1 (mixing department) has a single process line, whereas there are three parallel production lines in stage 2. The mix is produced in the mixing department and stored in the aging vessels. The mixing department can feed all vessels. Each production line has a certain number of dedicated vessels with different sizes. After a minimum (2 hours) and maximum (72 hours) standing time in the vessels, the mix is used in one of the production lines. When an aging tank is filled, it has to be emptied and cleaned before filling again.

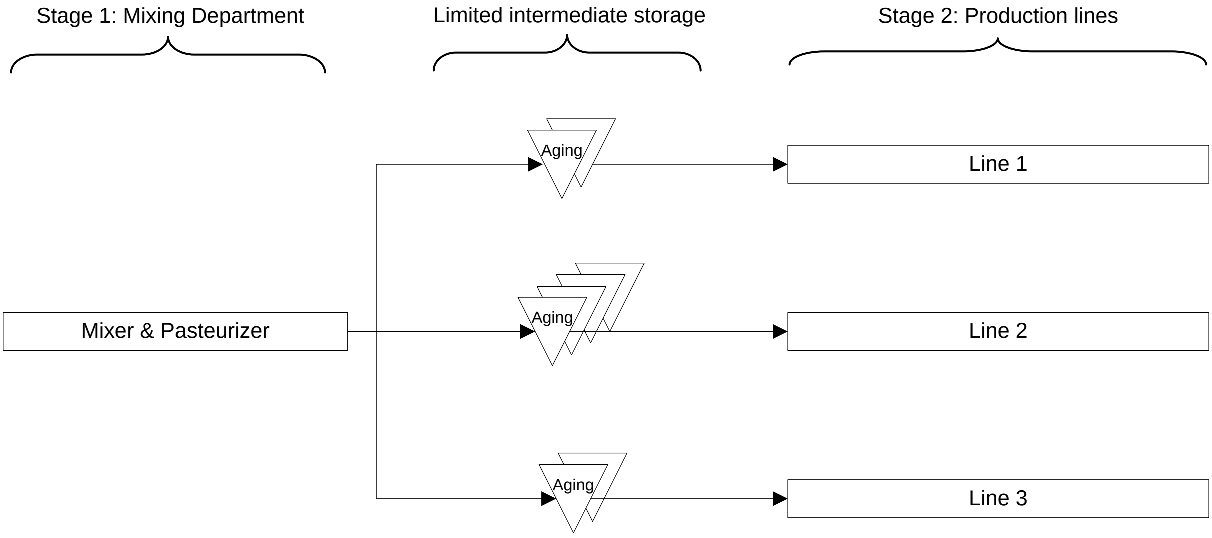


Figure 3-1: Two-step manufacturing process with intermediate storage.

Following sub sections further explain the stages and the intermediate storage. The production planning and scheduling is based on the stage 2. Therefore, for a better understanding the explanations are given in the backwards direction of the production flow.

3.2.1. Stage 2: Production lines

As said before, production lines have different capabilities of producing different sizes of the product. Besides the size capabilities, some lines are not capable of producing certain products due to inclusions that are added or two-flavoured content.

Production in stage 2 is done in batches (referred as “production batch” in the remaining of the report). When production is changed between different recipes or sizes in the same production line, a changeover is required. This changeover takes a considerable time (depending on the sequence of recipes and sizes). When a new production batch starts in the line, there is material loss associated with the start-up. Due to the changeover time and start-up material loss, in practice each product is produced only once in a week and there are minimum run times for each product depending on the line. Shorter than these run times, production is considered not efficient.

The processing rate of a product in a production line mainly depends on the filler in the packaging stage. The fillers, which are dedicated to the production lines, depend on the size of the product. In addition, some recipes require special fruit-feeder equipment for extra inclusions, which affects the production rate. Thus, the process rate depends on the product (recipe and the size) and the line that product is allocated to. (See Appendix C for processing rates)

3.2.2. Limited intermediate storage (Aging tanks)

Each production line has dedicated aging tanks with certain sizes in front of the line. Besides the function of buffer between stages, these tanks are also responsible for the aging of the base mixes. The required aging time for all Ben & Jerry’s ice cream is 2 hours. While this indicates a minimum storage time, a maximum storage time is imposed by the perishability of the intermediate products, i.e. 72 hours. However, this time limit is not a restriction within the week due to the limited capacity for the aging of the base mixes needed for the production. The 72 hours time limit is restrictive when the base mix is prepared on Friday and used in the production lines on next week Monday.

As well as the aging time, the filling and emptying operations in aging tanks take certain time and uses the limited storage capacity, since an aging tank cannot be filled again before it is totally emptied and cleaned. Whereas the filling rate is the same as the processing rate of stage 1 (mixing), the emptying rate is the same as the processing rate of stage 2 (production lines).

3.2.3. Stage 1: Mixing department

There are two mixers which are working parallel and responsible for preparing mixes. A mixer can only process when filled half. The processing rate in the mixing department is determined by the processing rate of the pasteurizer, which depends on the base mix type. Base mixes and processing rates in pasteurizer are given in Appendix B.

Two mixers are both connected to one pasteurizer and always working synchronized to prepare the base mixes. Hereafter, the mix department (plant) refers to two mixers and one pasteurizer together.

The mixing department cannot prepare the base mix needed for one production batch at once. The reasons are as follows:

1. The storage size limitations in the aging tank: The base mix prepared in the mixing department has to stay in the aging tanks at least 2 hours. However, aging tanks have limited capacity. In most of the cases, the production batch size exceeds the total aging tank capacity of a production line. In this case, the mixing department prepares one part of the total production batch size, sends it to the aging tanks and waits for available aging tank capacity to prepare the next part of the batch.
2. The mixing department’s processing rate is much higher than the production line’s processing rate. There is only one mixing department feeding three production lines. To be able to keep each

line's production simultaneous (which also reduces the make span of the production[1]), overlapping of mixing and production can be achieved by splitting the production batch in smaller batches (called sublot) in the mixing department.

Therefore, the base mixes are prepared in sublots in the mix department and supplied to the lines. "*Production batch*" refers to the batch in the production line, and "*sublot*" refers to the batch in the mixing department. One production batch may have more than one sublot. A rough representation of an example weekly schedule is given in Figure 3.2.

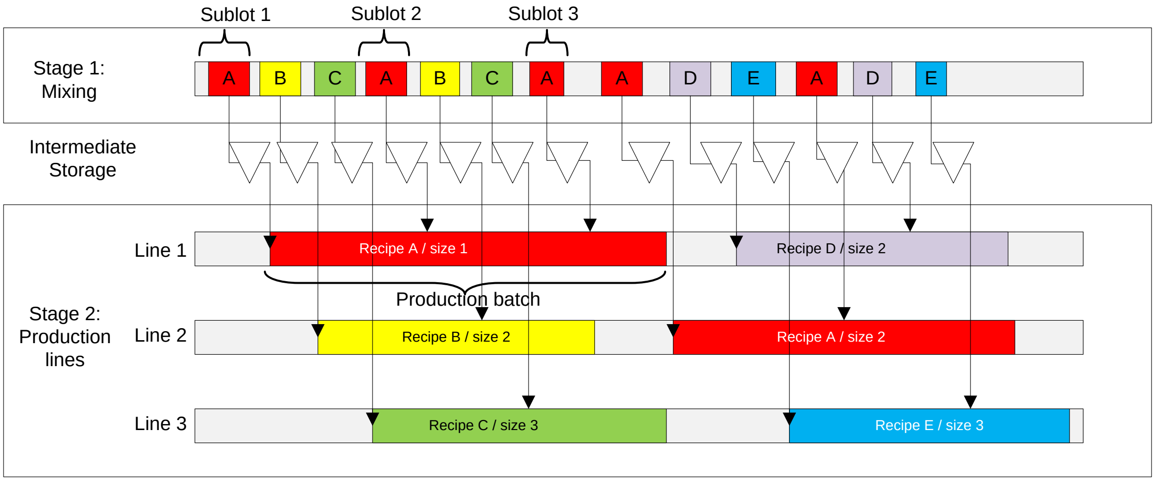


Figure 3-2: Representation of a weekly schedule in two departments

Each colour in the figure represents a recipe. In line 1, the production batch size for Recipe A/size 1 requires three sublots from the mixing department. Between these sublots, the mixing department prepares sublots for other production batches for other lines.

Several recipes have the same base mixes. For example, if Recipe A and Recipe B have the same base mixes, there is no changeover needed in the mixing department between sublots A and sublots B.

3.2.4. Coordination between departments and aging tanks

Two departments and the aging tanks coordinate each other for a production with a shorter make span. The detailed production representation is given in Figure 3.3 for two-sublot production in line 2, which has four dedicated aging tanks. The red and blue arrows represent the material flows.

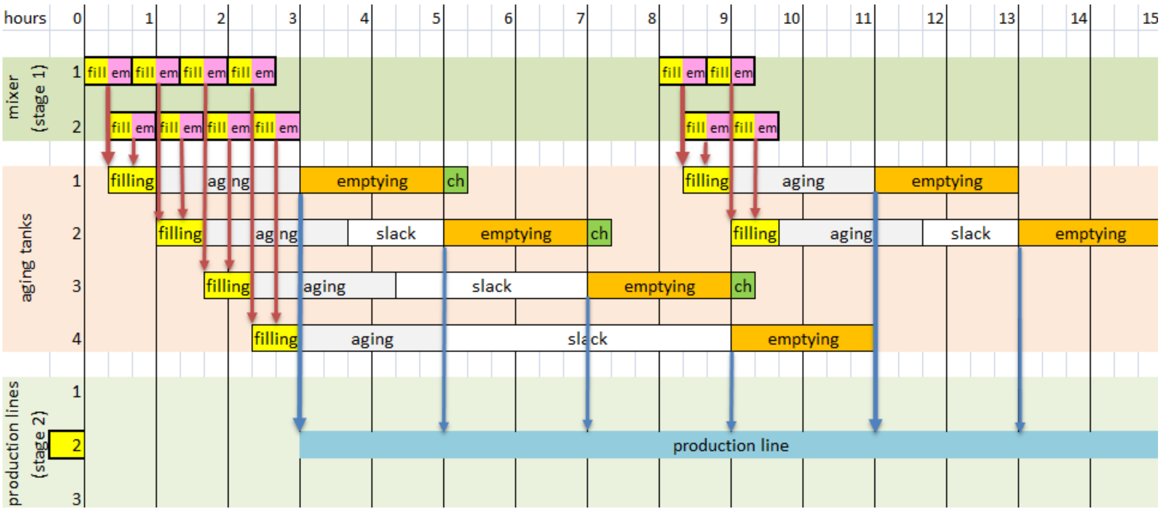


Figure 3-3: Representation of coordination between departments and intermediate storage

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[1] Make span is defined as the time it takes to finish a fixed number of jobs. (Hopp & Spearman, 2008)

In previous section, the overlapping of the mix preparation and production in the lines is mentioned. The filling, aging and emptying processes in the aging tanks also overlap with both departments' processes. When the first mixer in stage 1 is finished processing, the filling of the first aging tank starts immediately. The mixers continue processing after each other to prepare the entire sublot and fill the necessary numbers of aging tanks. (In the figure, all aging tanks are filled). As soon as the aging of the first aging tank is finished, it starts emptying and the production in stage 2 starts at this moment. Therefore, the production in stage 2 does not have to wait for the whole sublot to finish aging process.

The filling and emptying rates of an aging tank depend on the processing rates of the departments:

- The filling rate of the aging tank is equal to the processing rate of the mixing department.
- The emptying rate of the aging tank is equal to the processing rate of the production line.

3.3. Stock Keeping Units (SKUs)

SKU defines an item of stock that is completely specified by the characteristics of the end product. (Silver et al., 1998). In SU Hellendoorn, the determinants of the SKU are the recipe, the cup size, the cluster and the pallet size.

Every year Ben & Jerry's launches new ice cream recipes. On the other hand, the production of some recipes can stop due to a high amount of scrap or low profit. Appendix C shows the recipes and corresponding demands for 2010. Ben & Jerry's recipes have several cup size options within 150 ml, 500 ml and 4500 ml. Appendix C details the demand for 2010 for each recipe and size.

Countries are aggregated in clusters. The label of the packaging changes depending on the cluster. The MSUs in different countries can have different way of storage resulting in a different required pallet size. There are two kinds of pallets, which contain different numbers of ice cream cups.

As explained in previous sections, the production rates in both departments, line capabilities in packaging and changeover times depend on the recipe and size of the product. However, any of these is not affected by the cluster or pallet type. Therefore, in this research, the distinction in end products is made only based on the recipe and cup size. When referred to a 'product', it corresponds to a specific recipe and size that is aggregated through all clusters and pallet sizes. Figure 3.4 represents the SKU code formation. The factors inside the dashed square are included in the scope of this project.

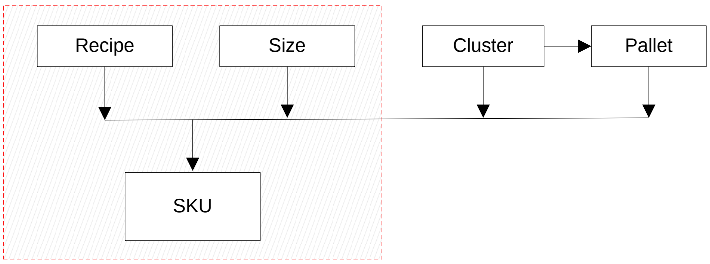

Figure 3-4: Stock Keeping Unit (SKU) under scope

3.4. Decision Hierarchy

It is explained in Chapter 1 that some planning decisions regarding the production in SU Hellendoorn are made in Unilever Supply Chain Company (USCC). This section gives the decision hierarchy among USCC and SU Hellendoorn. The decisions can be separated in three levels, i.e. aggregate, tactical and operational. Figure 3.5 shows the decisions that are made at each level.

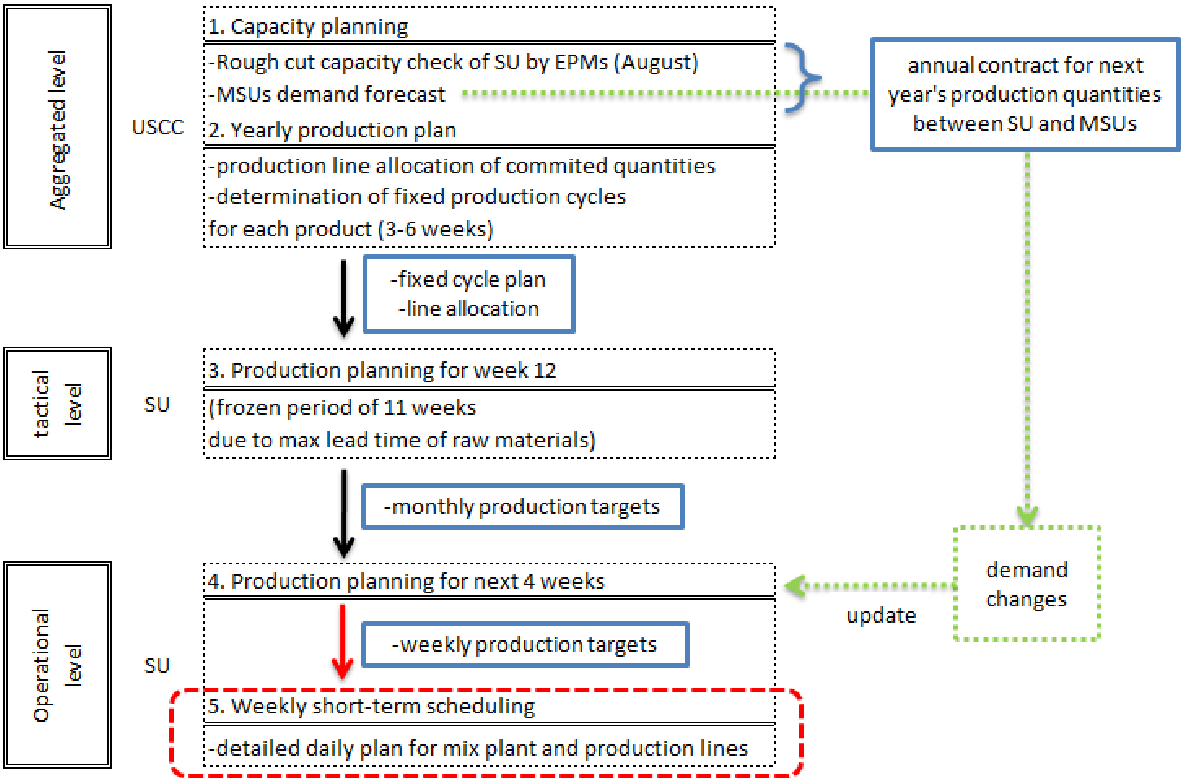

Figure 3-5: Decision hierarchy regarding production planning in SU Hellendoorn

3.4.1. Aggregate level

The capacity planning and yearly production plan of SU Hellendoorn are executed by USCC. The capacities of the different Sourcing Units are investigated via a rough-cut capacity check by European Planning Managers (EPMs) in August. Forecasting of demand from Marketing and Sales Units (MSUs) is performed. Based on the demand forecasts and the capacity check, SU receives the committed demand figures in October. An annual contract regarding the production quantities of the coming year is made between the SU and the MSUs. Yearly production planning is also performed at this level. After allocating the production lines to the committed demand volumes, fixed production cycles (3-6 weeks) are determined for products, which are used during the planning horizon.

3.4.2. Tactical level

Tactical level decisions are performed by SU. A frozen period of 11 weeks is used (due to the max lead-time of raw materials that is 11 weeks). Production planning for week 12 is made and updated each week. The decision that are made on a higher level, i.e. line allocation and the fixed cycle plan, are used as input. Budé (2008) performed a research concerning medium-level planning in which line allocation decisions are integrated in this level.

3.4.3. Operational level

Production planning for the mix plant and production lines is made for the coming 4 weeks. The production plan for the coming 11 weeks is used as an input but can be updated based on the demand changes in APO (Advance Planner & Optimizer).

A multistage scheduling tool in INFOR is used for short term scheduling in SU. A detailed production plan for a week is made which includes the daily plan (expected production starting times and durations) for the mix plant and for each line. The topic of this research is related to the short term scheduling, i.e. weekly scheduling. Further detailed information about the current short-term scheduling is given in next section.

3.5. Current scheduling

The scheduling in SU Hellendoorn focuses on the scheduling of the packaging lines. This schedule is then passed to the mixing department, in which a schedule is being made to satisfy the packaging demand (Bongers & Bakker, 2006). However, this may lead to infeasible schedules in the upstream departments. To create a feasible solution, manual intervention is needed for the mixing schedule.

The current scheduling is based on the factory simulation model in INFOR Advanced Scheduler. Figure 3.6 depicts the data flow diagram that is required for INFOR. The model uses the factory structure (key equipments and connections, given in Figure 3.1), the material flow and the change-over structures as input, and distributes the weekly mix plant schedule, ingredient order calls and weekly production schedule to the relevant departments in an Excel file. The data flow diagram generated by Bongers & Bakker (2009) is given in Figure 3.6.

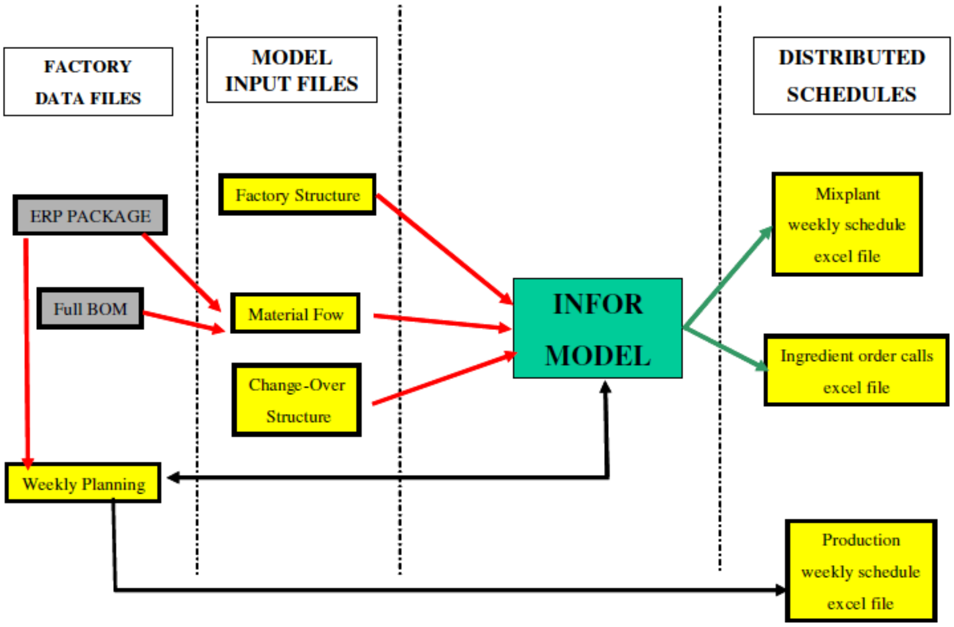

Figure 3-6: Data flow diagram required for INFOR (Bongers & Bakker, 2009).

In the factory simulation model, three key equipments are taken into account: (1) Pasteurizer, (2) aging vessels and (3) production line. An overview of INFOR screen is shown in Appendix D. The first part of the scheduling regarding pasteurizer displays the duration of each base mix's processing and changeovers between. The second part corresponds to the aging vessels. Each tank's filling, aging, extra waiting time and emptying durations are shown here. The third part shows each production line's processing and changeover durations.

Weekly buckets are used for scheduling. A detailed schedule of a week is frozen one week before, on Thursday. The factory is operating in three shifts for 5 days (no production at the weekend). Thus, all the equipment is available for 120 hours a week. However, base mixes can be prepared and kept over the weekend in the aging tanks as long as the maximum storage time is obeyed (72 hours).

Chapter 4. Rework in SU Hellendoorn

This chapter provides information about the main limitations for reworking the waste and the waste generation in SU Hellendoorn. First, the main rework limitations that are enforced by reworking a perishable product via mixing are explained. In the second section, the main waste sources in the production are provided together with the reasons of the waste generation and the characteristics under the mixing limitations. The third section deals with the selection of the waste source that is under the scope of this research. In this section, first the potential value that can be added by scheduling each waste source is discussed. Then, the waste data that is obtained from SU Hellendoorn is analyzed. Based on these analyses, the waste source under the scope of this research is decided.

4.1. Main rework limitations

The problem of "reworking perishable product by mixing it with a new batch of a product" has its specific limitations. This section discusses the two main limitations: Storage time and conditions, and the mixing restrictions.

