OPTIMIZING MIXING DEPARTMENT SCHEDULES

Optimizing utilizations of the mixing lines at Ben & Jerry's, The Netherlands | By Youp Johannink

Abstract

Research about the maximization of the utilization of the mixing lines of Ben & Jerry's Hellendoorn

Youp Johannink

MSc Industrial Engineering and Management student | University of Twente | S2220547

Optimizing utilization of the mixing lines at Ben & Jerry's

Master thesis report

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Author

Youp Johannink
S 2220547
y.johannink@gmail.com

University of Twente

Dr. M.C. Van der Heijden
Dr.ir. A.G. Leeftink
Faculty of Behavioural Management and Social Science

Ben & Jerry's

S. Heeres
Manager Focussed Improvement

Management Summary

This report studies a unique (re-)scheduling problem of jobs in a production plant of one of the most famous ice cream producers in the world, Ben & Jerry's. Given rapidly growing competition, wider product varieties, complex plant structure, changing production plans, efficient methods for initial scheduling and re-scheduling are required by any production plan. In this problem, the current (re-) scheduling process, which can be best described as a constructive heuristic based on the Earliest Due Date (EDD) rule, is described. The goal of this study is, by means of practical and theoretical research, to create methods to improve the schedules in terms of total changeover time.

Problem statement

The production plant of Ben & Jerry's is strictly divided into two production departments, the mixing department, and the packaging department. In Figure 1, a simplified overview of planning the mixing processes is visually given. The actual plant consists of four pre-mixers, two pasteurization lines, 24 aging tanks, and five packaging lines. Schedules for the mixing department are created in such a way that the packaging department can produce in the size and the sequence as planned. During a production week, due to unforeseen events, schedules for the mixing department need to be altered. Currently, (re-)scheduling is time consuming (two hours for initial scheduling and 200 minutes for re-scheduling, weekly) because of the lack of a (re-)scheduling method.

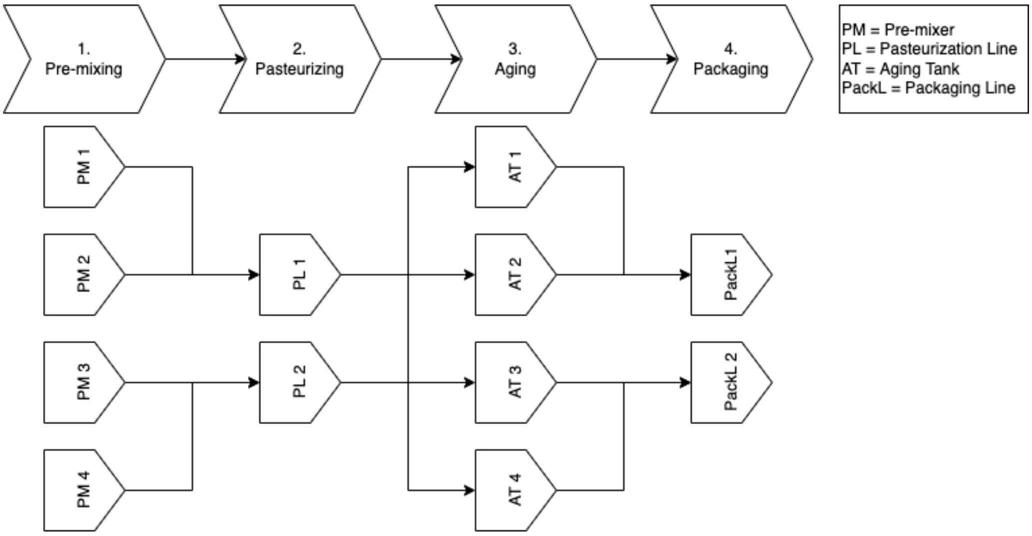

Figure 1 - Planning process mixing department

The planning process of the mixing department consists of four steps, (i) the assigning of a job to a pre-mixer, (ii) the pasteurization of a job by the attached pasteurization line, (iii) sending a job from the pasteurization line to an aging tank, (iv) sending a job from the aging tank to the attached packaging line. Currently, the planners of the mixing department schedule jobs by common sense and experience. The current (re-)scheduling process can, as mentioned, best be described as a constructive heuristic based on the 'Earliest Due Date' (EDD) rule. The current OEE[1] of the mixing department is 54.3%. The goal of the organisation is to achieve an OEE of 63.6%. This research focusses on the complete planning process of the mixing department. The goal of the research is to maximize the utilization of the pre-mixers and the pasteurization lines by minimizing the total changeover time of these components. Also, research is performed about decreasing the necessity