4.1.1. Storage of waste

The end product (ice cream) and its intermediate products (base mixes and ice cream before packing) are deteriorating materials as the quality decreases by time. Thus, waste created from an end or intermediate product can only be reworked within a limited time when stored under the right conditions. If this time limit is exceeded, the ice cream has to be disposed. There are three options of storage, each allowing different storage times for the waste:

- 1st option: Ambient storage: maximum 4 hours
- 2nd option: -5/+5°C storage: maximum 72 hours
- 3rd option: Freezers: couple of months

The main factor determining the allowed storage duration is the storage temperature. As the temperature of the storage decreases, the time that ice cream can be stored increases. However, a lower temperature requires more energy, which in turn results in higher storage cost.

There is no production during the weekend. When only the first two options are considered, the reworking of the waste that is created in a certain week by mixing it in the production of the following week is highly limited. Only if the waste is created on Friday, it can be used on next Monday by storing it over the weekend with the second storage option. The only other way to enable rework by mixing the waste in later week's production is by using the freezer storage option.

Regarding the freezer storage option, the ice cream that is frozen has to be defrozen very slowly to prevent the deterioration of the ice cream. It can take approximately 2 days to defreeze. This time lag has to be taken into account in the scheduling of the rework. There is also a quality concern related to the defreezing operation. When the frozen ice-cream bulk is defrozen, the outer layer starts melting first. Two days later when finally the innermost part is melted, the outer layer is already defrozen for 2 days. There may be quality difference between these parts. Above all these time and quality concerns, the freezing option is highly undesirable due to the high energy cost. Besides, storing ice cream for months requires extensive storage space. These result in high storage cost associated with the freezer storage option. In addition, from the scheduling point of view the problem is trivial since the same product is produced approximately every month (high demand products are even produced every week), which creates opportunity to rework the waste by mixing it with the same recipe as long as the reworking time is known in 2 days advance for defreezing the ice-cream. To be able to evaluate the benefit that can be gained by freezer option, analyzing the trade off between the gain from material cost and the cost of storing and reworking the waste is sufficient. Therefore, the freezer storage option will not be included in the further scheduling problem.

4.1.2. Rework matrix

The other main restriction of rework is the amount of waste that can be mixed with the new batch. This mixing limitation is expressed by "*allowable rework percentage*" which is the percentage of the new batch size that can be constituted from the waste. For instance, if the allowable rework percentage is 10% and the new batch size is 10 ton, then the maximum waste amount that can be mixed with the corresponding batch is 1 ton. The main determinant of the allowable rework percentages is the recipes of the products that will be mixed together. The allowable rework percentages for each recipe pair is reflected in "*Rework Matrix*".

According to the current rework matrix obtained from Hellendoorn, only same recipes of ice cream can be mixed with each other for reworking purposes. Although, SU Hellendoorn uses reworking based on this limited rework matrix, the other ice cream factories of Unilever use a more relaxed rework matrix in which the possibilities of rework via mixing increase with the option of mixing compatible recipes. There are general mixing rules that can be used to relax the rework matrix:

- Base mix: If products share the same mix, the allowed percentage can be high. Otherwise, a product with a lighter base mix (e.g. vanilla ice cream) can be mixed with a product with darker base mix (e.g. chocolate ice cream). However, the other way around is not possible. In addition, some base mixes use Fair Trade ingredients. The products that are not produced from Fair Trade base mix cannot be mixed with a product that has a Fair Trade base mix.
- Flavours: Ice cream with strong flavour such as mint or coffee cannot be mixed with ice creams that do not include the same flavour.
- Allergens: Products have allergens information in their label. A product with a certain allergen such as gluten or nuts cannot be mixed with a product that does not have the same allergens.
- Frozen Yoghurt (Low fat): Mixing frozen yoghurt with regular ice cream is allowed in a limited extent. However, the other way around is not possible.
- Dairy and non-dairy, and diabetics and non-diabetics can never be mixed together. Currently Ben & Jerry's has no non-diary or diabetics products, therefore this rule is not relevant to our research.

The type of the ice cream waste (i.e. with/without flavour or with/without inclusion) determines which mixing rules to use in the rework matrix. For instance, if the waste is generated before flavouring, the mixing rules that are enforced by the flavours and allergens resulting from inclusions are not considered when constructing the rework matrix. Therefore, for each waste type, a separate rework matrix should be considered. A general rework matrix representing the end-products considering all the mixing rules is given in Appendix E.

As a result, the types rework matrices can be classified as follows:

1. Limited rework matrix: only mixing between same recipes allowed
2. General rework matrix: mixing between different recipes allowed

4.2. Waste sources

During the production of ice cream from mixers to packaging, waste can be generated due to the start-up of the new product batches, human mistakes or machine failures. Figure 4.1 gives the production flow diagram with the main waste sources together with the ways of reworking each waste.

The general production flow can be explained as follows: The required raw material based on the recipe is transferred to the mixing vessels for mixing process. Then the mix is pasteurized and homogenized, and stored in the aging tanks. After the aging time, when the line starts production, the base mix is withdrawn from the aging tanks, flavoured in flavouring tanks and pumped through a continuous freezer. In the freezer, the temperature drops and air is added. After the freezer, if required according to the recipe, inclusions are added to the ice cream by a fruit feeder and variegater. Then the ice cream enters to the packaging stage to be filled in the cups by automatic fillers and covers are placed on the cups. After this stage, (not shown in the diagram) cups pass through hardening tunnel, then are wrapped together with packaging foil, placed in pallets, and finally become ready for storage.

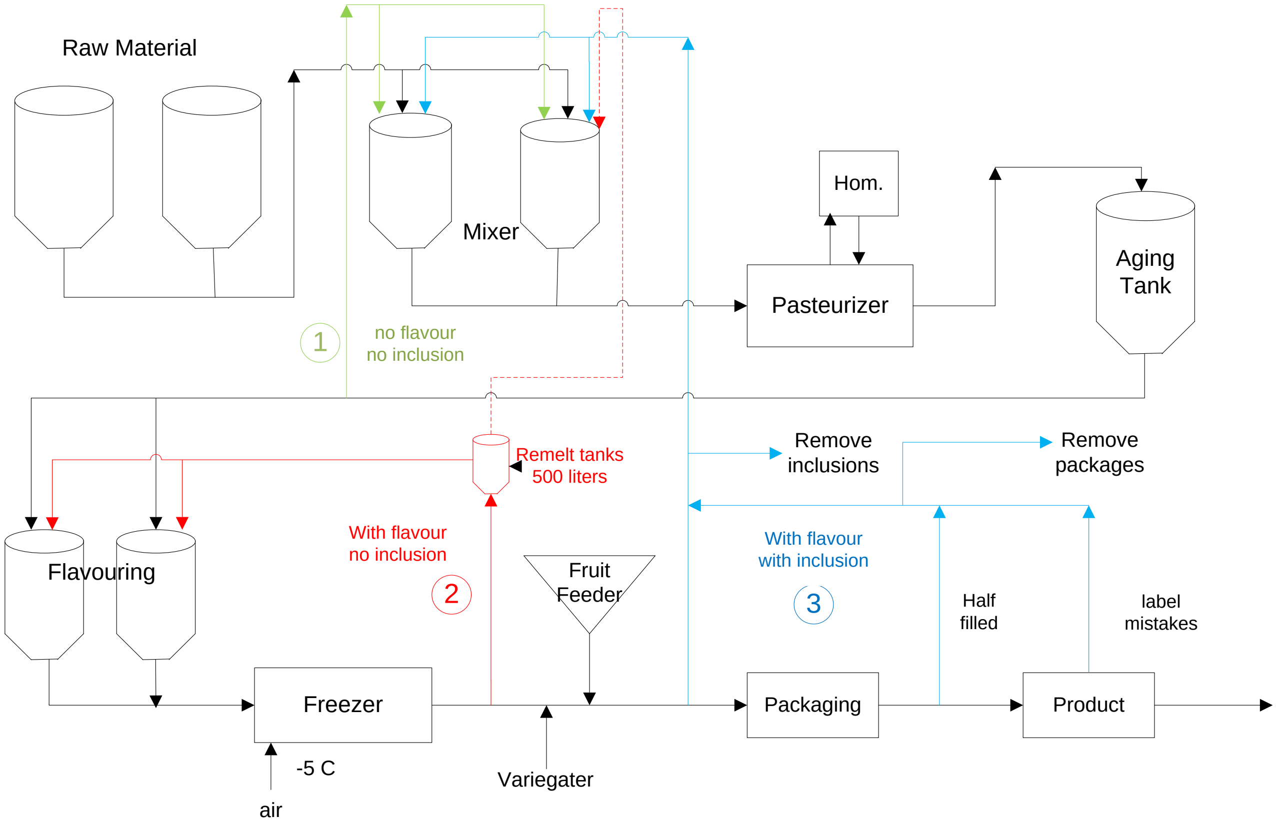

Figure 4-1: The general production flow with rework flows

The rest of this section gives detailed information about the three waste generation sources that are shown by numbers and different colours in Figure 4.1.

4.2.1. Flow 1: Breakdown/mistake in mixer

The ingredients are transferred from the raw material tanks to the mixers in the required amounts based on the recipe. The transfer is performed via an automated system or manually depending on the frequency of the recipe. (Recipes that are produced more frequently are mostly automated). When done manually, mistakes such as a wrong proportion of addition or missing ingredients can be done by the workers. When done automatically, same mistakes can result from a machine failure. In any of these cases, the whole batch in the mixer leads to a defective batch that has to be reworked. This defective batch can be caught after the aging tank. The reworkable material is without flavour and inclusions. Therefore, the allowable rework percentage is high. The defective batch is mixed with several new batches in the mixer before processing again.

4.2.2. Flow 2: Freezer start-up

In the start-up of the freezer, the initial temperature of the freezer is higher than required to freeze the flavoured mix and convert it to the ice cream. As a result, a certain initial amount of the production batch exits the freezer as defective material, which is called start-up loss. The amount of waste depends on the line and type of ice cream and is lower than the amount created by flow 1. This waste has to be first melted and then mixed with a new batch in the flavouring tank, or back in mixer and processed in the freezer again. The waste generation occurs in every start-up of the freezer, therefore the timing is known in advance. The reworkable material is with flavour since it is created after flavouring. Thus, the allowable rework percentage is lower.

4.2.3. Flow 3: Breakdown/mistake in production lines

Throughout the production line, inclusions adding, filling and packing processes take place. During these processes, a line can be blocked due to several reasons such as a worker mistake, or a breakdown in the variegater or filler. When the problem occurs, fixing immediately starts. While the problem is being solved, the ice cream continues to be transferred from freezers, since it is a continuous process. There is no buffer within the stations; therefore, the ice cream received in this blocked period has to be stored in a separate vessel. This waste in the vessel can be reworked. It is also possible to encounter a problem after the ice cream is packed, such as half filled cups or wrong labels. The waste amount that is resulted from a breakdown or mistake can vary in a large extent depending on the problem (from very small amount to volume of a mixer tank). If the waste includes inclusions, or already filled in the cups, inclusion and/or package removal is necessary before reworking the ice cream. Reworking is possible by mixing this material with the new batch in the mixer. The material is still with flavour so the allowable rework percentage is low.

4.3. Waste source scope selection

It is shown in the previous section that each waste source has different characteristics. This section discusses the potential value that can be added by scheduling the rework of these waste sources and analyzes the waste data from SU Hellendoorn. Based on these, the scope of the research in terms of the waste source is concluded.

4.3.1. Potential of Flow 1: Breakdown/mistake in mixer

The frequency of the worker mistake/machine breakdown in the mixing department is low (couple of times a year). Even if this happens once a week (if one mixer batch size becomes defective), the amount of waste constitutes a very small percentage of weekly production volumes. Therefore, the value that can be added by scheduling this rework stream is low. As a result, no further attention will be given to this waste source.

4.3.2. Potential of Flow 2: Freezer start-up

The capacity of one flavouring tank is much smaller than an aging tank. Therefore, the material is transferred from aging tanks to flavouring tanks in small batches, flavoured and then transferred to the continuous freezer. Every flavoured batch should follow each other in the freezer for the continuous process. In the start-up, the first flavoured batch entering the freezer creates waste when exiting the freezer. The production batch is most of the time more than 10 times of a flavouring tank capacity, so there will be a certain number of flavouring batches required. In addition, flavouring takes 30 min (filling + processing +emptying). So every half an hour a new flavouring batch starts processing, which is an opportunity for mixing the waste that is created by the first flavouring batch when exiting the freezer. As a result, from the scheduling point of view, the problem is trivial and no scheduling is needed to evaluate the value of the rework.

Although the timing of the defective material generation is known in advance and problem is trivial, Hellendoorn factory does not rework this rework stream currently. The reason is as follows: The start-up loss, which can be mixed back in the flavouring tank, does not pass the pasteurizer again. The waste is stored in a storage vessel before rework. When filling and emptying the vessel, contamination of material with air occurs. In this case, a second pasteurisation is required to the waste, otherwise the reworking of this waste is not allowed due to the hygienic reasons. An option can be to install a system that will enable the start-up loss to enter back to the flavouring tank via a closed pipe. In this way, no contamination will occur. During the transfer via a closed pipe, melting of the ice cream is also necessary. To evaluate the value of reworking this start-up loss, the trade-off between the gain from material cost when rework is used and the investment cost required for closed pipe system has to be investigated.

Another option for reworking this stream can be mixing the start-up loss in the mixer. Then the waste will pass through pasteurizer again. The waste can be mixed with the next sublot of the same production batch, if the next sublot starts processing in the mixer after the waste is generated. This is the general case if a production batch includes more than one sublot.

On the other hand, rather than looking for solutions to rework the start-up loss, investment can also be done for the minimizing the start-up loss, and even eliminating it. Some options can be using other materials that are cheaper than ice cream for the start-up of the freezer and dispose it after or by developing technologies in the freezer to eliminate the initial temperature problem.

4.3.3. Potential of Flow 3: Breakdown/mistake in production lines

The breakdown in a line or worker mistake cannot be foreseen, so the timing and the amount of defective material creation is unpredictable. Moreover, it is also unknown at which part of the production line (e.g. before or after fruit feeder) the problem will occur. When a breakdown/ worker mistake occurs, a considerable amount of material can be lost. The amount varies substantially depending on the reason.

Scheduling is required for the value evaluation of this flow, since reworking is done in the mixer by mixing it with a base mix of another sublot of the same production batch or another recipe's production batch. For reworking to be possible, there should be a compatible product's production (enforced by the rework matrix) within the limited storage time for the waste. Scheduling approaches that can be considered for the scheduling of this rework stream are explained in Chapter 6.

In addition, extra investment is needed to remove the inclusions and/or packages from the defective material, if necessary, to be able to rework it. A possible system for inclusion removal can be a melting sieve that keeps the inclusions separate and the ice cream penetrates through it accompanied with a melting process. If the package removal is automated, the investment required will be higher accordingly.

4.3.4. Waste data analysis

6 weeks waste data (first 6 weeks of 2011) is obtained from SU Hellendoorn and analyzed for each waste source. To see the results in a yearly base, estimation of the yearly waste amount is done by using the 6-weeks waste data and production volumes realized in 2010. There is no waste data belonging to 2010. Therefore, the fact that the waste amount that is generated in a period is directly proportional to the production amount in that period is used for estimation. It is assumed that the production trend in 2010 (the production amount levels in each 6-weeks period) is the same as in 2011. The ratio of the waste amount to the production amount for the first 6 weeks is used to calculate the waste amounts that are generated in other 6-weeks periods.

As a result, the estimated yearly waste amounts that are created by each waste source are compared in Table 4.1. For the first waste source, it is assumed that breakdown/mistake in mixer is observed 5 times a year. As stated in table, 87% of the waste is generated by the third waste source, i.e. Breakdown/mistake in production lines.

Waste sources	Percentage (%)
#1: Breakdown/mistake in mixer	3
#2: Freezer start-up	10
#3: Breakdown/mistake in production lines	**87**

Table 4-1: Yearly waste amount percentages for each waste source

When the waste data regarding the unexpected waste from production line (waste source #3) is investigated, it is observed that the biggest portion of the waste is generated after the fruit feeder. Figure 4.2 shows the distribution of the waste amounts between fruit feeder and after fruit feeder, as well as between production lines. The waste amount differences between lines can be explained by the process rate differences: line 2 is the fastest line and line 3 is the slowest line.

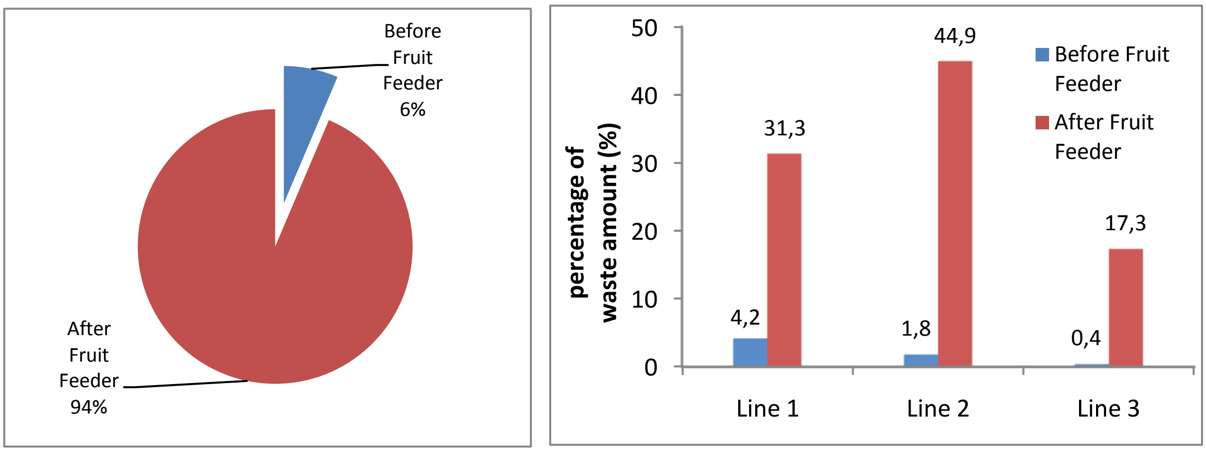

Figure 4-2: Waste amount distribution over location (before vs. after fruit feeder) and over lines based on 6 weeks data in 2011

4.3.5. Conclusion waste source scope selection

This section explains the potential value that can be added by scheduling the rework of three main waste sources of SU Hellendoorn. In addition, the waste data from SU Hellendoorn is analyzed. The first rework source (breakdown/mistake in mixer) occurs rarely and unexpectedly. The second source (freezer start-up) occurs for each production batch in the start-up of the production line. Although the timing is exactly known, based on the reasons explained before, scheduling the rework of this waste source is not required. The third rework source (breakdown/mistake in production lines) results in the biggest amount of waste in the production. The occurrence (the timing, amount and position in the line) is highly unexpected. The waste that is generated in the production line can be reworked by mixing it in the mixer with a new batch. As explained before, the scheduling of ice cream production integrated with rework is required to rework this waste source. Moreover, since the waste amount created by this rework source is high, the potential saving that can be obtained from reworking is also expected to be high. It is concluded that 94 % of the waste generated in the production lines is after the fruit feeder, i.e. with inclusions. Therefore, further focus will be given to unexpected waste generation after the fruit feeder.

To conclude, the waste sources #1 (breakdown/mistake in mixer) and #2 (freezer start-up) will not be point of attention in the rest of this research. The waste that is generated by #3 waste source (breakdown/mistake in production lines) after the fruit feeder will be considered further in the scheduling problem.

Chapter 5. Rework opportunity analysis

This chapter analyzes the current opportunities of rework under the limitations given. The mixing opportunities are discussed under two scenarios, i.e. limited and general rework matrix.

The Hellendoorn factory is currently using the limited rework matrix in where only the same recipes are allowed to be mixed. However, in other factories of Unilever the limitations are less strict. In this case, a relaxed general rework matrix can be generated based on the general mixing rules. Since a model that is applicable to other factories of Unilever with similar characteristics is aimed, it is decided to consider both scenarios.

When the waste is generated, it has to be reworked within 72 hours after its generation due to the storage time limitation. Rest of this section explains the possible ways of reworking the waste via mixing under two different rework matrix scenarios. The information is summarized in Table 5.1.

5.1. Limited rework matrix (only mixing between same recipes allowed)	**5.2. General rework matrix** (mixing between different recipes allowed)
5.1.1.Mixing in the current week's production	*All mixing opportunities in 5.1*
• Mixing between different sizes of the same recipe • Mixing between sublots of the same production batch • Batch splitting (out of scope)	*Mixing between different recipes*
5.1.2.Mixing between consecutive weeks	• Based on the rest of the week's production
• From Friday to Monday • Freezer storage option (out of scope)	

Table 5-1: Reworking opportunities under two rework matrix scenarios

5.1. The limited rework matrix

The possible ways of reworking based on the limited rework matrix can be classified in two parts: mixing in the current week's production and mixing between consecutive weeks production.

5.1.1. Mixing in the current week's production

Mixing between different sizes of the same recipe:

The rework matrix is based on the recipe. However, one recipe has several size options. The number of different SKUs produced in a week ranges from 3 to 13 of which only from 0 to 4 products have different size production in the same week. Figure 5.1 depicts the frequency of the different size production that is observed in 2010. Four products that have 3 size options and generated the most production amount (Appendix C) are analyzed. According to the figure, most of the weekly production takes place for only one size of a certain recipe. For instance, between the weeks that Caramel Chew Chew (CCC) recipe is produced, only 12 % of these weeks different sizes of this recipe are produced in the same week. This situation provides limited opportunities for mixing with the different sizes of the same recipe.

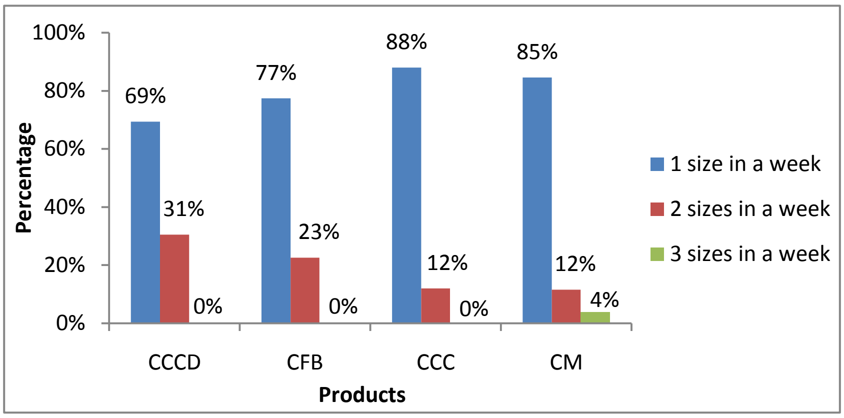

Figure 5-1: The percentages of the weeks that produced the same size of recipe (2010)

Rework opportunities can be increased by producing different sizes of a same recipe in the same week. After the products are assigned to the weeks, in the detailed scheduling, these two products (same recipe, different size) should be scheduled in a way that a waste that is generated from one size's production can be reworked by mixing in the other size's production which starts within 72 hours after the waste is generated. However, decisions of determining weekly production targets belong to the medium planning level, which is not in the scope of this research.

<u>Mixing between sublots of the same production batch:</u>

As explained before, the mixing department prepares base mix for a production batch in sublots. Sublots can create opportunity to rework the waste created from one production batch by mixing it with another sublot of the same production batch in the mixer. This requires enough time lag between sublots since the waste is generated a certain time after the former sublot is prepared. For example, if the waste is generated through the end of the production in the line, it cannot be reworked by mixing with another sublot since the latter sublot is already prepared and waiting in the aging tank, or there are no more sublots. To summarize, this reworking opportunity depends on the timing of the waste generation, the production run length, and number and sizes of the sublots.

<u>Batch splitting:</u>

Each start-up of a product in a production line requires changeover time; therefore result in cost and capacity consumption. In addition, there is material loss associated with start-up. As a result of these consequences, the current scheduling is done in a way that each product (defined with recipe and size) is produced only once in a week, i.e. batch splitting in production lines is not allowed. In this situation, the opportunity for the waste to be reworked by mixing with the same product decreases.

On the other hand, if the batch splitting would be allowed, weekly production creates more opportunity to rework. The waste generation risk can be taken into account by splitting the batches into two separate batches and allow one batch to be produced in the first half of the week and the other in the second half of the week. If there is waste created from the first batch, it can be reworked by mixing with the second batch in 72 hours. However, batch splitting requires extra set-up. When the set-up costs are compared with the profits that can be gained by reworking, it is observed that the batch splitting in a week is not profitable. There is also a risk that no waste will be generated or the capacity of the production lines will not allow for an extra set-up. Thus, any batch splitting in a week for a product will be out of scope.

5.1.2. The mixing between different weeks

<u>From Friday to Monday:</u>

When a 72 hours storage limit is considered, the waste created on Friday of a week can be reworked by mixing with the same recipe (any size) only if it is produced again at the beginning of the next week while satisfying 72 hours storage time limit.

Freezer storage option:

When the waste is stored in freezers, it can be reworked any time of the following months. However, this option is already kept out of scope for this research due to previously explained reasons.

5.2. General rework matrix

If the current rework matrix can be relaxed based on the general mixing rules given in chapter 4, the waste material can be reworked by mixing with other compatible recipes within a week. The recipes that allow mixing for each recipe with a certain allowed percentage are expressed in the "General Rework Matrix". As the waste source under the scope of this research is the waste material that is generated after the inclusions are added, all the mixing rules mentioned in section 4.1.2 are considered in this rework matrix.

When reworking is used based on the general rework matrix, besides the opportunities created by the limited rework matrix given in previous section, the opportunities created by mixing different recipes are also considered. However, the opportunities by mixing different recipes are limited by two important factors: the mixing allowances allowed by the rework matrix and the rest of the week's production portfolio. If a product, which the waste can be mixed with, will be produced within the storage time limit of the waste, the reworking opportunity occurs.

In this research, a model which takes the rework matrix and the production targets of the rest of the week as an input and gives the rework opportunities by considering the storage time limit and cost efficiency is developed in the following chapters.

5.3. Conclusion rework opportunity analysis

This chapter gives the analysis of rework opportunities which are mainly determined by the type of the rework matrix and 72 hours storage time limit for the waste. It is concluded that when the limited rework matrix is used, the reworking opportunities by mixing the same recipes within the same week are (1) mixing between the different sizes of the same recipe, (2) mixing between the different sublots of the same production batch. Mixing between consecutive weeks is only possible if the waste is generated on Friday and the same recipe is produced on Monday. When a general rework matrix is used, besides the opportunities under the limited rework matrix scenario, the opportunities that are created by mixing between different recipes are included. These opportunities are limited by the rest of the week's production portfolio based on the rework matrix. A model is required to evaluate these opportunities by considering the rework limitations based on the minimization of the relevant costs. The model is developed in such a way that the rework opportunities discussed in this chapter are included.

Chapter 6. Model Development

This chapter explains the model development process based on the production and rework characteristics, problem description under the scope and the research assignment. First, the scheduling approaches that can be used for the characteristics of the focused waste source are explained. The second section gives the requirements that have to be incorporated in the model. Finally, the review of the literature that is used during the model development is provided in the third section.

6.1. Scheduling approaches

The waste source, which is under the scope of this research, generates waste when an unexpected breakdown or human mistake occurs. The timing, location and the amount of the waste cannot be known beforehand. Different scheduling approaches can be used to deal with the stochastic situation of this waste source. These approaches can be classified as proactive scheduling and reactive scheduling.

6.1.1. Proactive schedule

In proactive scheduling, the decisions are made not only based on the current situation but also based on the forecast of the future situation. When making the scheduling decisions (which batch to start and when) integrated with rework, the waste material that is already stored for rework, as well as the expected waste generation in the future, which is forecasted by the schedule, are taken into account.

To be able to develop a proactive schedule, which integrates the rework of the unexpected waste from production lines, the waste generation during the week has to be forecasted in advance. The solution of the schedule highly depends on the timing and the position of the breakdown/mistake in the line, and the amount of waste generated. A slight difference in the forecast from the real life situation can result in different results. Forecasting of an unexpected breakdown/mistake with the combination of the variables of timing, position and waste amount is a complex process and will always result in forecast error. Therefore, the results of the proactive schedule will be far from the real life situation.

6.1.2. Reactive schedule

In reactive scheduling, the decisions are made only based on the current situation. When making the scheduling decisions (which batch to start and when) integrated with rework, only the waste material that is already stored for rework is taken into account, but not the future waste generation. In other words, as the name suggests, the schedule reacts to the observed situation.

In practice, the schedule for a week is confirmed one week before, on Thursday. At this time being, the only 'waste in storage' information that can be used for the scheduling of the following week is the waste that is stored in the freezers. The waste material that is stored in the other types of storages by Thursday cannot be reworked in the following week's production due to the time limit (max 72 hours). Therefore, when the freezer option is not included, the only waste material that can be reworked in the following week is the material that is created after the confirmation of the schedule for the following week. In this case, the schedule, which is already confirmed, has to be updated as waste generation information is obtained.

Figure 6.1 gives a representation of a weekly schedule update with an example situation. For instance, one production line stops due to a breakdown on Tuesday and results in a certain amount of waste. It is possible to rework this waste in 72 hours. As soon as this waste information is obtained, the schedule for the current week is updated. Any opportunity for reworking this defective material by mixing it with the same or compatible product until the end of Thursday's production is searched for. This can be done by changing the line allocation or production sequence in the week as long as the weekly capacity allows. In case another breakdown/mistake occurs in a line during the week, the schedule of the rest of the week is updated again based on the recent information (the waste amount created, location of the breakdown and the rest of the production quantities for that week).

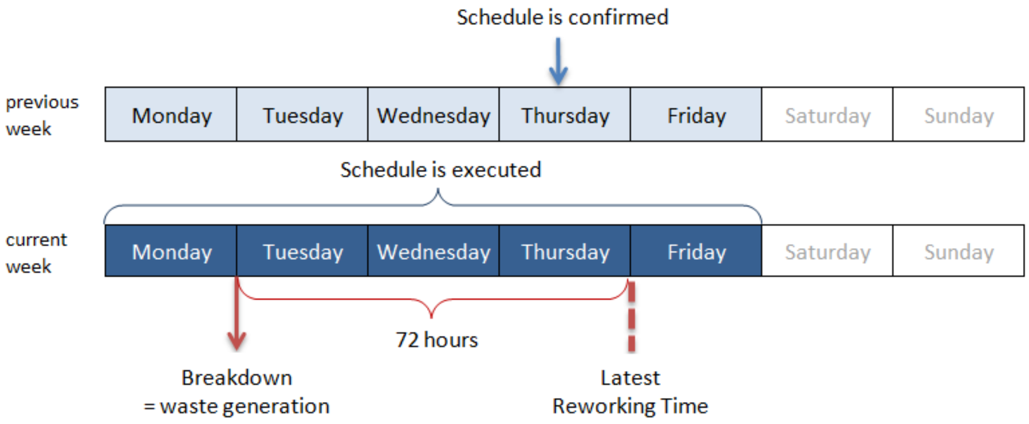

Figure 6-1: Representation of a weekly schedule update

Reactive scheduling requires the capability of production to adapt the revised scheduling decisions in a short time. For example, when it is decided to produce a production batch earlier, necessary raw material, equipment and worker for that product have to be available by that time.

The reactive scheduling can be further divided in two approaches:

1. Optimistic: When scheduling is done for the first time, a best-case scenario with no breakdowns is assumed. Then this optimistic schedule reacts to any problem occurring in the line, and the schedule is updated.
2. Pessimistic: When scheduling is done for the first time, a worst-case scenario with possible breakdowns is assumed. If no problem occurs, the schedule is updated according to the new situation. There may exist many scenarios with breakdowns. Therefore, this approach can result in many schedule updates.

The optimistic reactive scheduling approach will be further investigated for scheduling of the rework. The reasons for a need of schedule that reacts to a breakdown/mistake in a production line by updating the previous schedule, instead of a proactive scheduling approach, can be summarized as follows:

- The waste generation is unpredictable.
- The allowed storage time of the waste is short. (max. 72 hours)
- The only waste that can be reworked in the following week is the material that is created after the confirmation of the schedule. Therefore, the confirmed schedule has to be updated.

Reactive scheduling can be performed in two ways:

1. Partly update: A large fraction of the scheduling decisions already taken remains the same or experiences limited changes during the updating process. This can sharply reduce the scheduling problem size. On the other hand, the optimality is released by not considering a fraction of the scheduling decisions.
2. Full-scale rescheduling: All the scheduling decisions are taken into account during the updating process. The optimality of the new schedule is guaranteed. However, the computation costs can increase due to larger problem size.

The incorporation of the scheduling decisions in the model is considered in the next section by providing the reasons behind it.

6.2. Model Requirements

In this section, the requirements of the model are derived based on the defined problem under the scope and the production/rework characteristics. These requirements have been taken into account when reactive rework scheduling model is developed. The requirements which will not be considered in the model are also given together with the reasons for these choices.

6.2.1. Time Horizon

The input of the model is the production planning which defines in which weeks what quantities of which product should be produced. The output of the model will define the detailed schedule of the corresponding week. As a reactive scheduling approach is used, the model will be executed for the remaining time horizon each time an unexpected situation occurs. For this reason, the scheduling time horizon is smaller than one week.

SU Hellendoorn operates (except holidays and overtime) 5 days a week. Operation takes place in 3 shifts of 8 hours each. Therefore, in the model no discrete separation between days is needed.

6.2.2. Recipes and Sizes

Production line capabilities depend on the size of products, as well as on some recipes. The process rates in the mixing department depend on the base mix, which in turn is determined by the recipe. The process rates in the production lines depend on both the size and the recipe. Moreover, the changeover times and costs are related to the size and the recipe of the products which follow each other. Since these characteristics of the production should be incorporated in the model, a product is defined by recipe and size. (E.g. 500ml Caramel Chew Chew). Inputs (e.g. production targets) and outputs (e.g. batch sizes) of the model are all defined per recipe and size.

6.2.3. Unit of Measurement

The unit of measurement used in SU Hellendoorn differs depending on the department, and area of use. In the freezers, the air is added to the ice-cream which increases its volume, but keeping its weight fixed. At this point in the whole production process, there is also a switch in the measurement units. The end product is defined in terms of volume (150 ml, 500 ml and 4500 ml). Accordingly, the demands, penalty costs and processing rates are defined in terms of volume (liters, litons[2] or Zun[3]). However, raw materials (base mixes), waste amounts, rework and dispose costs are defined in terms of weight (kg, ton). As the user will enter the waste amounts as an input to the model at the moment of rescheduling, it is more practical to define the related parameters and variables in terms of weight. The conversions kg/liter for each end product is known (see Appendix B). Via straightforward calculations, necessary conversions can easily be done.

6.2.4. Production Target and Due Dates

The scheduling should be such that the production target set by the weekly production plan is fulfilled. The production target volumes have to be delivered at the end of each scheduling period (week), thus each product in a week has Friday as the due date. In case of unfulfilled production targets in a week, depending on the product, either next week’s production targets are updated and the order is backlogged, or it becomes lost sale. Next subsection explains this distinction.

6.2.5. Lost Sales and Backlogging

The production targets are determined by the medium level production planning, which takes into account the long-term capacity and inventory planning. Therefore, these targets do not directly reflect the demand from MSUs, who are the customer of SU Hellendoorn. In case of unfulfilled production targets in a week, the following weeks’ production targets can be updated. If the upcoming weeks’ capacity allows, replacement of production amounts can take place. This situation can be considered as backlogging. However if the upcoming weeks do not allow for the replacement of the unfilled production amount before the due date of the real demand from MSU, then it results in lost sales.

Some products are produced more frequently than others due to high demand from MSUs. These products are classified as A products in ABC classification. Any failure in the weekly production

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[2] 1 liton=1000 liters

[3] Zun is related to the case sizes. There are 12, 8 and 2 cups in 1 zun of Shorty, Pint and Bulk respectively.

targets of these products can lead to lost sales to the end customers (mainly retailers) which involves high fines and the risk of losing shelf space in the customers' store. In the case of production replacement due to backlogging, the KPIs (Key Performance Indicators) in the SU Hellendoorn are affected in a negative direction.

For these reasons, penalty costs for the non-fulfilled production targets have to be incorporated in the model. When determining the values for the penalty costs, the situation of backlogging or lost sales has to be taken into account, as well as the importance of the product.

Depending on the value of the penalty cost, there can be situations in which it is cost effective to have lost sales or production replacement of a certain amount of production to be able to rework the waste on hand. Using realistic values for the penalty cost can provide insight for such situations. However, analysis of realistic penalty cost is kept out of the scope of this research.

6.2.6. Production Lines

The production lines are the lines including the freezers and packaging lines. Production lines have different capabilities, and different production rates and costs for each product they can produce.

6.2.6.1. Line capabilities

Each production line has different capabilities for producing different sizes (because of filler and hardening tunnel) and different recipes (because of fruit feeder). This imposes direct capacity restrictions in the production and thus has to be considered in the model.

6.2.6.2. Process Rate

The process rate depends on the product (recipe and the size) and the line that product is allocated to. As stated before, the process rate of a product in the production line mainly depends on the filler. Process rates are taken in the model as deterministic since the fillers in packaging stage can be considered stable, so the process rate does not fluctuate significantly (Budé, 2008).

6.2.6.3. Production Costs

The labour cost in the production lines forms the major part of the production cost that is relevant to the second stage of the scheduling problem. Different lines require different number of labours for the same product. When making the line allocation decision, different production costs of the lines have to be considered. The other variable production costs such as the raw material cost and packaging cost are not considered, since these cost items are not affected by the decisions that are made by the model. Except the base mix cost, which is considered separately in the material cost item, is affected by the rework decisions.

Concluding, when the line allocation decisions of the products are made, the model should consider capacity constraints (affected by the line capabilities and the process rates) and minimize the cost (affected by the production cost).

6.2.7. Aging Tanks

Each production line (in stage 2) has dedicated aging tanks with different sizes in front of the line. Base mixes have to stay in these aging tanks at least 2 hours but no longer than 72 hours. As well as these time limitations, the limited capacity of the aging tanks should be considered in the model to prevent any infeasible solutions resulting in tanks being over filled, or being emptied and filled at the same time.

6.2.8. Mixing Department

There are two mixers working parallel and responsible for preparing mixes. Base mixes are prepared in this department in terms of sublots. A sublot, depending on the size, can require multiple times of mix preparation in the mixers. The processing rate in the mixing department is determined by the emptying rate in the mixers which is the same as the processing rate in the pasteurizer. The pasteurizing rate of a product depends on the base mix type. A mixer can only process when filled half. This generates a technical restriction for the minimum sublot size.

6.2.9. Changeovers

Changeovers are required when another recipe or packaging size is to be produced. Before the end of the week, there is also a cleaning session of all production lines.

6.2.9.1. Changeover Times

Both stages (departments) require a certain changeover time, when production changes to a different product. These changeover times are represented by the changeover matrices separate for the mixing department and for each production line. In the mixing department (Stage 1), the base mixes of the products which follow each other determine the changeover time. As said before, different products can have the same base mix. In that case, there is no changeover time needed.

6.2.9.2. Changeover Costs

Each changeover requires time and labour during the changeover time. In stage 1, the changeover cost per hour is not sequence dependent. Changeover is always done by a certain number of labours. However, in stage 2 changeover cost per hour depends on the product that will be produced next. For instance, the production is changes from product A (7 workers) to product B (8 workers), then 8 workers have to work during the changeover.

Incorporation of changeovers is a requirement for the model, since sequence decisions made by the model affect total changeover cost.

6.2.10. Resource Restrictions

The discrete resource constraints that are applied implicitly in the model are the processing equipments which are the production lines, the mixers and the pasteurizer. Other resources such as labour and raw material are assumed unlimited. Different products require different number of workers in the production lines. The Hellendoorn factory is able to arrange flexible (temporary) workers when needed. Therefore, in this problem workers are assumed available when needed.

6.2.11. Rework

Integrating rework decisions in the model requires the incorporation of the following rework aspects:

6.2.11.1. Rework limitations

As explained in Chapter 4, the allowed waste storage time and rework matrix are the two major limitations for reworking. Their incorporation in the model is necessary. Whereas, the freezer option for waste storage will not be considered, the model to be developed needs to have the capability of analyzing different rework matrix scenarios: limited and relaxed.

6.2.11.2. Pre-Rework operations time

Before reworking a waste, it has to go under the pre-rework operations (inclusion and/or package removal) which take a certain time depending on the waste generation location (e.g. if the waste is generated before packaging, no package removal operation is needed which decreases the total pre-operation time) and the amount of the waste. Reworking of the waste cannot start before this time.

6.2.11.3. Rework operational cost

Reworking a waste requires labour during the time of handling the waste for storage and pre-rework operations. The rework operational cost directly depends on this time, indirectly depends on the waste amount and the location of the waste generation.

6.2.11.4. Material (base mix) savings

The waste that is reworked by mixing with a new product replaces the base mix that is used in the production of the new product. Therefore, the material (base mix) saving in case of a rework should be considered by the model.

6.2.11.5. Dispose Income

The waste that is not reworked will go to bio-digester which will generate income depending on the waste amount.

6.2.12. Rescheduling

To be able to account for the waste generated, and analyze if it is possible or cost effective to rework, the schedule which is already confirmed has to be rescheduled based on recent information. During rescheduling, there can be sublots whose production is already started in stage 1 or the production lines in stage 2 can be busy with production. The decisions regarding the already started sublots or production batches cannot be changed. Thus, these decisions have to be taken into account by not scheduling a production before these sublots or production batches are finished.

6.3. Literature Review

Based on the problem description and model requirements given above, the model to be developed in this research has to include the following characteristics; multi-stage production, limited intermediate storage capacity, multi-products, perishability of the intermediate products, batch sizing, sublot formation, sequence-dependent changeover times, rework option via mixing and reactive scheduling. Moreover, the model has to be capable of making the following decision; batch sizing, allocation, sequencing, timing and reworking. During the model development, the current literature has been investigated for similar studies. Although there are studies addressing similar problems, it is observed that a missing link exists between multistage batch scheduling and rework in process industry.

A wide range of studies about scheduling models for multi-stage batch facilities is available. A review is published by Méndez (2006) regarding the optimization methods for short-term scheduling of batch processes. The roadmap given by this study (Figure 6.2) is followed during the development of the mathematical model that is proposed in this research.

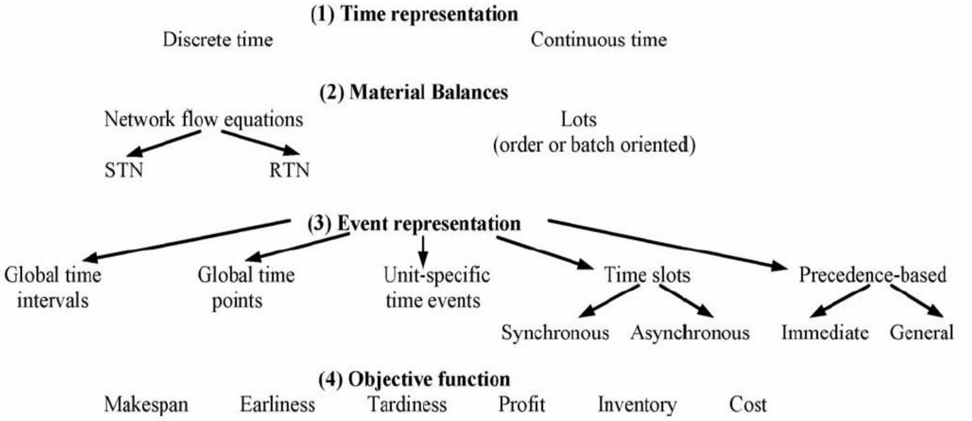


Figure 6-2: A roadmap for short-term scheduling models of batch plants (Méndez et al., 2006)

Floudas et al. (2004) compare continuous-time and discrete-time approaches for scheduling of chemical processes in his review. Discrete time representation includes the discretization of the time horizon into a number of fixed time intervals. This can result in two main limitations: First, the model can lead to suboptimal solutions as fixed time grid constraints the tasks to start and finish at predefined grid points. Second, the overall size of the model can unnecessarily increase due to the introduction of a large number of binary variables associated with each discrete time interval. A continuous-time approach can eliminate a major fraction of the inactive event-time interval assignments which results in much smaller sizes of mathematical programming problems requiring less computational efforts.