[1] Overall Equipment Efficiency of the mixing department: $\frac{Total\ amount\ of\ time\ producing}{Total\ amount\ of\ time\ producing + Losses\ (in\ time)}$

to re-schedule. Besides, the total running time of the created methods cannot exceed 20 minutes for the methods to create new schedules. The main research question is formulated as follows:

How should the scheduling and re-scheduling methods of production, changeovers, and planned stops be (re)designed to maximise the bottleneck's utilization *of the production process?*

Approach, methods, and evaluation

To evaluate the performance of the created methods, an objective function is set. Since the mixing department needs to supply the packaging department, the lateness must be considered. However, currently, lateness rarely happens. No lateness occurred in all experiments that are performed in this research. Also, no lateness occurred in the evaluated production weeks.

The current (re-)scheduling focusses mainly on the due date of jobs and very little on the total changeover time. The research is divided into two parts, the scheduling part which forms the base of the research, and the re-scheduling part.

Approach, methods, and evaluation of initial scheduling

First, for initial scheduling, a constructive heuristic with a priority rule is created. This method represents, approximately, the current way of (re-)scheduling. Thereafter, for initial scheduling, simulated annealing is used to optimize the schedules. In the research, three different settings of simulated annealing are used, namely, with the use of a move operator that forces the model to move jobs to a point in time (both later and earlier) that differs at most (i) six, (ii) 12, and (iii) 24 hours. Allowing the move operator to move jobs in time to a further point in time is an increase in the depth of the neighbourhood. The evaluation of the methods for initial scheduling is done by comparing the actual created production schedules (by the mixing planners in practice) and the actually executed production schedules (how jobs are sequenced and executed in practice) to the schedules created by the methods.

Approach, methods, and evaluation of re- scheduling

After all experiments for initial scheduling purposes are performed, the additions and alterations for re-scheduling are made to experiment the methods for re-scheduling purposes. The main differences between initial scheduling and re-scheduling are within the condition of the plant and the job list.

The evaluation of the methods for re-scheduling is different than for initial scheduling. The evaluation of one method for one production week works as follows: (i) first, a method creates a schedule, (ii) the simulation model runs until the first event[2], (iii) it is determined whether re-scheduling is necessary[3], (iv) if re-scheduling is necessary, a new schedule is created with the same method. This is repeated until the end of the production week. This evaluation method is visually shown in Appendix J.

To possibly decrease the necessity of re-scheduling, the use of aging tank buffers is tested. When using aging tanks buffers, one aging tank per attached packaging line is not used until it is necessary to use. It is considered necessary to use an aging tank when, otherwise, jobs will be delivered late.

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[2] An event in this case is when something unforeseen happens during a production week (for example, a machine breakdown or an altered production plan of the packaging department).

[3] It is considered necessary to re-schedule when (i) jobs will be delivered late because of a machine breakdown at the mixing department, or when (ii) aging tanks will be filled up due to breakdowns at the packaging department or alterations in the production plan of the packaging department.

When not using aging tank buffers, all aging tanks are used. The possibility of adding extra aging tanks is not investigated, since there is no availability to increase.

Results

After performing the experiments as mentioned above, the most important results are:

1. **When performing the constructive heuristic for both initial scheduling and re-scheduling, the schedules are very similar to the actual schedules in practice.** The average percentual differences (in total changeover time) between the actual executed production schedules and the schedules created by the constructive heuristic over the four evaluated production weeks is 2.1%.
2. **The best setting for both initial scheduling as for re-scheduling was the experiment with the move limitation of 12 hours.** The improvement of this experiment in terms of total changeover time was 15.4% for initial scheduling, and 11.0% for re-scheduling compared to the actual created schedules of the planners of Ben & Jerry's. These methods will improve the OEE by approximately 1.6% and 1.2% for initial scheduling and re-scheduling, respectively. All methods are executed within 20 minutes in all experiments.
3. **The use of aging tank buffers resulted in a decrease in the necessity of re-scheduling slightly.** The use of buffer tanks resulted in a decrease of necessity to re-schedule of 5.0%.