A general resource-constrained scheduling framework using a MILP sequential approach is studied by Marchetti et al. (2009) for multistage batch facilities with sequence-dependent changeovers. A general precedence notion is used to handle allocation and sequencing decisions. Formulating the sequencing constraints by using the general precedence concept is introduced by Méndez et al. (2001). The key binary variables are: Y_{ij}: binary, if batch (i) is allocated to unit (j); $X_{ii'}$: binary, if batch (i) precedes batch (i'). Here, the general precedence notion includes both the immediate predecessor and all batches processed before. Other continuous variables and parameters are: C_i : Completion time of order (i); pt_{ij} : processing time of order (i) in unit (j) ; $\tau_{ii'j}$: changeover time from order (i) to order (i') in unit (j); and H: time horizon.

$$C_{i'} - pt_{i'j} \geq C_i + \tau_{ii'j} - H(1 - X_{ii'}) - M(2 - Y_{ij} - Y_{i'j}) \tag{1}$$

$$C_i - pt_{ij} \geq C_{i'} + \tau_{i'ij} - HX_{ii'} - M(2 - Y_{ij} - Y_{i'j}) \tag{2}$$

These equations represent sequencing constraints by handling assignment and sequencing decisions independently through different sets of binary variables. Whenever batches i and i' are allocated to the same unit ($Y_{ij} = Y_{i'j} = 1$), then either the constraint (1) or (2) becomes active depending on whether $X_{ii'}$ is one or zero.

Another common point of these studies is the objective functions that are time-based (such as minimization of order earliness and minimization of makespan). When a more complicated objective function is involved such as minimization of total cost that includes changeover cost, the above defined general precedence binary variable (non-immediate $X_{ii'}$) cannot easily handle changeovers. Pinto et al. (1998) indicates an alternative representation for multiproduct problems which relies on the use of immediate precedence binary variable $X_{ii'}$ (the processing of batch i immediately before batch i'). This requires extra constraints to control active precedence binary variables to guarantee that all batches have exactly one predecessor and one successor (except the first and last job in the time horizon).

Immediate precedence notion is used by Kopanas et al. (2010) in simultaneous lot-sizing and production scheduling problem of multiproduct yogurt production lines. The proposed MILP model uses a continuous-time representation within each production day. To reduce the problem, aggregation of the products in families is applied. However, in this study multistage scheduling is not included. Instead the problem is mainly focused on the packaging stage. Timing and capacity constraints with respect to the fermentation stage are only considered for feasibility.

The literature regarding the general scheduling problem in multistage facilities discussed above, does not include all the characteristics of our problem such as sublot formation, rework and reactive scheduling.

Defersha (2010) studied a lot streaming problem in a flowshop environment with multi-stage manufacturing systems. Production batches are split into smaller sublots so that successive operations of a given batch can be overlapped. As the operation of a batch in second stage can start earlier but does not have to wait for the whole batch to finish its processing in earlier stage, the manufacturing makespan can be reduced. The decision variables that are used in the mathematical formulation regarding the sublot formation are adapted to our model. However, instead of using precedence decision variables, sequence decisions are made through the assignment of the sublots of a particular job to the runs of a machine. This kind of formulation is a disadvantage for changeover costs calculations due to the lack of immediate precedence variables.

Reactive scheduling of multistage batch facilities is addressed by Mendez et al. (2004). The proposed technique is able to update the current schedule when unforeseen events like deviations in processing times, equipment breakdown or batch reprocessing occur. The old tasks that are still to be processed are rescheduled and the new ones are inserted through the allowed modifications to the current schedule in such a way that every resource capacity constraint is satisfied at minimum make-span or average tardiness. The proposed MILP model is based on continuous time representation and includes sequence-dependent changeovers. Besides the relatively basic objective function, this formulation is the closest so far to our problem. However, as in Marchetti et al. (2009), general precedence decision variables are used in this study that do not allow to track changeovers explicitly and to add changeover costs to the objective function. When solving the problem, a rescheduling algorithm is iteratively performed which handles resource reallocation and batch reordering steps sequentially.

Rework of perishable items in process industries is addressed by several studies. Research contributions following this direction are presented by Teunter & Flapper (2003), Flapper & Teunter (2004), Inderfurth et al. (2006, 2007), Buscher & Lindner (2007), Barketau et al. (2008). However, these studies are focused on a single stage facility where production switches from regular production to rework. Rework of perishables via mixing in two-stage process industry has not been addressed before.

The available literature, offering MILP formulations to resource-constrained scheduling problems for multistage batch facilities with sequence-dependent changeovers, leaves us the challenge of integrating rework and rescheduling aspects of our problem under the conditions given in a way that the problem can be solved in a computationally economical time.

Chapter 7. Reactive scheduling model with rework

This chapter provides the conceptual model, the assumptions regarding the conceptual model, the mathematical model and finally a problem size reduction method.

7.1. Conceptual Model

The reactive scheduling approach is used to model the problem. When information regarding a breakdown or worker mistake leading to waste generation is received from the production lines, the schedule that is confirmed before is updated for the remaining time horizon by taking into account the new information. The new schedule takes the waste amount, the location and the timing of the waste generation and the rest of the week's production target quantities as input parameters, and gives a new schedule in which the rework option is included. The output gives the line allocation of each product and the sequence/timing of their production in both stages. The possibility of reworking depends on the rework matrix and the rest of the week's production (mixing possibilities of the products).

Reworking is mainly decided based on the trade off between "material saving - rework cost" and "dispose income". If the material saving-rework cost is bigger than dispose income, the model will always favour reworking. However, the main limitations of storage time and rework matrix determines the possibility of the rework which depends on the products that are produced in the rest of the week. The model also decides if it is profitable to change the sequence of the production or line allocation leading to more changeover or production cost but creating rework opportunity that will result in material saving.

Besides the timing and sequencing decisions, the other decisions that are made by the model are the sizes of the production batches for each product in Stage 2 and the number and size of the sublots of each production batch in Stage 1. The decision variables regarding the sublots in Stage 1 constitutes the biggest part of the problem size. A "maximum number of sublots" parameter is defined to limit the decisions of number of sublots for each product. Theoretically, this number is calculated by "Production batch size divided by the minimum sublot size".

It is assumed that each product (defined by recipe and size) is produced only once in a week due to set-up concerns in the production line. The number and amount of the products to be produced in a week is known. Decision of not producing a product at all is not included in the model. The production targets are decided in the medium level planning and they are committed in the detailed scheduling level. Therefore, the penalty cost for not producing a ton of production target is high. However, in case of a capacity shortage, the model can decide not to produce a portion of the production target.

7.1.1. Waste and Rework

The mixing possibility considered in this model is as follows: the waste created in the production line (after the Fruit Feeder), which is with inclusions, can be with or without package. After it undergoes the necessary treatments (melting, inclusion removal and if necessary package removal), it is sent back to the mixing department to rework it by mixing with one or more sublots of another production batch. If there are still sublots of the same production batch to be prepared in mixing department, it is also possible to rework the waste by mixing it with the same production batch. The treatments, which are necessary to perform to the waste before reworking, (referred as 'Pre-rework operations' in the rest of the report) take a certain time depending on the waste amount and waste generation location. Thus, the waste can be reworked only after this time. Besides this earliest time of rework, a latest time that the waste can be reworked is also included in the model resulting from the 72 hours storage time limit of the waste after its generation.

At the time of rescheduling, it is possible to have previously taken decisions and actions regarding the waste that is generated earlier. The pre-rework operations can already be performed to this waste. To account for such a situation, another waste generation location is assumed which does not require any pre-rework operation time, so ready to be reworked. The waste generation locations that are considered in the model can be summarized as follows:

- Location 1: already pre-reworked, without inclusion, no pre-rework time required.
- Location 2: before packaging, with inclusion, certain pre-rework time required
- Location 3: with inclusions and package, pre-rework time more than location 2 required.

Since the schedule is updated at the time of a waste generation, 'Rescheduling Time' in the model corresponds to the latest waste generation time. However, other wastes that are generated before but rework/dispose decisions are not made yet, as well as the latest generated one, are taken into consideration in the model through the following input parameters:

1. The generation time of the waste belonging to a product type
2. The location of the waste generation as binary data

When the waste is generated, it has to be stored in the waste storage tanks before the pre-reworking operations for melting process. If the waste is waiting for a reworking decision, it also has to wait in these storage tanks. After the pre-reworking operations, the waste is stored again during the waiting time until reworking. The storage tanks are also used when handling the waste before reworking via mixing in the mixing department. Figure 7.1 shows the flow diagram of the waste generation and rework integrated with the regular production.

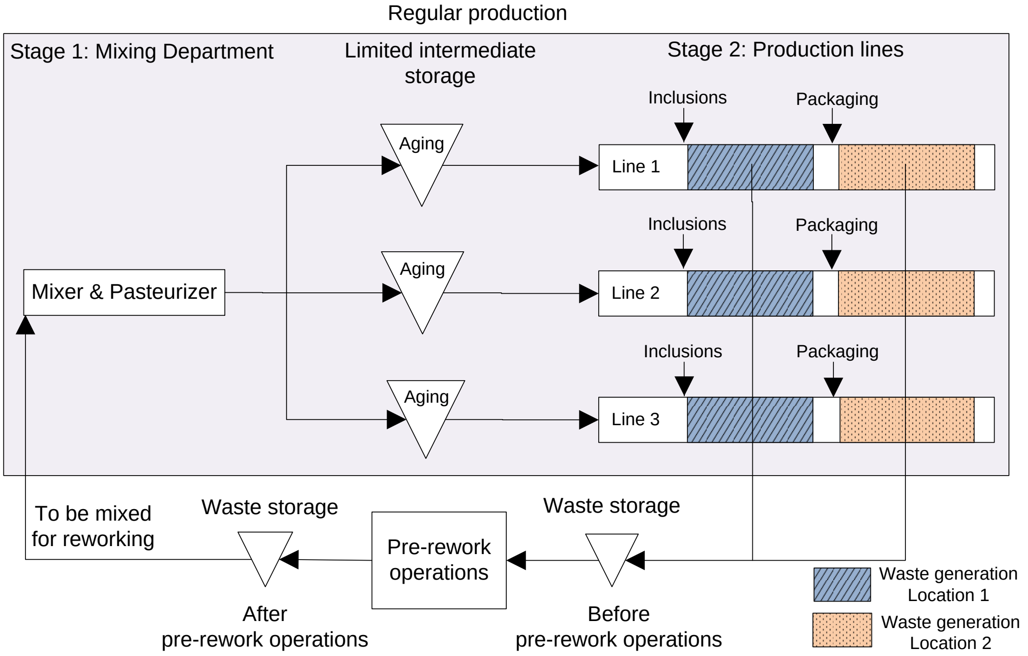


Figure 7-1: Flow diagram of the waste generation and rework integrated with the regular production

The storage tanks for the waste and equipments for the pre-rework operations have to be invested at the moment that it is decided to rework. It is explained before the waste amount that is resulted from a breakdown or mistake in the lines varies substantially. It is also possible that two different wastes have to be stored at the same time. It is assumed that the resources (storage tanks and equipment/labour for pre-rework operations) are not restrictive for reworking the total amount of waste.

7.1.2. Rescheduling

At the moment of rescheduling, there can be sublots whose production is already started in stage 1 (mixing department) or in stage 2 (production lines). It is assumed in the model that the decisions that are made belonging to these sublots (e.g. the line allocation and starting time of these sublots in stage

2) cannot be changed. However, the subsequent sublots of this production batch are treated in the model as the new production quantity. In the original plan, the subsequent sublots were supposed to follow the sublot that is under the production. However, the decisions regarding the subsequent sublots, which are not started to be produced yet, can be remade according to the new situation. It may be more profitable to produce the leftover sublots later in the week or in another line when rework opportunity is considered. This situation leads to batch splitting in the overall week, when the production before the rescheduling time is considered. The sublots, which are already in the production, are not considered as a part of the production target anymore, but the leftover sublots represent the new production batch. Since the model is interested in the rest of the week's schedule and it will take the new production targets as input, it does not have to be capable of batch splitting. The option to decide the leftover production in a later time is not considered as batch splitting in the model when the new scheduling horizon after the rescheduling time is considered. A start-up cost factor is included in the model to account for this situation. Start-up cost is calculated based on the changeover time between the product under the current production in the line and the first product to be produced in the same line. If the leftover production of the currently produced product is the first product to be produced, the changeover time between the same products is zero, therefore there is no start-up cost incurred.

The sublots whose production is already started will occupy the production lines for a certain time. These already made decisions will be entered to the model as an input, which indicates the time of the production left of a certain product in a certain line. Only after this time, a production belongs to a new decision can start in a production line. Also for Stage 1, at the time of rescheduling, the mixer can be busy with producing a sublot. A sublot's production belonging to a new decision can only start after the mixer's current operation is finished.

7.1.3. Limited intermediate storage

As explained before, the intermediate storage (aging tank) capacity should be taken into account to avoid overlapping of the aging tanks by the sublots. The occupation of the tanks by the sublots depends on two decision variables of the model:

1. Line allocation, which determines the number and the size of the aging tanks that have to be used and the emptying rate of the aging tank (equal to the processing rate of the allocated line)
2. Sublot size, which determines the number of tanks that are occupied.

Incorporating limited aging tank capacity explicitly in the model increases the problem size in a large extent and the constraints require non-linear constructions (due to the multiplication of the decision variables). Therefore, a simplification is searched for to incorporate the limited aging tank capacity in the model implicitly. A concept, which is called t^{slack} , is developed to prevent overlapping in the aging tanks. The concept interprets the physical capacity limit in terms of time restrictions.

Figure 7.2 is given to visualize the concept. The example situation refers to a production line which has two dedicated aging tanks. When one aging tank finishes emptying, the other one starts emptying immediately for continuous production in stage 2. After the aging of the first aging tank is done, the production in stage 2 can start. In this example, there are two sublots generated for the production batch in stage 2. The blue arrows in the figure represent material flows.

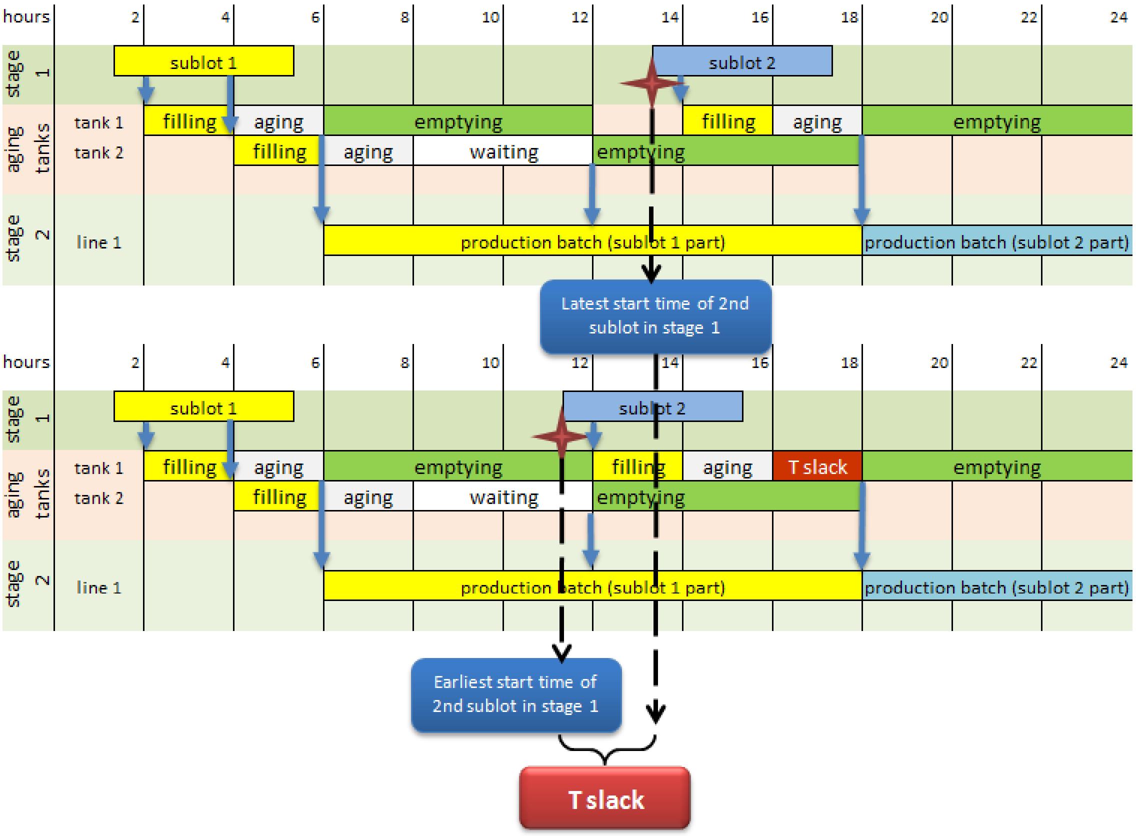


Figure 7-2: Visual explanation of t^{slack}

In practice, the base mixes are prepared in sublots in stage 1 and transferred to the aging tanks. After at least 2 hours aging time in the first aging tank, the emptying starts and the base mixes are transferred to the production lines. When the production of the first sublot is finished in stage 2, the second sublot has to be ready in the aging tanks to be transferred for the continuous production in the lines. The second sublot has to be prepared in the mixers in a way that it is ready on time in aging tanks taking into account 2 hours of aging time. This poses a latest time to start the processing of the second sublot in stage 1. The first example schedule in Figure 7.2 points the latest start time of the next sublot in stage 1. If the processing of the second sublot in stage 1 starts earlier, it can wait in the aging tanks for extra time. However, to be able to start processing the next sublot, one aging tank has to be emptied. The poses an earliest start time of the second sublot in stage 1. It is shown in the second example schedule in Figure 7.2. The time difference between the latest and earlier start points is called “t^{slack}”. It can be defined as *“the maximum allowed time for a sublot to start the processing in stage 1 earlier than it is needed”*. If the sublot starts processing earlier in stage 1, it will occupy the aging tank for extra time which is the same as t^{slack}. Therefore, t^{slack} can be also interpreted as *“the maximum allowed time that a sublot can occupy the aging tank for extra time”*. Figure 7.2 shows both interpretations.

The value of t^{slack} has to be estimated in such a way that the occupation of the different sublots in the aging tanks does not overlap. By using the figure, a formula that can be used for estimation is generated as follows:

$$\begin{aligned} t^{slack} = \ & processing\ time\ of\ sublot\ in\ stage\ 2 \\ & - emptying\ time\ of\ one\ aging\ tank \\ & - filling\ time\ and\ aging\ time\ of\ one\ aging\ tank \end{aligned} \tag{7.1}$$

This estimation works only when all the aging tanks are filled by the sublot. Because, otherwise the second sublot starts filling the empty aging tank, and the situation does not impose any earliest start time of the sublot in stage 1.

Eq. 7.1 can be written more specifically as:

$$t^{slack} = \frac{Max\ sublot\ size}{processing\ rate\ in\ stage\ 2} - \frac{one\ aging\ tank\ capacity}{processing\ rate\ in\ stage\ 2} - \left(\frac{one\ aging\ tank\ capacity}{processing\ rate\ in\ stage\ 1} + aging\ time\right) \tag{7.2}$$

The factors in Eq. 7.2 depend on the product types and the line that the product is allocated which is a decision variable of the model. However, the user has to enter only one t^{slack} value as an input parameter. Therefore, the minimum of the t^{slack} values for all the combinations of products and the capable lines is accepted as the t^{slack} value. A calculation tool in Excel is developed which calculates this value automatically once the user enters the products that have production in the remaining week.

7.1.4. Inputs and outputs

The inputs and outputs of the model can be given as follows:

Inputs:

- The number and type of products
- The number and type of base mix recipes
- The number of production lines operating in parallel
- The capability of the production lines
- The number and size of aging tanks dedicated to each production line
- The aging times for base mixes
- The production rate for every product at each production line
- The minimum and maximum (depending on the aging tanks) sublot sizes
- The changeover times and costs for every pair of products in each production line
- The changeover times and costs for every pair of base mixes in the mixing department
- The costs regarding production lines operating costs (labor costs)
- The material costs of each product
- The number and type of locations for waste generation
- The reworking times and costs for each location
- Dispose income from disposing the waste
- Type (product type) and the amount of waste
- Time and location of the waste generation
- Rescheduling time
- Time left for the products that is under production currently for each line
- Time left for the sublots that is under production in mixing department
- The production target amounts for each product
- The capacity (hours available) in the current week
- t^{slack} value

Outputs:

- The allocation of products to production lines
- The sequencing of products in each production line in stage 2
- The production amounts for each product (production batch sizes)
- The sequencing of sublots in stage 1 (mixing department)
- The number of sublots of a product to be produced in stage 1
- The size of each sublot
- The starting time of the production batches in stage 2 (production line)
- The starting time of the sublots in stage 1 (mixing department)
- Amount of waste that is reworked for each product
- The sublots in which waste is added for reworking

The outputs of the model are determined in a way that the objective function representing the total relevant costs is minimized.

7.2. Assumptions regarding the conceptual model

Scheduling problems are classified as NP-Hard problems and no standard solution techniques are available (Kallrath, 2002). It is computationally expensive to solve real-life scheduling problems by exact methods, such as mathematical programming (Kopanos et al., 2010). The scheduling model includes detailed model specifications mentioned before. When modelling such a detailed scheduling problem, a rigorous model is aimed so that it can be used in other case studies by changing the necessary parameter values. To implement a model which represents the reality and which is solvable in a reasonable time requires several assumptions. The assumptions used in the conceptual model are given in sub sections according to the relation with the production, rework and rescheduling aspects of the model.

Production related:

1. Production batch splitting is not allowed.
2. First assumption enforces another assumption: a product is produced at most in one production line in a week.
3. A sublot can stay extra in the aging tanks for t^{slack} time (after 2 hours of aging tank).
4. Worker capacity in the production is assumed non-restrictive.

Rework related:

5. Waste is stored under necessary conditions when generated until the decision of rework/dispose.
6. Pre-rework operations, including inclusion and packaging removal, are performed after the rework decision regarding a waste is made. For example, although a certain waste is generated earlier, if it is decided to rework the waste at the time of rescheduling, it has to go under the pre-rework operations first before it can be reworked by mixing with a new sublot.
7. The resources (storage tanks and equipment/labour for pre-rework operations) are not restrictive for reworking the total amount of waste.
8. More than one type of waste product cannot be added with the same sublot of a new product.

Rescheduling related:

9. The decisions regarding the sublots which mixing and production already has been started cannot be changed. Production in the lines can only start after these sublots are finished in the allocated lines.
10. If the product that is under production has still sublots that are not prepared in the mixing department yet, it can be decided to produce these sublots later. The leftover sublots represent the new production target for the corresponding product. This flexibility can increase the model's opportunities for reworking.

7.3. Mathematical model

Index:

$i, i^*, \bar{i}, i'$	Product
$s,\ s^*$	Sublot
j	Line (in stage 2)
l	Location of waste generation

Sets:

I	Set of products
I^{demand}	Set of products which have production amount in the current week at the moment of rescheduling
I^{left}	Set of products running in Stage 2 at the moment of rescheduling
I^{waste}	Set of waste products
S	Set of sublots
S_i	Subset of sublots for product i, $\mathrm{S_i} = \{1, \dots, \mathrm{N_i^{max}}\}$
J	Set of lines, $\mathrm{J} = \{1, 2, \dots, \mathrm{N^j}\}$
J_i	Set of lines that can process product i
J_i^{busy}	Set of lines that are busy with product $\mathrm{i} \in \mathrm{I^{left}}$
L	Set of waste generation locations = {1,2,3}

Parameters:

c^{ch_1}	Cost of changeover in stage 1 per hour (€/hour)
$c_{ij}^{ch\_2}$	Cost of changeover in stage 2 when production changed to product i in line j per hour (€/hour)
c^{d}	Income from disposing waste (€/ton)
c_{i}^{m}	New material cost for product i (€/ton)
c_{ij}^{prod}	Production cost of producing product i in line j in stage 2 per hour (€/hour)
$c_{i}^{p\_lost}$	Penalty cost for lost sale product i (€/ton)
$c_{\bar{i},l}^{r}$	Operational cost of reworking product $\bar{i}$ generated in location l (€/ton)
C^{week}	Weekly capacity of lines (hour)
$L_{i,j}^{capability}$	Binary data equal to 1 if product i can be produced in line j, 0 otherwise
$L_{\bar{i},l}^{waste}$	Binary data equal to 1 if product $\bar{i}$ is generated in location l, otherwise 0
$m_{\bar{i}}^{w}$	Amount of waste of product $\bar{i}$ generated (ton)
M	Big number
N^{j}	Number of lines
N_{i}^{max}	Maximum number of sublots of product i
Q_{i}	Production target for product i (ton)
$q_{\bar{i}i}^{allow}$	Allowable percentage of product i that product $\bar{i}$ can be mixed with for rework
$s_{ii^*}^{1}$	The changeover time from product i to product i^* in stage 1 (hour)
$s_{ii^*j}^{2}$	The changeover time from product i to product i^* in line j in stage 2 (hour)
t^{age}	Aging time (hour)
t^{slack}	Time allowed for a sublot to be prepared in advance (extra storage time allowed in aging tanks) (hour)
T^{limit}	Time limit that ice cream can stay in rework storage tanks (hour) (currently 72 hours)
$T_{i',j}^{left}$	Time of production left of product i' in line j in stage 2 (hour)
T^{left_1}	Time of production left in stage 1 (hour)
$T_{l}^{prerework}$	Time of pre-rework operations for the waste created in location l (hour/ton)
T^{pre_fixed}	Time of fixed pre-rework operations (hour)
$t^{reschedule}$	Time of rescheduling
$T_{\bar{i}}^{waste}$	Time of waste generation of product $\bar{i}$
v^{m}	Mixer capacity (ton)
v_{j}^{tank}	One aging tank capacity for line j (ton)
$v_{j}^{total\_tank}$	Total tank capacity for line j (ton)
ρ_{i}^{1}	The process rate of product i in stage 1 (ton/hr)
ρ_{ij}^{2}	The process rate of product i in line j in stage 2 (ton/hr)

Variables:

$m_{\bar{i}}^{d}$	Amount of waste product $\bar{i}$ disposed (ton)
$m_{\bar{i}}^{r}$	Total amount of waste product $\bar{i}$ reworked (ton)
P_{i}	Actual production of product i (ton)
P_{ij}	Actual production of product i in line j (ton)
R	Binary variable equal to 1 if rework is performed, 0 otherwise

Binary Decision Variables:

$R_{\bar{i},s,i}$	Binary variable equal to 1 if rework created by product $\bar{i}$ is reworked by mixing with sublot s of product i, 0 otherwise
Y_{ij}	Binary variable equal to 1 if product i is produced in line j, 0 otherwise
$X_{sis^*i^*}^{1}$	Binary variable equal to 1 if sublot s^* of product i^* is processed immediately after sublot s of product i in stage 1, 0 otherwise
$X_{ii^*j}^{2}$	Binary variable equal to 1 if product i^* is processed immediately after product i in

	line j in stage 2, 0 otherwise
$X_{ij}^{start-up}$	Binary variable equal to 1 if line j starts up with product i in stage 2 after the moment of rescheduling, 0 otherwise
γ_{si}	Binary variable equal to 1 if size of sublot s of product i is non-zero ($K_{si} \geq 1$), 0 otherwise

Continuous Decision Variables:

$m_{\bar{i},s,i}^{r}$	Amount of waste product $\bar{i}$ reworked by mixing with sublot s of product i (ton)
K_{si}	Size of the sublot s of product i (ton)
T_{si}^{1}	Starting time of sublot s of product i in stage 1
T_{i}^{2}	Starting time of product i in stage 2

Assumptions regarding the mathematical model:

1. When the filling time of the first aging tank is calculated, it is assumed the tank is completely filled. In reality, if the sublot size is smaller than one aging tank capacity, the aging tank is not completely filled.
2. The time left for the current sublot production in stage 1, includes the changeover time after this sublot, which is the max changeover time between any sublots in stage 1.
3. A waste for a certain product can be generated only in one location in one rescheduling horizon because decision variables belonging to the wastes ($R_{\bar{i},s,i}, m_{\bar{i},s,i}^{r}$) do not include location index (l).

Objective:

The objective function minimizes the sum of the new material cost, penalty costs for lost sales, dispose cost for the waste, rework operational cost, start-up costs and the changeover costs minus the cost savings by reworking the waste, i.e. material cost saving.

$$\begin{gathered} Min\ Total\ cost\ per\ week = New\ material\ cost - Material\ cost\ saving + Production\ cost \\ + Penalty\ cost - Dispose\ income + Rework\ operational\ cost \\ + Startup\ cost + Changeover\ cost \end{gathered}$$

$$\begin{gathered} Min\ Total\ cost\ per\ week = \sum_{i \in I} c_i^m P_i - \sum_{\bar{i} \in I^r} \sum_{s} \sum_{i} c_i^m m_{\bar{i},s,i}^{r} + \sum_{i \in I} \sum_{j \in J_i} c_{ij}^{prod} \frac{P_{ij}}{\rho_{ij}^{2}} \\ + \sum_{i} c_i^{p_{lost}} (Q_i - P_i) - c^d \sum_{\bar{i} \in I^r} m_{\bar{i}}^{d} + \sum_{\bar{i} \in I^r} \sum_{l} L_{\bar{i},l}^{waste} c_{\bar{i},l}^{r} m_{\bar{i}}^{r} \\ + \sum_{i} \sum_{i'} \sum_{j \in J_{i'}} X_{ij}^{start-up} c_{ij}^{ch\_2} s_{i'ij}^{2} + \sum_{i} \sum_{i^* \neq i} (c^{ch\_1} \sum_{s} \sum_{s^*} X_{sis^*i^*}^{1} s_{ii^*}^{1} + \sum_{j} c_{i^*j}^{ch\_2} X_{ii^*j}^{2} s_{ii^*j}^{2}) \end{gathered}$$

Constraints:

1. Allocation constraints

Eq. 1.1 guarantees that each product is allocated to one production line that is capable of producing that product.

$$\sum_{j \in J_i} Y_{ij} = 1 \quad , \qquad \forall\, i\, \in I^{demand} \tag{7.3}$$

2. Batch and sublot size constraints

Total production amount of product i is the sum of the production amounts for each line (Eq. 7.4). Production amount for a line can be more than zero only if it is allocated to that line (Eq. 7.5). Eq. 7.6 makes sure that the product is not allocated to a certain line, if the production amount is zero for that line.

$$\sum_{j \in J} P_{ij} = P_i \ , \qquad \forall\, i\, \in I^{demand} \tag{7.4}$$

$$P_{ij} \leq Q_i Y_{ij} \ , \quad \forall i\, \in I^{demand}, j \in J_i \tag{7.5}$$

$$Y_{ij} \le P_{ij} \ , \qquad \forall\, i \in I^{demand}, j \in J_i \tag{7.6}$$

The sum of sublot sizess for a product i is equal to total production amount for that product (Eq. 7.7). Whereas Eq. 7.8 states the lower limit (min. sublot size allowed v^m) of the sublot size, Eq. 7.9 states the upper limit of the sublot size (the total aging tank capacity of the allocated line). Eq. 7.10 forces the sublot size to be 0, if that sublot does not exist ($\gamma_{si} = 0$). The first sublot of the product should exist since the product is forced to be produced (Eq. 7.11).

$$\sum_{s \in S_i}^{N_i^{sublot}} K_{si} = P_i \ , \ \forall \ i \in I^{demand} \tag{7.7}$$

$$\gamma_{si} v^m \le K_{si} \quad , \forall\, s \in S_i \ , i \in I^{demand} \tag{7.8}$$

$$K_{si} \le \sum_{j \in J_i} Y_{ij}\, v_j^{total\_tank} \quad , \forall\, s \in S_i \ , i \in I^{demand} \tag{7.9}$$

$$K_{si} \le M \gamma_{si} \ , \qquad \forall\, s \in S_i \ , i \in I^{demand} \tag{7.10}$$

$$\gamma_{1i} = 1 \ , \qquad \forall\, i \in I^{demand} \tag{7.11}$$

3. Timing & Precedence constraints

During the construction of the timing and precedence constraints, the representation of the production given in Appendix F is used.

For each product, the processing start time in stage 2 is equal or bigger than the completion time of the first sublot of the same product in stage 1, i.e. start time in stage 1 + mixer filling& processing time+ tank filling time+ aging time. Here the tank filling time is calculated as $\frac{\sum_j Y_{ij} v_j^{tank}}{\rho_i^1}$ based on the first assumption regarding the mathematical model. If the sublot is prepared earlier, it can wait in the aging tank. However, due to the capacity restrictions in the aging tanks, we allow the sublot to be prepared only t^{slack} time in advance (Eq. 7.13) (Assumption 3 in section 7.2).

$$T_i^2 \ge T_{1i}^1 + \frac{v^m + \sum_j Y_{ij} v_j^{tank}}{\rho_i^1} + t^{age} \quad , \ \forall \ i \in I^{demand} \tag{7.12}$$

$$T_i^2 \le T_{1i}^1 + \frac{v^m + \sum_j Y_{ij} v_j^{tank}}{\rho_i^1} + t^{age} + t^{slack} \quad , \ \forall \ i \in I^{demand} \tag{7.13}$$

Eq. 7.14: In stage 1, when sublot s* of product i* is processed after sublot s of product i, the process start time of sublot s* in stage 1 should be equal or bigger than the completion time of sublot s of product i in stage 1, i.e. start time of sublot s of product i + process time (in stage 1)+ the setup time. The last items in the equation make sure that sublot s of product i precedes sublot s* of product i* in stage 1 and the sizes of sublots s, s^* are non-zero. In case sublots are not consecutive or empty, the equation becomes redundant.

$$T_{si}^1 + \frac{K_{si}}{\rho_i^1} + s_{ii^*}^1 \le T_{s^*i^*}^1 + C^{week}\left(1 - X_{si,s^*i^*}^1\right) + C^{week}\left(2 - \gamma_{si} - \gamma_{s^*i^*}\right) , \\ \forall\, s \in S_i \ , \qquad s^* \in S_{i^*}, \quad i, i^* \in I^{demand} \tag{7.14}$$

Eq. 7.15: In the formulation, we want the sublots to start processing in the sequence of sublot number. If the next sublot of sublot s of product i, which is sublot $s+1$ of product i, exists then we want it to start processing in stage 1 after sublot s of product i. In case sublot $s+1$ of product i is empty ($\gamma_{s+1,i} = 0$), the equation becomes redundant.

$$T_{s+1,i}^1 \ge T_{si}^1 - C^{week}\left(1 - \gamma_{s+1,i}\right) , \\ \forall\, s \in S_i \ , \quad i \in I^{demand} \tag{7.15}$$

Eq. 7:16: In stage 2, when product i^* is processed after product i, the process start time of product i^* in stage 2 is equal or bigger than the completion time of product i in the same line, i.e. start time of product i + process time (in stage 2)+ the setup time. The last item in the equation makes sure that product i precedes product i^* in line j. In case the products are not consecutive in the same line, the equation becomes redundant.

$$\begin{gathered} T_i^2 + \frac{P_i}{\rho_{ij}^2} + s_{ii^*j}^2 \leq T_{i^*}^2 + C^{week}\left(1 - X_{i,i^*j}^2\right) \quad , \\ \forall\ j \in J_i \cap J_{i^*}, \qquad i, i^* \ \in I^{demand},\ i < i^* \end{gathered} \tag{7.16}$$

In stage 1, the next sublot $(s + 1)$ of the same production batch has to start on time for the continuous production of the product in stage 2. There is a latest time to start the process in stage 1, which is given in RHS of the Eq. 7.17 (start of the production batch in stage 2 + process time of earlier sublots in stage 2 – time needed for sublot $s + 1$ to be ready for stage 2). The processing of sublot s+1 in stage 1 can start at most t^{slack} time earlier than the latest start time (Eq. 7.18) (Assumption 3 in section 7.2). The last two terms in the RHSs ensure that the equation is valid for nonzero sublot $s + 1$, and product i which is allocated to line j.

$$T_{s+1,i}^1 + \left(\frac{v^m + v_j^{tank}}{\rho_i^1} + t^{age}\right) \leq T_i^2 + \sum_{s=1}^{s} \frac{K_{s,i}}{\rho_{ij}^2} + C^{week}\left(1 - \gamma_{s+1,i}\right) + C^{week}\left(1 - Y_{ij}\right) \ , \tag{7.17}$$
$$\forall\, s \in S_i,\ i \in I^{demand}\ , j \in J_i$$

$$T_{s+1,i}^1 + \left(\frac{v^m + v_j^{tank}}{\rho_i^1} + t^{age}\right) + t^{slack} \geq T_i^2 + \sum_{s=1}^{s} \frac{K_{s,i}}{\rho_{ij}^2} - C^{week}\left(1 - \gamma_{s+1,i}\right) - C^{week}\big(1 - Y_{i} \tag{7.18}$$
$$\forall\, s \in S_i,\ i \in I^{demand}\ , j \in J_i$$

Eq. 7.19: Every product i has to finish processing in stage 2 before reaching the capacity of the week for each line j . Last multiplication term makes sure the equation is valid when product i is allocated to corresponding line j.

$$T_i^2 + \frac{P_i}{\rho_{ij}^2} \leq C^{week}\left(2 - Y_{ij}\right) \qquad \forall i \in I^{demand}, j \in J_i \tag{7.19}$$

4. Precedence relations

The total number of active sequencing variable for a line in stage 2 is limited by the number of products that are allocated to corresponding line, which is expressed by the number of active allocation variables (Y_{ij}) (Eq. 7.20). In stage 1, the same limitation is enforced by the active binary sublot size variables (γ_{si}) (Eq. 7.21).

$$\sum_i \sum_{i^* \neq i} X_{ii^*j}^2 = \sum_i Y_{ij} - 1 \quad , \qquad \forall j \in J \tag{7.20}$$

$$\sum_i \sum_{i^*} \sum_s \sum_{s^*} X_{si,s^*i^*}^1 = \sum_i \sum_s \gamma_{si} - 1 \tag{7.21}$$

Equations 7.22 to 7.25 ensure that all sublots and products can have at most one successor and one predecessor. If there is no production of that product $(Y_{ij} = 0)$ or sublots are empty ($\gamma_{si} = 0$), then there are no successors or predecessors.

$$\sum_{i^* \neq i} X_{ii^*j}^2 \leq Y_{ij} \quad , \qquad \forall i \ \in I^{demand}, j \in \ J_i \tag{7.22}$$

$$\sum_{i^* \neq i} X_{i^*ij}^2 \leq Y_{ij} \quad , \qquad \forall i \ \in I^{demand}, j \in \ J_i \tag{7.23}$$

$$\sum_{i^*}\sum_{s^*} X^1_{si,s^*i^*} \leq \gamma_{si} \quad , \quad \forall\, s \in S_i\,, \quad i\ \in I^{demand} \tag{7.24}$$

$$\sum_{i^*}\sum_{s^*} X^1_{s^*i^*si} \leq \gamma_{si} \quad ,\forall\, s \in S_i\,, \quad i\ \in I^{demand} \tag{7.25}$$

5. Rescheduling constraints

At the moment of rescheduling, any line j may be producing a product i′. The left production time is given by $T^{left}_{i',j}$. Production in stage 2 can start after the left production is finished and, if necessary, a setup is performed. If product i is not allocated to that line ($Y_{ij} = 0$), RHS of the Eq. 7.26 becomes very small, so the equation becomes redundant. It is also possible that stage 1 is busy; Eq. 7.27 makes sure that a sublot can start in stage 1 only after when stage 1 is available again. Time left for stage 1 is given by T^{left_1}, which includes the maximum changeover time between any two sublots in stage 1 (second assumption regarding the mathematical model).

$$\begin{gathered} T^2_i \geq t^{reschedule} + T^{left}_{i',j} + s^2_{i'ij} - C^{week}\left(1 - Y_{ij}\right) \\ \forall i \in I^{demand}, i' \in I^{left}, j \in J_i \end{gathered} \tag{7.26}$$

$$\begin{gathered} T^1_{si} \geq t^{reschedule} + T^{left\_1} \\ \forall s \in S_i\,,\ i\ \in I^{demand} \end{gathered} \tag{7.27}$$

At the time of rescheduling, the model will also decide with which product to start the production. Every line has a start-up product (Eq. 7.28). A product can start up a line if it is allocated to that line (Eq. 7.29). Eq. 7.30 gives the relation between sequencing variables in stage 2 and start-up variable. If a product is a start-up product, it does not have any predecessor indicated by the sequencing variables ($\sum_{i^* \neq i} X^2_{i^*ij} = 0$), then the equation forces the variable $X^{start-up}_{ij}$ to be 1.

$$\sum_i X^{start-up}_{ij} = 1 \quad , \qquad \forall j \in J \tag{7.28}$$

$$X^{start-up}_{ij} \leq Y_{ij} \quad , \qquad \forall i\ \in I^{demand}, j \in J_i \tag{7.29}$$

$$X^{start-up}_{ij} \geq 1 - \sum_{i^* \neq i} X^2_{i^*ij} \quad , \qquad \forall i\ \in I^{demand}, j \in J_i \tag{7.30}$$

6. Rework related constraints

Eq. 7.31&7.32 provide the relation between the decision variables of the reworked amount and binary rework variable. If the waste from product $\bar{\imath}$ is not reworked by mixing with sublot s of product i ($R_{\bar{\imath},s,i} = 0$), then the corresponding rework amount ($m^r_{\bar{\imath},s,i}$) has to be zero (Eq. 7.31). If the reworked amount is zero ($m^r_{\bar{\imath},s,i} = 0$), then the binary variable determining the rework has to be also zero (Eq. 7.32). To a new sublot s of product i, only one type of waste product can be added (Eq. 7.33).

$$m^r_{\bar{\imath},s,i} \leq m^w_{\bar{\imath}} R_{\bar{\imath},s,i} \qquad \forall s \in S_i\,,\ i\ \in I^{demand}, \bar{\imath}\ \in I^{waste} \tag{7.31}$$

$$R_{\bar{\imath},s,i} \leq M m^r_{\bar{\imath},s,i} \qquad \forall s \in S_i\,,\ i\ \in I^{demand}, \bar{\imath}\ \in I^{waste} \tag{7.32}$$

$$\sum_{\bar{\imath} \in I^{waste}} R_{\bar{\imath},s,i} \leq 1 \qquad \forall s \in S_i\,,\ i\ \in I^{demand} \tag{7.33}$$

Eq. 7.34&7.35 represent the material balance equations. Total reworked amount of product $\bar{\imath}$ is the sum of the reworked amount with sublots. Eq. 7.34 indicates that the reworkable created that is not reworked has to be disposed. Eq. 7.35 ensures that the total reworked amount cannot exit the amount of waste created for the corresponding product.

$$m^r_{\bar{i}} = \sum_s \sum_i m^r_{\bar{i},s,i} \qquad \forall \bar{i} \in I^r \tag{7.34}$$

$$m^w_{\bar{i}} = m^d_{\bar{i}} + m^r_{\bar{i}} \qquad \forall \bar{i} \in I^r \tag{7.35}$$

The waste amount of product $\bar{i}$ that is reworked by mixing with the sublot s of product i cannot exceed the allowed amount, which is determined by the rework matrix, i.e. $qa_{\bar{i}i}$ multiplied by the new sublot size (Eq. 7.36).

$$m^r_{\bar{i},s,i} \le \frac{q^{allow}_{\bar{i}i}}{100} K_{si} \qquad \forall \bar{i} \in I^{waste}, i \in I^{demand}, s \in S_i \tag{7.36}$$

If rework created by product $\bar{i}$ is reworked by mixing with the sublot s of product i, then the production of the sublot s of product i should start in stage 1 within the allowed storage time of the defective material $\left(T^{limit}\right)$ after it is created $(T^{waste}_{\bar{i}})$. If the waste is not reworked with the sublot s of product i $(R_{\bar{i},s,i} = 0)$, the last term in RHS makes the equation redundant (Eq. 7.37).

$$\begin{gathered} T^1_{s,i} \le T^{waste}_{\bar{i}} + T^{limit} + C^{week}\left(1 - R_{\bar{i},s,i}\right) \\ \forall s \in S_i, \quad i \in I^{demand}, \qquad \bar{i} \in I^{waste} \end{gathered} \tag{7.37}$$

Eq. 7.38 indicates that to be able to rework product $\bar{i}$ by mixing with the sublot s of product i, corresponding sublot has to start after the waste is gone through the necessary fixed pre-operations (melting, handling) whose duration is T^{pre_fixed} and variable pre-operations (inclusion/package removal) whose duration is $T^{prerework}_l$ per kg waste reworked also depends on the waste generation location. The last two items on the LHS makes sure the waste is reworked by mixing with the corresponding sublot and the waste is generated in the corresponding location.

$$\begin{gathered} t^{reschedule} + T^{pre\_fixed} + T^{prerework}_l * m^r_{\bar{i},s,i} - C^{week}\left(1 - R_{\bar{i},s,i}\right) - C^{week}\left(1 - L_{\bar{i},l}\right) \le T^1_{s,i} \\ \forall s \in S_i, i \in I^{demand}, \bar{i} \in I^{waste} \end{gathered} \tag{7.38}$$

7. Variables constraints

Following constraints defines the nonnegative continuous variables and binary variables.

$$\begin{gathered} m^r_{\bar{i},s,i} \ge 0, \; m^d_{\bar{i}} \ge 0, \; K_{si} \ge 0, \; T^1_{si} \ge 0 \; and \; T^2_{\bar{i}} \ge 0 \\ \forall \bar{i} \in I^{waste}, i \in I^{demand}, s \in S_i \end{gathered} \tag{7.39}$$

$$R_{\bar{i},s,i}, \; Y_{ij}, \; X^1_{sis^*i^*}, \; X^2_{ii^*j}, \; \gamma_{si} \quad binary \tag{7.40}$$

7.3.1. Requirements of the model:

There are several requirements for the model to work properly enforced by the construction of the equations:

1. There is at least one product allocated to each line during the scheduling horizon for equation 4.1 to work as intended. ($\sum_i Y_{ij} \ge 1$). If there is no product to be produced in a certain line for that week, the line has to be left out from the 'Lines' set.
2. The capacity should be enough to start a product under the given conditions (minimum sublot size, aging time, etc.). This is required since it is forced to start the production of each product in the scheduling horizon.
3. The value of Big number (M) is kept as small as possible for stable solutions in the model. This leads to minimum amount of waste that can be entered to the model, which is imposed by Eq.6.2. ($R_{\bar{i},s,i} \le M m^r_{\bar{i},s,i}$). The waste amount that can be reworked by mixing with a single sublot has to be big enough to make RHS of the equation 1 when multiplied by M. For instance, if 50 is used for M, the minimum waste amount that can be entered to the model is 0.02 ton.