Conclusions

From the results, the following is concluded:

1. **The best simulated annealing experiments result in an improvement of the OEE of 1.6% for initial scheduling and 1.2% for re-scheduling.** The best way to schedule is by using simulated annealing with the use of a move operator and a move limitation of 12 hours to improve the current way of scheduling. The current way of scheduling can be described as scheduling according to the Earliest Due Date rule. The expected improvement in total changeover time when using this technique is around 15.4% for initial scheduling and 11.0% for re-scheduling. Also, the expected time that will be saved for the mixing planners is 320 minutes, weekly.
2. **The necessity of re-scheduling can be decreased slightly by using aging tank buffers (5.0% less)**. However, the improvement of the total changeover time is less than when all aging tanks can be used all the time (11.0% against 7.0%).

Recommendations

Finally, based on the results of the experiments and the conclusions, the two most important recommendations are the following:

1. **Implement the created (re-)scheduling methods that can automatically create schedules within 20 minutes, minimizes the total weighted changeover time, and without any lateness**. The method should be linked to all databases and other methods, that are currently used in the organization. The method should consist of a dashboard that represents the progress and status of all jobs and components of the mixing department. This dashboard will improve the communication between departments and the monitoring of the planning process.
2. **Investigate other use of buffers.** Because of the lack of data, it was not possible to efficiently evaluate all possible buffers. Ben & Jerry's is currently implementing and structuring the digitalization of all production processes. When accurate data is available about the performance of the components of the mixing department, possible buffers to decrease the necessity of re-scheduling can be investigated more efficiently.

Preface

The thesis in front of you marks the end of my life as a student at the University of Twente, and the end of my master Industrial Engineering and Management. During a period of around three years, in which I had the opportunity to develop myself and enjoy everything the University of Twente had to offer, I learned a lot, met many interesting people, and explored a whole different aspect of business. Therefore, I am truly grateful to everyone and everything that made this period a success for me.

I especially would like to thank Matthieu van der Heijden for all the knowledge and kindness offered as my first supervisor, which has helped me towards the research that resulted in this thesis. The discussions we had, and the feedback improved the quality of this research. Besides, the personal touch made the graduation period a pleasant time. I also would like to thank Gréanne Leeftink for giving valuable and accurate input for this thesis as well.

Moreover, I would like to express my gratitude towards my supervisors of Ben & Jerry's. First, I would like to thank Sybrand Heeres for the theoretical knowledge he was always happy to share, and the practical knowledge of Ben & Jerry's which was very valuable input. Secondly, I want to thank Niek Morshuis for the everyday guidance and for assuring the research period was great fun. The drive and enthusiasm of both really brought this research to a higher level.

Finally, I want to thank everyone outside Ben & Jerry's and University of Twente that supported me during this enjoyable period.

I sincerely hope you enjoy reading this and you will find this thesis meaningful.

Youp Johannink

Enschede, 2022

Abbreviations and glossary

Abbreviation	Explanation
C&S's	Chunks and Swirls
MP	Machine Performance
OEE	Overall Equipment Efficiency
CPI	Critical Performance Indicator
CUC	Customer Unit Cluster. One CUC consists of products that are the same but differ in packaging. The difference can be within the size of the packaging and the design of the packaging (different language but same packaging unit).
MAD	Magnum After Dinner
PM (e.g., PM A1)	Pre-mixer (e.g., Pre-mixer 1 of mixing line A)
PL (e.g., PL A)	Pasteurization Line (e.g., Pasteurization line A)
AT(s)	Aging Tank(s)
FT(s)	Flavour Tank(s)
EDD	Earliest Due Date
CIP	Cleaning In Place. Parts of the production process can be cleaned without being disassembled.
Base mix	A base mix is a mix needed to produce a product.
Job	A task to be performed by the mixing department. In this research, a job is a base mix that needs to be produced by the mixing department. Also, a job consists of information about due dates and the destination.
Batch	A quantity of base mix produced in a pre-mixer at once is called a batch.
Order	A task to be performed by the mixing department. An order resembles a production run of a packaging line. An order consists of information about the base mix needed to produce a product on a packaging line, the due date of the order, the packaging line that needs the base mix, and the quantity needed for the production run.
SA	Simulated Annealing
Actual total changeover time in practice	The actual total changeover time of a production week. So, how long the total changeover time was in practice during a production week
Actual total planned changeover time	The total changeover time as planned in the initial schedules created by the planners.
Actual created production schedule	The schedules that were created during or before a production week.
Actual executed production schedule	The actual executed production schedule. So, how jobs are actual executed in what sequence and at what time, in practice. The actual total changeover time in practice is the result of the actual executed production schedule

Contents

1. Introduction

In this chapter, a brief description of the company and an introduction to the research will be given. Also, the motivation of the research, the core problem, the problem statement, the research goal, research questions, approaches to answer the research questions, and the scope of the research are given.