7.4. Problem Size Reduction

As explained before the scheduling problems are NP-Hard problems, thus the solving time increases exponentially as the number of variables increases. The mathematical model given above includes many decision variables related to the decisions of batch sizing, sublot sizing, precedence and timing in both stages, and rework. Between these decision variables, the biggest size is created by the precedence variable in Stage 1 ($X^1_{sis^*i^*}$, Binary variable equal to 1 if sublot s^* of product i^* is processed immediately after sublot s of product i in stage 1, 0 otherwise).

7.4.1. Max number of sublots determination

$\mathrm{N_i^{max}}$, maximum number of sublots of product i is the parameter that determines the upper limit of the sublot set for each product. $\mathrm{S_i} = \{1, \dots, \mathrm{N_i^{max}}\}$. The parameter is theoretically equal to total production target for a product divided by the minimum allowed sublot size.

In practice, the majority of the sublot sizes are much more than the minimum allowed sublot size. The aging tank capacity and the rate of production lines are the main factors affecting the sublots sizes. It is observed that the main sublot sizes are half of the total aging tank capacity, which is dedicated to the line that the product is allocated. Therefore, it is expected that, sublot sizes will range from min sublot size to total aging tank capacity of the allocated line (max sublot size) but most of the sublot sizes will be around half of the total aging tank capacity of the allocated line. To reflect this generalization, the following formula is developed to determine the parameter of max number of sublots for product i:

$$N_i^{max} = \left\lceil \frac{Q_i}{Min_{J_i}(v_j^{total\_tank})/2} \right\rceil + 1 \tag{7.41}$$

The formula takes the production target for product i, divides it by the half of the minimum total tank capacity of the lines, to which the product i can be allocated. After rounding up the number, 1 is added. The reason why the total tank capacity of the line that the product is actually allocated is not used is that it depends on the outcome of the model (line allocation decision), which cannot be used to form the set. Otherwise the problem becomes nonlinear. Therefore, the aging tank capacity, which is the minimum between the tanks of the lines to which product i can be allocated, is used.

This method limits the sublots sets of the products in a reasonable extent by reflecting the actual practice, so that problem size reduction is obtained.

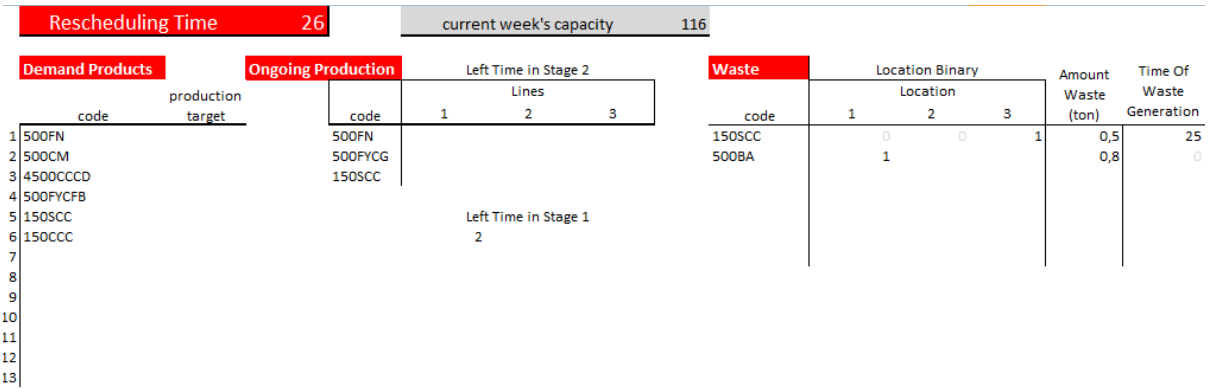
Chapter 8. Software Implementation

The reactive rework scheduling problem described in the previous chapter has been modelled as a Mixed Integer Linear Programming (MILP) Model. The aim of the model is to find the optimum schedule in the remaining time horizon which minimizes the objective function within the constraints defined. To solve this optimization problem, a mathematical programming tool, which is capable of solving MILP models, is required. AIMMS, which is a mathematical modelling tool integrating a modelling language, a graphical user interface and numerical solver, has been used in this research.

AIMMS has been chosen since Unilever has a license for AIMMS and the users of the model are familiar with this software. In addition, Souring Units of Unilever are using Excel spreadsheets for planning and decision making purposes and AIMMS is compatible with Excel. The AIMMS model has been implemented such that the user put the data in Excel and the AIMMS output is visualised in Excel.

Besides the data management feature, AIMMS handles the programming and user-interface separately. Programming details including parameter, variable and constraint definitions are placed in 'Model Explorer', which is divided in sections with relation to regular production, rework and rescheduling. Thus, it is easy to modify the related sections, or to leave out a part such as rework or rescheduling. The input parameters can be entered to the AIMMS via Excel. However, it is also possible to modify the inputs via the user-interface to see the effects on the outputs, which is displayed in the interface accompanied by graphs, as well as in Excel output page.

Excel input spreadsheets include production targets, product specifications, reschedule parameters, rework matrix and the changeover matrices for all lines of stage 2, as well as for stage 1. Besides the parameters, also the sets (product, waste and products currently in production) can be easily modified via Excel. Figure 8-1 represents the rescheduling input page in Excel in which user can enter the necessary input data at the moment of rescheduling.



Rescheduling Time 26

current week's capacity 116

Demand Products

	code	production target
1	500FN	
2	500CM	
3	4500CCCD	
4	500FYCFB	
5	150SCC	
6	150CCC	
7		
8		
9		
10		
11		
12		
13		

Ongoing Production

	Left Time in Stage 2 Lines		
code	1	2	3
500FN			
500FYCG			
150SCC			

Left Time in Stage 1

2

Waste

	Location Binary Location			Amount Waste (ton)	Time Of Waste Generation
code	1	2	3		
150SCC	0	0	1	0,5	25
500BA	1			0,8	0

Figure 8-1: Rescheduling input page in Excel

The code of the mathematical model for reactive scheduling with rework in AIMMS is given in Appendix G.

The intended users of the model are the production planners in the detailed scheduling level. A user manual is prepared to and given in Appendix H.

Chapter 9. Validation and Verification

The constructed model has been verified and validated in order to be sure that the results give a good representation of the reality. Sargent (2008) explains the modelling process including several verification and validation steps as shown in Figure 9.1.

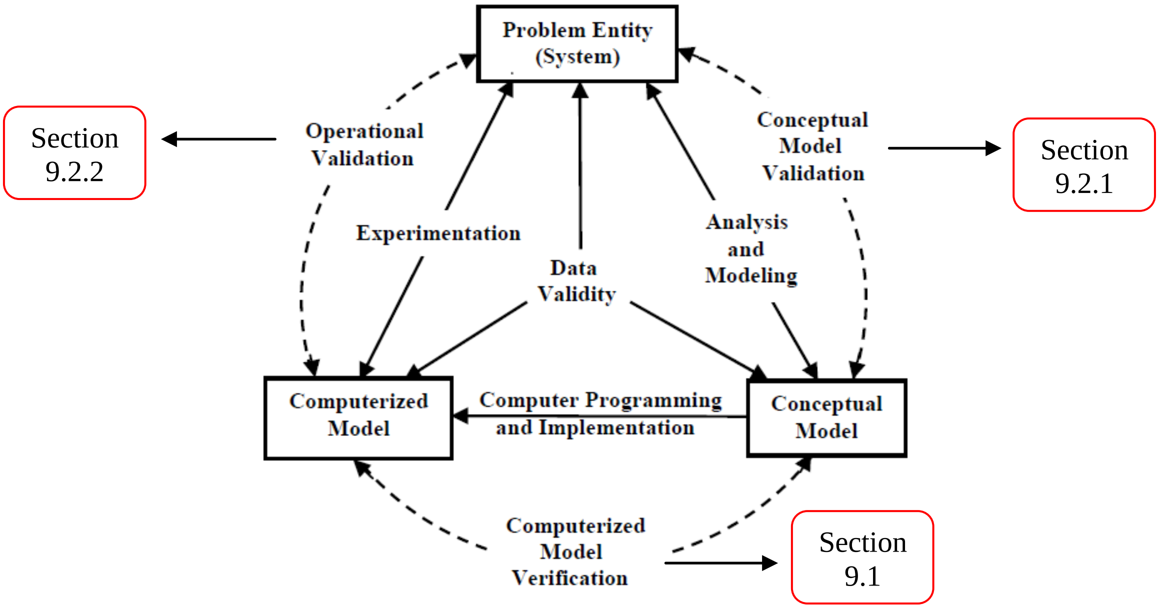


Figure 9-1: Modelling Process (Sargent, 2008)

In the first section, the process of computerized model verification is discussed. The second section explains the validation of the conceptual model and computerized model to see whether these models represent the real problem entity under the scope of this research.

Although general applicability of the model is aimed, the data that is obtained from SU Hellendoorn has been used to develop and test the model. Through these tests, CPLEX 12.0 solver through the AIMMS interface has been used. A base-case that is used for testing including the input sets is given in Appendix I. The validity of Hellendoorn data is not questioned in this research.

9.1. Model Verification

Verification is performed to see whether the conceptual model is correctly translated into AIMMS and the AIMMS model runs as intended.

9.1.1. AIMMS Consistency Checks

AIMMS has built-in consistency checks and diagnostic tools. The consistency of the parameters, variables, constraints is checked automatically by AIMMS during programming. When there is any error, such as indexes in a sum variable or definition of sets, AIMMS compiler gives error reports. The end-model presented in this research did not result in error reports.

Diagnostic tools of AIMMS such as an identifier cardinalities tool and data pages are further analyzed. With the identifier cardinalities tool, the sizes of each parameter, variable and set are observed. Data pages of each sets and parameter shows the transferred data from Excel. When the data in AIMMS and Excel compared, no inconsistency is observed.

9.1.2. Output Consistency Checks

The variables of the model are affected by each other; therefore, they have to be consistent. For instance, products should start processing according to the precedence variables for each line. It is also checked whether the model is calculating processing times, as well as the total cost factors, such as total changeover cost or rework cost, correctly. These are all done in the output page of Excel with the help of basic calculations. It is also crucial to check if the constraints are obeyed, such as if the products start processing after the line is available again or sublots in stage 1 really start in the right time. All these basic calculations result correctly, and no inconsistency is found.

9.1.3. Extreme Condition Test

According to Sargent (2008), a simulation model should have a structure and outputs that are plausible for any extreme and unlikely combination of levels of factors in the system. However, the model developed in this research is an optimization model with a specific aim of scheduling rework, which can react to some extreme conditions different from a simulation model. Hereafter is discussed how the model react to several extreme conditions.

9.1.3.1. Extreme Production Target

As explained in the requirements of the model (section 7.3.1), the model requires at least one product to be produced in each line for a feasible solution. This condition occurs due to the constraints regarding the precedence relationships (Equations 7.19&7.20). In addition, if there is no product to be produced in one line, i.e. a production line is out of operation, in the current time horizon, corresponding line has to be discarded from "Lines" set. As soon as it is deleted, the model reacts to the new situation and only schedules for the lines that are operating.

The production targets in a week are determined by the medium-level planning thus it is not expected to face with an extreme situation of very high production target knowing the fact that limited line capacity is not enough for sure. Expected output of the model in such a situation is to produce only some part of the production target which is allowed by the capacity. Then the non-produced part will result in penalty cost. However, as told before, the reactive scheduling model is a relatively large problem especially because of the sublots formation in the first stage. When an extreme demand occurs, the solution set and the computation time increase exponentially. In that case, it is not possible to solve such a big problem due to the out of memory situation.

9.1.3.2. Extreme Waste Amount

When zero waste amount is entered, the model gives a schedule for regular production in which rework doesn't exist. When high waste amount (e.g. 1000 ton) is entered in the model, the model reworks the allowed amounts as far as the storage time limit is obeyed and disposes the non-reworked amount. In both cases, the model reacts as expected.

9.1.3.3. Extreme Available Capacity

In case of a zero available capacity, the model reacts in the same way as in no production target case due to the precedence constraints (Equations 7.19&7.20). At least one line allocation is needed for these constraints to work. Moreover, the model is aimed for scheduling the rework, given the weekly production target that is decided in another planning level. Therefore, every product in the model is forced to start, but a part of it allowed not to be produced in case there is not enough capacity. If there is limited capacity enough to start each product, model produces as much as the capacity allows and non-produced parts result in penalty cost.

When there is excess capacity (e.g. 480 hours in a week), line 2 produces every product that it is capable of, due to high processing rate, which reduces the time of processing and therefore the production cost. Although there is excess time horizon, model produces the products as soon as possible to account for the rework.

9.1.3.4. Extreme Cost Parameter Values

Extreme Penalty and Production Cost: In case of high production cost or zero penalty cost, the model produces the minimum allowed amount (one sublot with minimum sublot size) for each product. If production cost is zero, model produces every product as long as the capacity allows (still different process rates of the lines is a concern) however, line preference is not made any more since production in every line is zero. If penalty cost is too high, the model gives preference to producing as much as the capacity allows.

Extreme Changeover Costs: When changeover cost for Stage 1 is high, the model chooses the number of sublots for each product as low as possible. When changeover cost for Stage 2 is high, the line allocation and sequence decisions are made based on the minimization of total changeover times.

When changeover costs are zero, the model makes the optimization decisions based on the maximization of the material saving from reworking.

Extreme Rework Related Cost: If the rework cost or dispose income is too high, the model does not choose to rework and dispose everything. If it is other way around (zero rework cost or dispose saving), the waste is reworked as much as the constraints allow.

9.2. Model Validation

Once it is verified that the conceptual model is correctly translated into AIMSS, validation of the conceptual and mathematical model is performed to see whether the conceptual model and the AIMSS model is a correct representation of the real system by taking the objectives of the research into account.

9.2.1. Conceptual Model Validation (Justification of Assumptions)

The validation of conceptual models is necessary to check if the assumptions underlying the conceptual models are correct and they reasonably represent the problem for a given purpose (Irobi et al., 2004). When implementing the model, the real life case is simplified in several points by making related assumptions. This section discusses the justification of the concept model assumptions given in section 7.2. In addition, the justification of the assumptions regarding the mathematical model is also included in this section.

<u>Assumptions related to production:</u>

1. *Production batch splitting is not allowed.*

This assumption represents the reality at SU Hellendoorn. The changeovers in the production lines are long and costly; therefore, batch splitting is not used in the practice. In section 5.1, the reasons why batch splitting is not included in the scope of this research explained with some calculations. In addition, the current literature about batch scheduling does not allow batch splitting (see section 6.3). Therefore, this assumption can be considered valid.

2. *A product is produced at most in one production line in a week.*

This assumption is enforced by the first assumption for the products that can be produced in more than one line. For instance, one size can be produced in both line 1 and line 2. According to the assumption, it is not possible to produce this size product separately in two lines in a week. Production of the same product in two lines requires two times of changeover. The justification of the first assumption is also valid for this assumption. This assumption holds in any case for the sizes that can be produced only in one line.

3. *A sublot can stay extra in the aging tanks for t^{slack} time (after 2 hours of aging tank).*

The parameter of $\mathrm{t}^{\mathrm{slack}}$ is assumed to be able to deal with the limited storage capacity (aging tanks) between the stages. The validity of this estimation is checked with different parameter values of $\mathrm{t}^{\mathrm{slack}}$ based on the output of the base case situation. It is found out that when t^{slack}=2 hour is used, 40 % of the times that aging tank is used, filling and emptying tanks are overlapped with an average of 2.2 hours. When t^{slack}=1 hour is used, the overlapping occurs less and with shorter times, i.e. 24 % of the times occurred with average overlapping time of 1.5 hour. It can be concluded that decreasing the value of t^{slack} can decrease the overlapping but does not prevent it. Therefore, the reasons of overlapping are further investigated.

Most of the overlapping occurs in the last tanks when a sublot uses the whole tank capacity (maximum sublot size). When the sublot sizes are smaller than the maximum sublot size, "t^{slack}" rule is applied more often which prevents the overlapping of the aging tanks. In addition, when a sublot size is much smaller than an aging tank capacity, it results in unutilized capacity in aging tanks. If the minimum sublot sizes are increased, then the unnecessary capacity occupation can be decreased. As a result, the overlapping in the aging tanks can be decreased in following ways:

- Maximum sublot size can be decreased.
- Minimum sublot size can be increased.

The results of these changes on the solutions are investigated. When the maximum sublot sizes are decreased half, the problem size increases in a big extent due to the increased sublot numbers, accordingly the computation time also increases exponentially. If the model is run for the whole week (the waste generation at the beginning of the week), the model cannot find an optimum solution due to out of memory situation. If the model is run with less product numbers (e.g. in the middle of the week), an optimal solution is found in around 20-30 minutes. Although the computation time increases in a big extent with “less maximum sublot size” method, it is observed that the overlapping problem in the aging tank is solved in the base case. Increasing the minimum sublot size alone does not solve the overlapping problem.

It is concluded that when t^{slack}=1 hour is used; the overlapping occurs 24 % of the times with an average overlapping time of 1.5 hour. Therefore, the assumption fails in 24 % of the times.

The overlapping of the aging tanks can be manually corrected by delaying the base mix preparation of the part of the sublot that causes overlapping. This correction can be done by the model by decreasing the maximum sublot size when the problem size is smaller (if the waste is generated in later days of the week).

4. *Worker capacity in the production is assumed non-restrictive.*

Since the model does not change the production quantities to be produced in a week, the total amount of workers needed in a week will not change. Only changing a line allocation can result in a change in the necessary number of workers for a product. The Hellendoorn factory is able to arrange flexible (temporary) workers when needed. Therefore, in this problem workers are assumed available when needed. The temporary workers are more expensive than the permanent workers, which is not included in the problem. Therefore, this assumption can affect the results in negative direction and give a solution with less cost than the reality. (The assumption decreases the lower bound of the solution space).

Assumptions related to rework:

5. *Waste is stored under necessary conditions when generated until the decision of rework/dispose.*

The model is aimed to make rework/dispose decision immediately when the waste is generated. However, it also considers the cases if a decision is not made belonging to a waste immediately. This is expected to occur not often and if it occurs, the duration between waste generation and the decision will not be long. Therefore, assuming the waste storage is enough for these exceptionally short durations can be considered reasonable. If in reality the waste storage is not available when the rework/dispose decisions are delayed, they have to be disposed, which result in less cost savings. Therefore, as in the fourth assumption, this assumption can also affect the results in negative direction and give a solution with less cost than the reality.

6. *Pre-rework operations are performed after the rework decision regarding a waste is made.*

Although a certain waste is generated earlier, if it is decided to rework the waste at the time of rescheduling, it has to go under the pre-rework operations first before it can be reworked. To perform pre-rework operations to a waste, which is not known yet if it will be reworked or not, can lead to unnecessary cost if the waste is disposed eventually. Therefore, the assumption can be considered valid.

7. *The resources (storage tanks and equipment/labour for pre-rework operations) are not restrictive for reworking the total amount of waste.*

While the investments for the waste storage tanks are done, the maximum amount of waste that is expected to rework in one scheduling horizon will be taken into account, therefore the storage tank capacity is not expected to be limited. The capacity of the equipment/labour for pre-rework operations is considered such a way that operations can be performed on only one type of waste at a time. If at the moment of rescheduling, it is decided to rework two different wastes they cannot go under the operations at the same time. However, reworking of these wastes also cannot be done at the same time since they will be mixed with different sublots. By performing the operations first to the waste that will be reworked first, the capacity in the equipment/labour can be kept non-restrictive. In reality if the resources are not enough so, a waste cannot be reworked since it cannot be stored or cannot catch the reworking time due to longer pre-rework operations than planned, the waste has to be disposed. Then, the effect of the assumption on the solution is the same as in the fifth assumption: assumption can give a solution with less cost than the reality.

8. *More than one type of waste product cannot be added with the same sublot of a product.*

This assumption can be considered valid since the rework matrix is defined for only two product types mixing. There is no available data (rework matrix) showing the allowed percentages when more than two types of product can be mixed.

Assumptions related to rescheduling:

9. *The decisions regarding the sublots which mixing and production already has been started cannot be changed.*

Since the decisions related to stage 1 (sublots size decisions) are affected by the decisions related to stage 2 (line allocation decisions), any change in these decisions at this point cannot lead to better results. Especially if the sublots started to fill the dedicated aging tanks, which starts in a short time after the mixer is filled for the first time, the line allocation decisions cannot be changed any more. Therefore, this assumption can be considered valid.

10. *If the product that is under production has still sublots that are not prepared in the mixing department yet, it can be decided to produce these sublots later.*

If there is no action taken yet to the subsequent sublots of a production batch, the decisions regarding these sublots can be changed by accounting for any rework opportunity. If the line allocation of the subsequent sublots is changed or it is decided to produce these sublots later, it leads to batch splitting in the overall weekend. However, entering the subsequent sublots in the model as the new production target for the corresponding product (not considering the already produced sublots) doesn’t interfere with the first assumption. This assumption provides extra flexibility to the model to increase the opportunities for reworking and does not impose any limitations to the model. Therefore, the assumption can be considered valid.