1.1. Ben & Jerry's

"From a converted gas station in Burlington, Vermont, America, to places whose names we can't even pronounce properly; this journey began in 1978 when two boys founded an ice cream company." This is the first quote on the Dutch 'about us' page of Ben & Jerry's The Netherlands. It represents how a 'small' business can lead to great success.

In 43 years, Ben & Jerry's has become an international leader in the ice cream market with four plants in The United States, The United Kingdom, and The Netherlands. In 1978 two friends started offering courses on how to make ice cream.

Nowadays, Ben & Jerry's Hellendoorn has around 150 employees and delivers ice cream tubes globally. This research will be conducted for 'the focus team' of Ben & Jerry's Hellendoorn. The department consists of ten employees. The manager of this department is Sybrand Heeres, who is the supervisor of the research (Over ons, 2022).

1.2. Research motivation

The Dutch plant in Hellendoorn of Ben & Jerry's (from here referred to just as Ben & Jerry's) has two premixing chambers (called pre-mixers) on two sides (so four in total) of the production line that come together before a pasteurization line. After that, base mixes go through a pasteurization line (there are two in the plant and identical). Further, there are buffers, a manifold that directs base mixes to the 'right' aging tanks, aging tanks, a section where flavours are manually added, flavour tanks, five conveyor belts where tubes are filled with ice cream (packaging lines), and a freezing component where the tubes get frozen again. The process of production is visually summarised and represented in Figure 2. The process will be visualised in more detail further in the report.

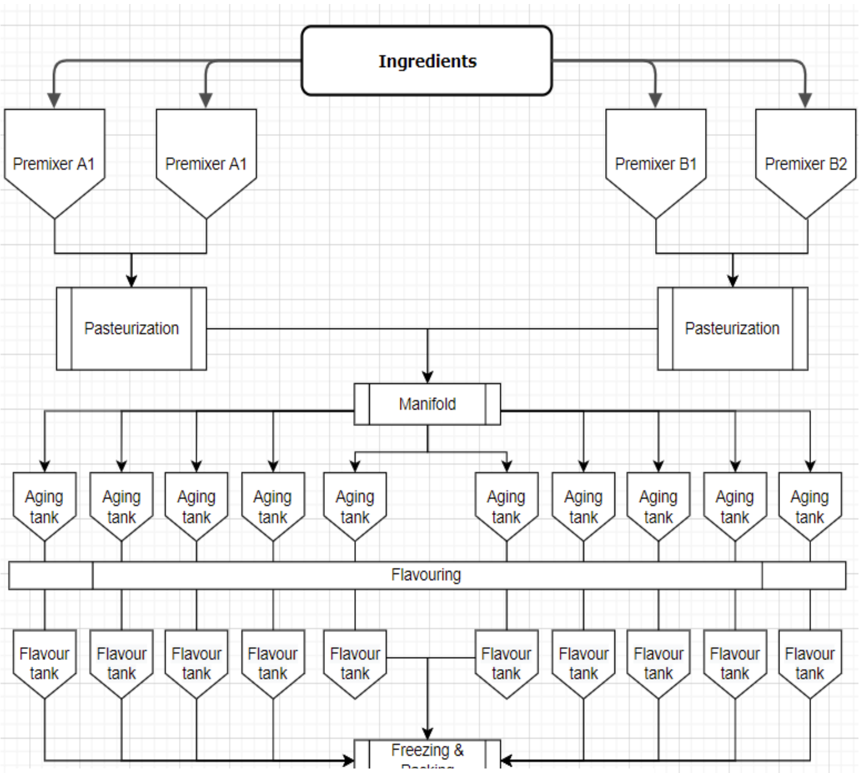

Figure 2 - Production process Ben & Jerry's Hellendoorn

These packaging lines pack mainly three different packings (0.1L mini cups, 0.465L pints, and 4.5L bins), all with different types of ice cream mixes. In total, Ben & Jerry's produces about 250 different products, which are referred to as Stock Keeping Units (SKUs).