Assumptions regarding the mathematical model:

11. *When the filling time of the first aging tank is calculated, it is assumed the tank is completely filled.*

This assumption does not represent the reality for SU Hellendoorn case. In reality, if the sublot size is smaller than one aging tank capacity, the aging tank is not completely filled. Since the filling time of the aging tanks for the sublots (size is smaller than one aging tank capacity) are longer in the model than in reality, the assumption increases the occupation of the aging tank in the model. If the first sublot is less than one aging tank capacity, the production batches can start later in the model than in reality. However, the time differences between the model and the reality for these sublots are respectively short (e.g. 0.5-1 hour) and only occur for the explained sublot sizes. This assumption does not affect the cost results, but can increase the overlapping of aging tanks or the make-span of the production. An extension to the model that releases this assumption is given in Chapter 10.

12. *The time left for the current sublot production in stage 1, includes the changeover time after this sublot, which is the max changeover time between any sublots in stage 1.*

The changeover times in stage 1 are low. Neglecting the difference between the changeover times and taking the maximum changeover time to be on the safe side can result in slightly less available capacity than the reality. Since the affect of the assumption on the solution is small, the assumption can be considered reasonable.

13. *A waste for a certain product can be generated only in one location in one rescheduling horizon.*

This assumption does not represent the reality for SU Hellendoorn case. By taking into account only one waste generation location for a certain product, possible further cost reductions are ignored. If the waste amounts that are generated in similar times from two locations are aggregated in one location, which is later in the line, the cost results will be higher (rework operation cost is higher than the earlier locations). Therefore, the model can result in more cost than the reality. An extension to the model that releases this assumption is given in Chapter 10.

9.2.2. Operational Validation

Operational validation is determining whether the model's output behaves according to the model's intended purpose over the domain of the model's intended applicability (Sargent, 2008). The intended purpose of the developed model in this research is to find a cost optimum schedule in which the new situation resulted from a breakdown/human mistake is taken into account via reworking. Updated information regarding the production targets and earliest line availability are also input parameters, thus the model is also useful to react the updated situation by rescheduling. Two different techniques are used: Using historical Data (Comparison with practice) and Sensitivity Analysis.

9.2.2.1. Historical Data (Comparison with practice)

Currently the Hellendoorn factory does not rework the waste systemically. Although some amount is reworked based on the limited rework matrix, it is based on the worker's experience and is not recorded. Thus, the operational validity of model's reworking feature cannot be checked with this technique. However, it can be checked if the model can reschedule with an assumed breakdown situation. The model output is compared with the real schedule for a week. The results show that when only production costs are concerned, the real schedule that is applied results in lower cost. However, when changeover costs are calculated, the AIMMS shows better results in terms of total changeover cost. When the production and changeover costs summed up, the output of AIMMS gives lower cost.

From the comparison, it is also observed that the process times are generally calculated in AIMMS slightly more than it is in reality (1%-4% per ton).

9.2.2.2. Sensitivity Analysis

To evaluate the operational validity of the rescheduling with rework model, a sensitivity analysis is performed to analysis the influence of changes in input values on the output of the model. Since it is intended to find a cost optimum solution in computationally economic time, the output of the model is considered two-way: solution and computation time.

Effect Input Data on Solution

The effect of input parameters on the solution depends not only on the value of the parameters, but also on the relationship with the other input parameters and the waste and product sets elements. The main trade off when deciding to rework the waste or not is the "material saving - rework cost" vs. "dispose income". If the "material saving - rework cost" is bigger than the "dispose income", the model will always favour reworking. However, the main limitations of storage time and rework matrix determines the possibility of the rework which depends on the products that are produced in the corresponding week. Other input parameters, such as changeover and production costs, will affect the solution when the sequence of the production or line allocation can be changed leading to more changeover or production cost but creating rework opportunity that will result in material saving. These effects are occasionally (occurs when a specific combination of product set is to be produced), thus will not be analyzed here. During the tests, realistic values from Hellendoorn factory are used for production and changeover cost parameters, therefore these values are fixed, and sensitivity of the rework cost and rework matrix is performed in this section.

To see the effect of changes in rework related inputs on the solution, one more waste product is added to the base case and waste amounts are increased. Now the base case includes three waste products with each 2 ton.

The rework cost is increased incrementally in three cases for each location of the waste generation. The results of the model for each case are given in Table 9.1. The screenshots of AIMMS giving the solutions for each case are given in Appendix K.1. The solutions (line allocation, sequence, sublot sizes) do not change depending on the rework cost parameter for the given base case.

	Case #: Rework cost (%), Location 1,2,3		
	Case 1:	Case 2:	Case 3:
Total reworked amount (ton)	6	6	4
Profit from reworking (% increase)		-16 %	-50%
Total Cost (% increase)		0.2%	0.6%
Computation time (sec.) (# of integer variables=738)	499.69	1672.78	50.26

Table 9-1: Effect of rework cost on the results

As table indicates, when the rework cost is equal to the possible saving from reworking, the waste is not reworked anymore but disposed. As the rework cost increases, the profit that can be gained from reworking decreases (although the waste is reworked).

To analyze the effect of rework matrix on the solution, three different rework matrix scenarios (for case 1 rework cost) are tested: Two different cases of general rework matrix; optimistic and pessimistic and also limited matrix. The difference between the optimistic and pessimistic scenario is the allowed rework percentage values. In the optimistic rework matrix, allowed amounts are higher. However, in limited matrix only the same recipes are allowed to be mixed with each other. The results are given in Table 9.2.

	General rework matrix		Limited rework matrix
	Optimistic	Pessimistic	
Total reworked amount (ton)	6	6	1
Profit from reworking (% increase)		0%	-91%
Total Cost (% increase)		0%	1%
Computation time (sec.) (# of integer variables=738)	499.69	1349.25	50.26

Table 9-2: Effect of rework matrix on the results

Table shows that the results are not different between optimistic and pessimistic scenarios. The reason is the allowed rework amount in the model is capable of reworking a total 6 ton of waste. However, in the pessimistic scenario more new products have to be used for rework, which takes more time for the model to optimize the cost. On the other hand, in the limited matrix only the waste that has the same recipe's production in the current week is reworked. In addition, 1 ton out of 2 ton is reworked, since the production amount for the corresponding recipe only allowed for 1 ton rework. The total cost increased when the limited rework matrix is used.

The screenshots of AIMMS giving the solutions for each rework matrix are given in Appendix K.2. It is observed that when limited rework matrix is used instead of general rework matrix (pessimistic or optimistic), the sequence in the second production line is changed. The reason is when there is no material saving from reworking with the limited rework matrix, the least changeover cost is achieved with a different sequencing. Between the optimistic and pessimistic rework matrix scenarios, the sequencing decisions do not change.

To conclude, the total cost is sensitive to the input parameters of the rework cost and the rework matrix (general vs. limited). When the general matrix is used, the total cost does not change with the percentage amounts (optimistic vs. pessimistic). On the other hand, the sensitivity of the solution (line allocation and sequencing decisions of the model) to the rework cost and rework matrix depends on the changeover structure (times) and production costs of the products in the remaining time horizon. It is shown that when limited matrix instead of general rework matrix is used, one sequencing decision has changed based on the changeover costs.

Effect Input Data on Computation Time

The computation time depends on many factors that will be analyzed in two ways: problem size (number of integer variables in the model) and input sets/parameters. As said before, the reactive scheduling problem is an NP-Hard problem thus the computation time increases exponentially, as the problem size increases. The biggest contribution to the problem size is the number of sublots in stage 1 determined by the production target amount. In addition, the type of waste products and the production portfolio in the corresponding week are also the main determinants of the computation time. Therefore, we used two cases which have different waste types:

1. Case A: The waste products (150CFB and 150SCC) are fighting for the same rework source
2. Case B: The waste products (150BA and 150SCC) are not fighting for the same rework source

By rework source, the new product with which the waste can be reworked by mixing is meant. The model is solved for these different two cases. The number of products in the remaining time horizon is fixed, and demands are increased incrementally. Available capacity is also kept fixed. The effect of the problem size (number of integer variables) as well as the input parameters (waste products) on the computation time is presented in Figure 9.2.

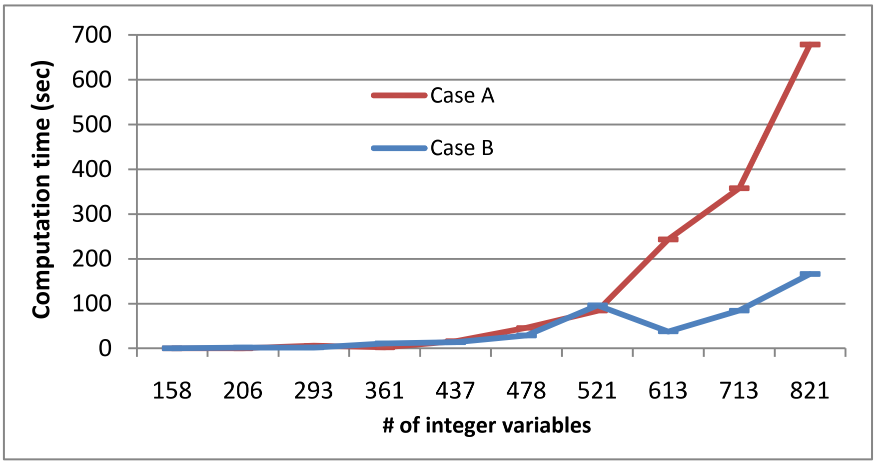


Figure 9-2: Computation time

In Case A, both wastes can be mixed with only one product that has production in the rest of the week. In case B, one of the wastes can be mixed with only one other product, whereas the other can be mixed all other products. As can be seen from Figure 9.2, the computation time increased with the problem size. However, the increase in Case A is in larger extent since it is more difficult for the model to find the optimum solution when two wastes fight for the one product to be mixed with.

Chapter 10. Some Extensions to the Model

This section explains the possibilities to extend the created model by relaxing two of the assumptions discussed in section 7.2 (regarding the conceptual model) and section 7.3 (regarding the mathematical model). In the model, the following assumptions have been made that make the model different from the reality at SU Hellendoorn.

10.1. Waste generation more than one location

The assumption of *"A waste for a certain product can be generated only in one location in one rescheduling horizon"* is released in this section to match the model more with reality.

The model is modified where the location index (l) is added to the waste parameters and (decision) variables so that a waste is defined with the location it has generated as well as the product type it belongs to. The modified parameters and variables are as follows:

No more need of the parameter:

$L^{waste}_{\bar{i},l}$	Binary data equal to 1 if product $\bar{i}$ is generated in location l, otherwise 0

Modified Parameters:

$m^{w}_{\bar{i},l}$	Amount of waste of product $\bar{i}$ generated in location l (ton)
$T^{waste}_{\bar{i},l}$	Time of waste generation of product $\bar{i}$ in location l

Modified Variables:

$m^{d}_{\bar{i},l}$	Amount of disposed waste product $\bar{i}$ created in location l (ton)
$m^{r}_{\bar{i},l}$	Total amount of reworked waste product $\bar{i}$ created in location l (ton)

Modified Decision Variables:

$R_{\bar{i},l,s,i}$	Binary variable equal to 1 if rework created by product $\bar{i}$ in location l is reworked by mixing with sublot s of product i, 0 otherwise
$m^{r}_{\bar{i},l,s,i}$	Amount of waste product $\bar{i}$ created in location l reworked by mixing with sublot s of product i (ton)

The part of the mathematical model that is modified (objective function and rework related constraints) can be found in Appendix L.

10.2. Calculation of the filling time of an aging time

The assumption of *"When the filling time of the first aging tank is calculated, it is assumed the tank is completely filled"* does not represent the reality for SU Hellendoorn case. In reality, if the sublot size is smaller than one aging tank capacity, the aging tank is not completely filled. In the mathematical model, this assumption affects the dark coloured parts of the following constraints:

$$T_i^2 \geq T_{1i}^1 + \frac{v^m + \sum_j Y_{ij} v_j^{tank}}{\rho_i^1} + t^{age} \quad , \ \forall \ i \ \in I^{demand} \tag{7.12}$$

$$T_i^2 \leq T_{1i}^1 + \frac{v^m + \sum_j Y_{ij} v_j^{tank}}{\rho_i^1} + t^{age} + t^{slack} \quad , \ \forall \ i \ \in I^{demand} \tag{7.13}$$

We are interested in whether the sizes of the sublots are less than one aging tank or not. The following formulation is developed to trace this property of the sublot size K_{si}:

$$K_{si} = \sum_j Y_{ij} v_j^{tank} + z_{is}^{+} - z_{is}^{-}$$

Then the equations are replaced by:

$$T_i^2 \geq T_{1i}^1 + \frac{v^m + \sum_j Y_{ij} v_j^{tank} - z_{is}^{-}}{\rho_i^1} + t^{age} \quad , \ \forall \ i \ \in I^{demand} \tag{7.12-II}$$

$$T_i^2 \leq T_{1i}^1 + \frac{v^m + \sum_j Y_{ij} v_j^{tank} - z_{is}^{-}}{\rho_i^1} + t^{age} + t^{slack} \quad , \ \forall \ i \ \in I^{demand} \tag{7.13-II}$$

This new formulation requires two decision variables z_{is}^{+}, z_{is}^{-} to control if the sublot size exceeds one aging tank capacity (then $z_{is}^{+} \geq 0$) or if the sublot size is less the aging tank capacity (then $z_{is}^{-} \geq 0$). The variables cannot be both positive. A binary variable is required to make sure that only one of them is positive:

$$W_{si} = \begin{matrix} 1\ if\ z_{is}^{-} \geq 0\ and\ z_{is}^{+} = 0 \\ 0\ if\ z_{is}^{-} = 0\ and\ z_{is}^{+} \geq 0 \end{matrix}$$

Then the relationships between the decision variables are given by the following constraints:

$$z_{is}^{-} \leq v_j^{tank} W_{si} + M\left(1 - Y_{ij}\right) - v^m \gamma_{si} \tag{7.41}$$

$$z_{is}^{+} \leq \left(v_j^{total\_tank} - v_j^{tank}\right)\left(1 - W_{si}\right) + M\left(1 - Y_{ij}\right) \tag{7.42}$$

The equations also include the sublot size restrictions (Equations 7.8 and 7.9). If $\mathrm{z_{is}^{-}} \geq 0$, it cannot be more than v_j^{tank} to prevent any negative sublot size. The last item in Eq. 7.41 enforces the minimum sublot size (v^m) constraint if the sublot is not empty ($\gamma_{si} = 1$). If the sublot is empty ($\gamma_{\mathrm{si}} = 0$), we need $z_{is}^{-} = v_j^{tank}$, therefore lower limit for z_{is}^{-} is enforced by the following formula:

$$z_{is}^{-} \geq v_j^{tank}\left(1 - \gamma_{si}\right) \tag{7.43}$$

Eq. 7.42: If $z_{is}^{+} \geq 0$, it cannot be more than $\left(v_j^{total\_tank} - v_j^{tank}\right)$ to make sure that the sublot size does not exceed the total aging tank capacity ($K_{si} \leq v_j^{total\_tank}$).

As a result, if $W_{si} = 0$, then Eq. 7.41 makes $z_{is}^{-} = 0$ and Eq. 7.42 allows $z_{is}^{+} \geq 0$. If $W_{si} = 1$, $z_{is}^{-} \geq 0$ is allowed, and $z_{is}^{+} = 0$ is enforced.

It is explained before that the aging tank capacities change depending on the line that the product is allocated. Therefore the line allocation decision variable (Y_{ij}) is included in the Eq. 7.41&7.42 to enforce the equations only when the allocated line's aging tank is concerned.

To conclude, replacing the decision variable K_{si} by three other decision variables (z_{is}^{+}, z_{is}^{-} and W_{si}) enables the model to calculate correct filling time of the aging tank when sublot size is smaller than an aging tank capacity.

Chapter 11. Investment Analysis

The decisions that are made by the rescheduling with rework model are all operational decisions. However, there are several investments required to make rework possible. These investments are waste storage tanks and equipments for inclusion/package removal. The investment cost is a one-time payment that is done at the moment that it is decided to use rework. The saving that can be gained from rework should be in a way that the investment cost is covered in a certain time. This time corresponds to "Payback Period". The Payback period is defined as the number of years it takes before the cumulative forecasted cash flow equals the initial investment (Brealey et al., 2008).

The cash flows for the rework case and their timings are given in Table 11.1.

Cash Flows	Time 0	Every week
Initial Investment	$-C_o$	
Expected cash flow from reworking		C_r
Maintenance cost cash flow		$-C_m$
Total	$-C_o$	$C_r - C_m$

Table 11-1: Cash flows

Initial investment C_o includes the following cost items:

C_o = Cost of rework storage Tanks+ Cost of inclusion removal equipment ($c^{inclusion}$)
+ Cost of packaging removal equipment ($c^{package}$)

The calculation of rework storage tanks cost item requires the following additional definitions:

v^s	Storage tank capacity for waste to be reworked (ton)
c^{tank}	Cost of a storage tank for the waste to be reworked with capacity v^s (€/tank)
m^{max}	Maximum amount of waste that is expected to be reworked in a week

Since the storage of the waste is required both and after pre-rework operations (inclusion/package removal), cost of storage tanks are multiplied by two. Using these parameters:

Cost of Rework Storage Tanks $= 2 * c^{tank} \frac{m^{max}}{v^s}$

Therefore, $C_o = 2 * c^{tank} \frac{m^{max}}{v^s} + c^{inclusion} + c^{package}$

Weekly cash flows include $\mathrm{C_r}$, expected average cash flow from reworking which is the output of the reactive scheduling model and $\mathrm{C_m}$, maintenance cost cash flow, which is required to maintain the inclusion/packaging equipments operational. Then;

Weekly Cash Flow $= C_r - C_m$

We need to calculate the present value (PV) of these weekly cash flows. The same cash flow is received periodically. Therefore, the following annuity interest factor is used for this calculation:

$PVIFA(i_w, T)$ = Present Value Interest Factor of Annuity with weekly interest rate i_w, and Period T

$$PVIFA(i_w, T) = \frac{(1 - \frac{1}{(1+i_w)^T})}{i_w} \qquad (11.1)$$

The following formula can be used to calculate the present value (PV) of these cash flows.

$$Present\ Value = Weekly\ Cash\ Flow * PVIFA(i_w, T) \qquad (11.2)$$

The smallest T value, which makes the Present Value equal to or higher than the initial investment, is the payback period for the investment.

$$Initial\ Investment \leq Present\ Value \qquad (11.3)$$

$$C_o \leq (C_r - C_m) * PVIFA(i_w, T) \qquad (11.4)$$

The calculation can easily be done with an Excel Spreadsheet. This investment tool can be used by the company during the investment decision.

Chapter 12. Insights for SU Hellendoorn

This chapter discusses the insights for the SU Hellendoorn which are gained by the waste analysis and the developed reactive scheduling model. Finally, an investment analysis is done based on the potential savings from reworking.

12.1. Waste analysis

The only waste data available is 6 weeks data in 2011. The waste amount in a week, which is directly proportional to the weekly total production quantity, can change due to the seasonal effects in the production. However, this 6 weeks period represents the average production quantity level according to the 2010 production quantities (Appendix C). Therefore, the yearly results can safely be extrapolated from the weekly results. When weekly figures are given, the average of these 6 weeks is taken (Tables 12.1&12.2). The waste data is analyzed to gain more insight about the magnitude and frequency of the waste generation in the production lines of SU Hellendoorn.

The scope chosen for this research is the breakdowns or worker mistakes in the production lines after the addition of the inclusions, which result in a relatively high amount of waste per occurrence. A start-up loss is in average 0.3 ton therefore, more than this amount can be classified as big amount wastes. (<0.3 ton; small amount waste and >0.3 ton; big amount waste). Table 12.1 gives the percentages of the weekly waste amounts and number of occurrences of each class of waste.

Waste amount class	Waste amount Percentage	Number of occurrences Percentage
Small (<0.3 ton)	47%	79%
Big (>0.3 ton)	**53%**	**21%**

Table 12-1: Magnitude and frequency of the waste occurrences

As the Table 12.1 indicates, whereas the number of occurrences for big amount wastes are low (21%), they constitute more than the half (53%) of the total waste amount. The reactive scheduling model is aimed to be used in case of big waste amount occurrences.

In addition, the distribution of the waste amount (big waste amount class) through the waste generation locations (after the inclusions are added) is analyzed and result is given in Table 12.2.

Waste type	Waste amount percentage
Without package	65%
With package	35%

Table 12-2: Waste amount distribution through the waste generation locations

As Table 12.2 indicates, 65% of the big waste amounts are without package and 35% of them with package. This distribution affects the rework cost, and in turn potential savings if the wastes are reworked.

12.2. Potential Savings

The rescheduling model developed in this research reacts to the breakdown/human mistake situations, which generates a considerable amount of waste (big waste amount class in Table 12.1). The output of the model highly depends on the characteristics of the waste generation and the production at the moment of waste generation. The input sets and parameters such as exact timing of the waste generation and the production targets of the rest of the week after the rescheduling time affects the solution of the model to a big extent. Currently, there is no real case data available from practice including these necessary input data. The waste data obtained from SU Hellendoorn includes the waste generation information together with the shifts they are generated in, but not the exact timing. Moreover, the situation of the production (which sublot is under production, the time left for production in the lines) is unknown. Therefore, it is impossible to determine the exact savings that can be gained by using the rescheduling model with the real case data.

However, the potential savings can be approximated by making several assumptions to the available waste data. It is assumed that each waste generation in a particular shift occurs at the beginning of the shift. The consequence of this assumption can be as follows: according to the model if the waste is reworked at the beginning of the next shift, this may not be possible in reality if the waste is generated through the end of the previous shift and the time between the waste generation and reworking is not enough for pre-rework operations. This situation can occur if the waste is reworked by mixing with the next sublot of the same production batch. However, if there are other sublots to be produced, the waste can still be reworked. As a result, the assumption can slightly increase the waste amount that is reworked within the same production batch than the reality if the above given situation occurs.

The potential savings that can be obtained by reworking are directly proportional to the total waste amount that can be reworked, which is determined by the rework opportunities. In Chapter 5, the rework opportunities are given for two rework matrix scenarios: limited and general. It is explained that when the general rework matrix is used, the rework opportunities can be increased, however limited by the rest of the week's production portfolio and the main rework limitations. The potential savings that are gained by each rework matrix scenarios as well as by each rework opportunity are calculated based on the real waste data. Table 12.3 presents yearly reworked and disposed waste amounts when each rework matrix scenario is used.

Rework matrix scenario	Reworked percentage	Disposed percentage
Limited rework matrix	69 %	31 %
General rework matrix	83 %	17 %

Table 12-3: Yearly reworked and disposed waste percentages for each rework matrix

As the table indicates, when the general rework matrix is used instead of the limited rework matrix, the percentage of the waste that is reworked increased from 69% to 83%. Although the rework opportunities is increased by general rework matrix, 17 % of the waste is still disposed since the rest of the week's production portfolio doesn't allow for reworking the waste based on the rework limitations. Any improvement in this area (decreasing the loss from disposing) can be done in the medium planning level when weekly production targets are determined. As explained in Chapter 5, producing the different sizes of the same recipe in the same week will increase the reworking opportunities and decrease the disposed waste amount.

Relaxing the limited matrix (by using general rework matrix) can bring the company extra 22 % profit more than the profit that can be gained by the limited rework matrix.

The profit that is gained by reworking with general rework matrix scenario is distributed to the profit that is gained by reworking each waste type, i.e. without package and with package. (Table 12.4)

Waste type	Percentage of total profit
Without package	**72%**
With package	28%

Table 12-4: Yearly profit distribution from reworking each waste type

The biggest contribution to the total profit is from reworking the wastes that are generated before packaging. This is an expected result since 65% of the total waste is constituted by the wastes that are without package (Table 12.2) and the reworking cost is lower for this kind of waste.

It is also important to know which rework opportunities bring the biggest contribution to the total profit. As explained in Chapter 5, there are four rework opportunities included in this research, which are listed in Table 12.5. The reworked amounts by each opportunity are presented in percentages in the following table.

	Rework opportunities		Percentage of the total waste (%)	Percentage of the total profit[4] (%)
1	Mixing within the same production batch in the same week		**40.4%**	**47.3%**
2	Mixing with same recipe different size product in the same week		14.0%	18.0%
3	Mixing within different weeks, same recipe (from Friday to Monday)		13.0%	15.2%
4	Mixing with different recipe in the same week/different weeks	Limited rework matrix	1.2%	
		General rework matrix	15.3%	19.5%

Table 12-5: Yearly profit contribution from each rework opportunity

The biggest amount of waste is reworked by the opportunity of mixing within the same production batch in the same week. However, as explained before this amount can be slightly more than the reality due to the assumption made (waste generation at the beginning of the shift).

When the general rework matrix is used, the profit from mixing between different recipes corresponds to 19.5% of the total profit from reworking. Based on this information, the company can decide to adapt to the general rework matrix instead of the limited rework matrix.

12.3. Investment Analysis

The potential savings that are explained in the previous section are only possible when an initial investment for rework is done. The decision regarding the one-time investment is done separately from the operational decisions. In Chapter 11, the investment analysis technique of payback period has been explained. For the analysis, formulas 11.1-11.4 are used. One of the cash flows required for the analysis is the weekly-expected cash flows from reworking, which corresponds to the potential savings that have been calculated in the previous section. Two other cash flows that have to be estimated are initial investment cost and maintenance cash flows. The calculations for these values are given in Appendix M. As explained in the previous section, the weekly expected cash flows (gain from reworking) depend on the rework matrix used. Figure 12.1 presents the payback periods for each rework matrix scenario.

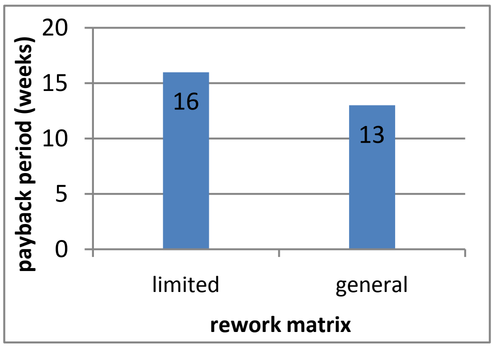


Figure 12-1: Payback period (weeks) for the two rework matrix scenarios

The results show that the payback periods are 15 and 12 weeks for limited and general rework matrix respectively. It can be concluded that the investment that is done for reworking pays its own cost in a short time. The results can change depending on the estimated cost for the initial investment. Therefore, a sensitivity analysis is performed to see the effect of increase in the initial investment cost on the payback period. The results are shown in figure 12.2.

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[4] Total profit is calculated when the general rework matrix is used

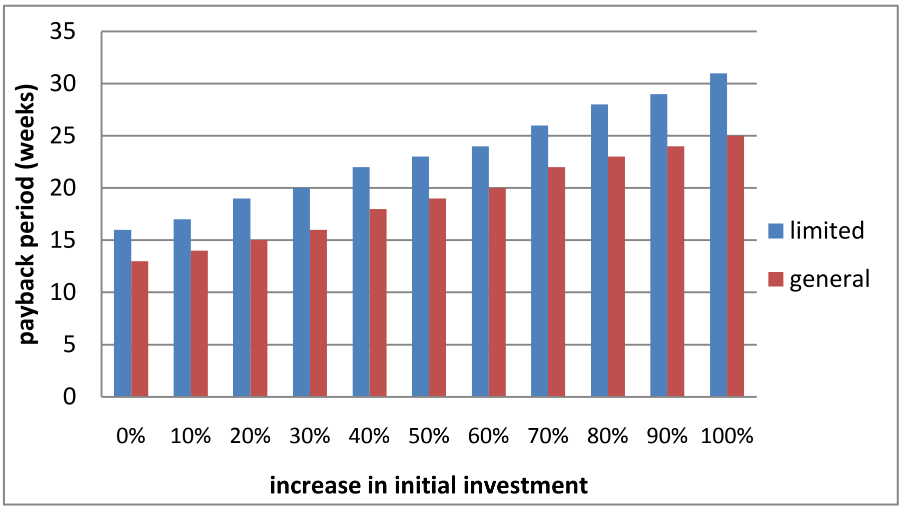

Figure 12-2: Payback period (weeks) for percentage increases in initial investment

The payback period increases as the cost of the initial investment increases. Even if the initial cost investments are doubled, the payback period is less than one year.

Chapter 13. Conclusions and Recommendations

This chapter gives an overview of the conclusions and recommendations that can be derived based on the research presented in the previous chapters. The first section gives the conclusions of the research and the second section explains the recommendations for both SU Hellendoorn and academics.

13.1. Conclusions

In this report, a scheduling tool which integrates rework with the regular production is described. The research assignment was: "*Design a scheduling tool for integral planning of ice cream production with rework which satisfies the required production targets and minimizes the total relevant cost.*" The scheduling tool is aimed to be as general as possible so that the tool can be applied to other ice cream factories of Unilever with only minor changes in the tool.

Besides the conclusions regarding the research assignment, the highlights of the answers to the sub-questions are also provided in this section to provide insight to the company about rework.

Reworking perishable ice cream via mixing has its two specific limitations: Storage time and conditions, and the mixing restrictions. The freezer storage option has the disadvantages of high storage cost and does not require scheduling due to long storage time (months). Therefore, only -5/+5°C storage with maximum 72 hours storage time was considered under the scope of this research. In addition, based on the analysis of mixing restrictions two rework matrix types were concluded:

1. Limited rework matrix: only mixing between same recipes allowed
2. General rework matrix: mixing between different recipes allowed

The waste source analysis concludes three main waste sources with different characteristics:

Waste sources	Occurrence (Timing)	Waste type	Scheduling required	Percentage Amount Waste (%)
#1: Breakdown/mistake in mixer	Unexpected	Base mix		3 %
#2: Freezer start-up	Deterministic	W/ flavour		10 %
#3: Breakdown/mistake in production lines	Unexpected	W/ flavour and/or inclusion and/or package	√	**87 %**

Table 13-1: Characteristics of the waste sources

Based on this analysis, it was decided to focus on the third waste source which requires scheduling for reworking (due to rework limitations with respect to storage time and mixing restrictions) and offers the highest expected potential savings by reworking. Characteristic of the selected waste source (unexpected occurrence) and the waste storage option under the scope selected (max. 72 hours) led to the adoption of a reactive scheduling approach.

The reactive scheduling model is aimed to be used when there is a breakdown or human mistake in the production line which leads to considerable amount of waste per occurrence. The user has to enter the necessary inputs, which are time of rescheduling, time and location of the waste generation, the time left before the production lines and mixers are available again and the rest of the week's production targets. The output is the detailed scheduling of the rest of the week by including rework if possible. The output defines the processing start time of each product in each stage of the production, line allocation, the amount of waste that is reworked, and the batches in which the waste is mixed with for reworking.

The reactive scheduling tool helps the planners to generate weekly detailed schedules that consider rework by satisfying the constraints and optimizing the relevant costs. Rework opportunities can be also increased with the production related decisions (line allocation, sequence, etc.) of the model.

The developed reactive scheduling model has been implemented in AIMMS accompanied with a user friendly interface. Excel connection is also provided for the user to easily enter the input to the model.

The output of the tool depends on many input factors such as the exact timing of waste generation, product types to be produced in the rest of the week and the allowed mixing percentages (rework matrix) with the other batches. The effect of the rework matrix on the solution is analyzed via a scenario analysis. Using less restricted mixing limitations (general rework matrix) resulted in higher rework opportunities, so higher saving via rework. The potential savings amount via reworking also depends on the location of the waste generation which affects the rework cost.

The model output based on the waste data from practice shows that not all the waste could be reworked due to rework limitations (mainly mixing limitations determined by the week's production portfolio). Whereas 69% of the waste is reworked under the limited rework matrix scenario, it increases to 83% under the general rework matrix scenario. The yearly potential savings are estimated as more than 100,000 Euro. Using general rework matrix contributes extra 22% more profit than limited rework matrix. The payback periods required for the initial investments are 16 weeks when limited rework matrix is used and 13 weeks when general rework matrix is used.

Rework matrix scenario	Percentage reworked	Payback Period (weeks)
Limited rework matrix	69 %	16
General rework matrix	83 %	13

Table 13-2: Result of the model runs with real waste data

The main conclusions that can be drawn from this research can be summarized as:

1. Reworking is potentially profitable due to high material cost for ice cream and high amount of waste generation in the production.
2. Reworking ice cream via mixing is limited by the storage time and mixing restrictions.
3. The waste source which offers the most potential savings for reworking (Breakdown/mistake in production lines) occurs unexpectedly. The waste can be reworked only after the confirmation of the corresponding week's detailed scheduling (under the 72 hours storage limit). Therefore, rescheduling approach is required.
4. Although rework is potentially valuable, not all the waste can be reworked due to rework limitations (mainly mixing limitations determined by the week's production portfolio).
5. The profit that can be gained by reworking under the limited rework matrix, which the SU Hellendoorn is currently using, is estimated more than 100,000 Euro/year.
6. Relaxing mixing limitations by allowing different recipes to mixed with each other contributes extra 22% profit.

13.2. Recommendations

This section presents the recommendations derived from the research conducted in this project. First, the recommendations for SU Hellendoorn and then the recommendations for academics will be given.

13.2.1. Recommendations for SU Hellendoorn

Since it is concluded that not all the waste can be reworked due to rework limitations (mainly mixing limitations determined by the week's production portfolio), the rework percentages can be increased by considering rework possibilities in the medium level of planning when the weekly production portfolio is decided (i.e. when the weekly production targets are determined). Planning the production of compatible products (i.e. the products between which mixing is allowed) in the same week will increase the reworking opportunities by mixing. The compatible products for both rework matrix scenarios are the products with same recipes but different sizes. It is shown (Figure 5.1) that in the historical production plan of SU Hellendoorn, the percentage of having production targets of same recipe/different size production in the same week is low (10%-30% of the weeks the recipe is produced). If this percentage is increased, the savings that can be gained by reworking can also increase. When the general rework matrix is concerned, it is also possible to increase rework opportunities by assigning recipes that are most capable of accepting other recipe types to be mixed with (e.g. New York Super Fudge, having dark base-mix, strong flavour and most of the allergens types) to each week. However, the higher planning level has also the other concerns such as inventory cost and capacity restrictions. Therefore, it is recommended to consider the reworking possibilities integrated with other decision factors in the mid-term planning.

The potential savings estimations are done by making several assumptions to the existing waste data in SU Hellendoorn since there was no data including exact timing of the waste generations. In addition, the rework costs are estimated for each waste generation location. For a more precise estimation of potential savings by reworking, it is recommended to collect waste generation data with exact timings, and analyze the rework cost factors further.

It is mentioned that the SU Hellendoorn, differently from other ice cream factories of Unilever, does not rework by mixing different recipes. It can be worth to investigate the reasons of this difference in applications.

13.2.2. Recommendations for academics

Integration of rework concerns in a higher level of planning, i.e. decreasing the risk of waste generation, (by assigning compatible products to the same week) to increase rework opportunities by mixing can be an interesting further research area.

In this research, intermediate limited storage capacity is not taken into account explicitly, but handled with converting physical capacity restriction to the temporal restrictions through an assumption (see section 7.1.3). Model operational validation showed that this assumption could result in overlapping of aging tanks in several cases. Decreasing the effect of this assumption (by decreasing the maximum sublot size) leads to bigger problem size and long computation time to solve the model. Incorporating intermediate storage capacity constraints to the developed model in a way that the computation time is not increased can be a further improvement possibility for the developed model.

In chapter 10, two extensions that release the two assumptions of the model are given. A further research can include these extensions and analyse the effects on the results.

Verification and validation of the model also showed that the computation time of solving the model can increase exponentially as the problem size increases. For solving bigger size problem instances, for example if more lines exist in the production, further research can be done to reduce computation time. Moreover, the efficiency of the model in AIMMS can be increased by analyzing the codes behind the model for any potential improvement and by using the many features of the complex AIMMS mathematical programming tool.

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List of Figures & Tables

List of Figures

Figure VI-1: Characteristics of the waste sources 10
Figure 1-1: Unilever Categories and Positions [2] 11
Figure 3-1: Two-step manufacturing process with intermediate storage. 14
Figure 3-2: Representation of a weekly schedule in two departments 16
Figure 3-3: Representation of coordination between departments and intermediate storage 16
Figure 3-4: Stock Keeping Unit (SKU) under scope 17
Figure 3-5: Decision hierarchy regarding production planning in SU Hellendoorn 18
Figure 3-6: Data flow diagram required for INFOR (Bongers & Bakker, 2009). 19
Figure 4-1: The general production flow with rework flows 22
Figure 4-2: Waste amount distribution over location (before vs. after fruit feeder) and over lines 25
Figure 5-1: The percentages of the weeks that produced the same size of recipe (2010) 27
Figure 6-1: Representation of a weekly schedule update 30
Figure 6-2: A roadmap for short-term scheduling models of batch plants (Méndez et al., 2006) 34
Figure 7-1: Flow diagram of the waste generation and rework integrated with the regular production 37
Figure 7-2: Visual explanation of $tslack$ 39
Figure 8-1: Rescheduling input page in Excel 49
Figure 9-1: Modelling Process (Sargent, 2008) 50
Figure 9-2: Computation time 57
Figure 12-1: Payback period (weeks) for the two rework matrix scenarios 63
Figure 12-2: Payback period (weeks) for percentage increases in initial investment 64

List of Tables

Table III-1: Characteristics of the waste sources V
Table III-2: Reworking opportunities under two rework matrix scenarios V
Table III-3: Result of the model runs with real waste data VI
Table 4-1: Yearly waste amount percentages for each waste source 24
Table 5-1: Reworking opportunities under two rework matrix scenarios 26
Table 9-1: Effect of rework cost on the results 56
Table 9-2: Effect of rework matrix on the results 56
Table 11-1: Cash flows 60
Table 12-1: Magnitude and frequency of the waste occurrences 61
Table 12-2: Waste amount distribution through the waste generation locations 61
Table 12-3: Yearly reworked and disposed waste percentages for each rework matrix 62
Table 12-4: Yearly profit distribution from reworking each waste type 62
Table 12-5: Yearly profit contribution from each rework opportunity 63
Table 13-1: Characteristics of the waste sources 65
Table 13-2: Result of the model runs with real waste data 66

Definition of Concepts

Batch production	A manufacturing technique of creating a group of components at a workstation before moving the group to the next step in production
Defective product	Product that does not fulfil the preset specifications set by the company
Lot streaming	A technique of splitting production lots into smaller sublots in a multi-stage manufacturing systems so that operations of a given lot can be overlapped
Perishable	Material or product whose quality decreases by time when waiting
Process industry	Businesses that add value to materials by mixing, separating, forming, or chemical reactions where processes may be either continuous or batch and generally require rigid process control and high capital investment
Production batch	The batch in the production line
Rework	all activities required to transform products that have not been produced or packaged according to preset qualifications into products that are
Scheduling	A decision-making process that is concerned with the allocation of limited resources to competing tasks (operations of jobs) over a time period with the goal of optimizing one or more objectives
Sublot	The batch in the mixing department
Waste	The material that is produced defective or is kept aside in case of a blockage in the production line

List of Abbreviations

AIMMS	Name of the advanced development environment for building optimization based operations research applications and advanced planning systems.
APO	APO is an acronym for Advanced Planner and Optimizer. It is the planning component within SAP.
EPM	European Planning Manager
Liton	Name used in the SU Hellendoorn for 1000 litres
MILP	Mixed Integer Linear Program
MSU	Marketing & Sales Unit
PV	Present Value
PVIFA	Present Value Interest Factor of Annuity
SAP	"Systems, Applications and Products in Data Processing". SAP is a provider of software related to enterprise resource planning and related applications such as supply chain management, customer relationship management, product life-cycle management, and supplier relationship management
SKU	Stock Keeping Unit
SU	Sourcing Unit
USCC	Unilever Supply Chain Company

Appendix L: Extensions to the model

A waste generation more than one location in one scheduling horizon

No more need of the parameter:

$L_{\bar{i},l}^{waste}$	Binary data equal to 1 if product $\bar{i}$ is generated in location l, otherwise 0

Parameters:

$c_{\bar{i},l}^{r}$	Operational cost of reworking product $\bar{i}$ generated in location l (€/ton)
$m_{\bar{i},l}^{w}$	Amount of waste of product $\bar{i}$ generated in location l (ton)
$q_{\bar{i}i}^{allow}$	Allowable percentage of product i that product $\bar{i}$ can be mixed with for rework
$T_{\bar{i},l}^{waste}$	Time of waste generation of product $\bar{i}$ generated in location l

Variables:

$m_{\bar{i},l}^{d}$	Amount of disposed waste product $\bar{i}$ created in location l (ton)
$m_{\bar{i},l}^{r}$	Total amount of reworked waste product $\bar{i}$ created in location l (ton)

Decision Variables:

$R_{\bar{i},l,s,i}$	Binary variable equal to 1 if rework created by product $\bar{i}$ in location l is reworked by mixing with sublot s of product i, 0 otherwise
$m_{\bar{i},l,s,i}^{r}$	Amount of waste product $\bar{i}$ created in location l reworked by mixing with sublot s of product i (ton)

Objective Function:

$$Min\ Total\ cost\ per\ week = \sum_{i\in I} c_i^m P_i - \sum_{\bar{i}\in I^r}\sum_{l\in L}\sum_{s}\sum_{i} c_i^m m_{\bar{i},l,s,i}^r + \sum_{i\in I}\sum_{j\in J_i} c_{ij}^{prod}\frac{P_{ij}}{\rho_{ij}^2}$$

$$+\sum_{i} c_i^{p_{lost}}(Q_i - P_i) - c^d \sum_{\bar{i}\in I^r}\sum_{l\in L} m_{\bar{i},l}^d + \sum_{\bar{i}\in I^r}\sum_{l} c_{\bar{i},l}^r m_{\bar{i},l}^r$$

$$+\sum_{i}\sum_{i'}\sum_{j\in J_{i'}} X_{ij}^{start-up} c_{ij}^{ch\_2} s_{i'ij}^2 + \sum_{i}\sum_{i^*\neq i}(c^{ch\_1}\sum_{s}\sum_{s^*} X_{sis^*i^*}^1 s_{ii^*}^1 + \sum_{j} c_{i^*j}^{ch\_2} X_{ii^*j}^2 s_{ii^*j}^2)$$

Rework related constraints:

$$m_{\bar{i},l,s,i}^r \leq m_{\bar{i}}^w R_{\bar{i},l,s,i} \qquad \forall s \in S_i,\ i \in I^{demand}, \bar{i} \in I^{waste}, l \in L \qquad (7.31\text{-II})$$

$$R_{\bar{i},l,s,i} \leq M m_{\bar{i},l,s,i}^r \qquad \forall s \in S_i,\ i \in I^{demand}, \bar{i} \in I^{waste}, l \in L \qquad (7.32\text{-II})$$

$$\sum_{l\in L}\sum_{\bar{i}\in I^{waste}} R_{\bar{i},l,s,i} \leq 1 \qquad \forall s \in S_i,\ i \in I^{demand} \qquad (7.33\text{-II})$$

$$m_{\bar{i},l}^r = \sum_{s}\sum_{i} m_{\bar{i},l,s,i}^r \qquad \forall \bar{i} \in I^r, l \in L \qquad (7.34\text{-II})$$

$$m_{\bar{i},l}^w = m_{\bar{i},l}^d + m_{\bar{i},l}^r \qquad \forall \bar{i} \in I^r, l \in L \qquad (7.35\text{-II})$$

$$m_{\bar{i},l,s,i}^r \leq \frac{q_{\bar{i}i}^{allow}}{100} K_{si} \qquad \forall \bar{i} \in I^{waste}, l \in L, i \in I^{demand}, s \in S_i \qquad (7.36\text{-II})$$

$$T_{s,i}^1 \leq T_{\bar{i},l}^{waste} + T^{limit} + C^{week}\left(1 - R_{\bar{i},l,s,i}\right)$$
$$\forall s \in S_i,\quad i \in I^{demand},\quad \bar{i} \in I^{waste},\quad l \in L \qquad (7.37\text{-II})$$

$$t^{reschedule} + T^{pre\_fixed} + T_l^{prerework} * m_{\bar{i},l,s,i}^r - C^{week}\left(1 - R_{\bar{i},l,s,i}\right) \leq T_{s,i}^1$$
$$\forall s \in S_i,\quad i \in I^{demand},\quad \bar{i} \in I^{waste},\quad l \in L \qquad (7.38\text{-II})$$