The organisation faces strong competition worldwide, resulting in the organisation needing to focus more on increasing efficiency and effectiveness, which can be achieved merely by either increasing output or decreasing input. Also, due to the highest inflation since the launch of Ben & Jerry's, the company must deal with the fact that inflation plays a more important role than ever (Swagerman, 2021). If the company does not increase its efficiency, the profit margins will decrease further to the point where the plant is no longer beneficial. The current Year-To-Date (YTD) Overall Equipment Efficiency (OEE) of the plant is 58.32%.

There are very accurate data available on the packaging lines. However, there are fewer data available about the mixing lines. Therefore, not all relevant performance indicators can be evaluated by the mixing department.

The plant makes various kinds of ice cream, all with different ingredients, including allergens. All ice creams contain a base mix. When a base mix needs to be processed by a machine that is different than the previously processed base mix on the same machine, the machine needs to be changed over. There are different types of changeovers; change of ingredients, cleaning of the components of the production process, and packaging.

The duration of changeovers is relatively high, mainly because of the cleaning of the components. In Appendix A, all changeovers needed between the production of two base mixes is given. Mainly, there are five types of cleanings, X5, flush + X5, flush + X3, complete installation cleaning, and Z3 + CIP-cleaning. The durations of the cleanings are five, six, 12, 90, and 120 minutes, respectively. This duration of cleaning depends much on the sequence of production. For example, after producing allergen products, the cleanings are more thorough and more time-consuming. The cleaning process is divided into two parts, from the pre-mixers to the manifold and from the manifold until packing. It is possible to clean the parts separately. Also, it is possible to clean one pre-mixer or a pasteurization line when another pre-mixer is cooking (also within the same mixing line).

The planning activities of the company are set as follows: first, the planning manager create a four-week-horizon production schedule for every packaging line, where some SKUs are produced once, and some are produced multiple times. The next step is the responsibility of the logistic partner of Ben & Jerry's, Genpacked. In this step, demand is forecasted, and a planning is created eight weeks ahead. The packaging planner then creates a week plan (schedule) according to the production cycles of the manager planning and the forecast of Genpacked. These schedules consist of production runs. A production run is a period in which a packaging line produces one product without any interference. The last step is where the mixing planners create a schedule for the mixing department. The mixing planners receive the schedule of the packaging department before a production week. The mixing operators create an order list corresponding to the schedule of the packaging department. For example, a packaging line that produces Cookie Dough ice cream at a speed of which it requires 10,000 litres of vanilla base mix per hour for four hours straight results in an order of 40,000 litres vanilla base mix. Then, because of the limited capacity of the pre-mixers of 4,000 litres, the order needs to be split up into jobs of 4,000 litres. Thus, this order results in ten jobs. The mixing planners are responsible for scheduling all jobs required by the packaging department. The mixing planners try to schedule those orders within the week and minimise the total changeover time of the most important components of the production process. This is done by common sense and experience since there is no optimisation method for this process.

The organisation is not completely sure what the bottleneck of the production is and, therefore, not completely sure what components of the production are most important. Hence, the bottleneck will be investigated first. The mixing planners want to plan in such a way these components' utilizations are maximised.

Packaging scheduling

When the packaging planner creates the week plans of the packaging lines, the total planned utilization of the lines is around 90.1%. This is calculated as follows:

$\frac{Time\ Component\ A\ produces}{Theoretical\ capacity} = \frac{Theoretical\ capacity - changeover\ time - plannedstops}{Theoretical\ capacity}$, where the theoretical capacity is the total available time per week (120 hours). So, as can be obtained from this formula, the planners do not consider unforeseen events. The ten per cent loss of utilization comes completely from planned stops and changeovers. The packaging planners create schedules by using the cycles of the planning manager.

However, because of unforeseen events, the realised utilization of the packaging department is 74.4%. The difference between realized and planned utilization comes from disturbances, planned stops, and unplanned stops. This great difference between the planned and realised utilization of 15.7% strongly indicates that initial schedules are not built to be able to handle unforeseen events.

The making of initial schedules takes two hours weekly. Because of unforeseen events, schedules need to be altered frequently; on average, packaging schedules are altered 4.7 times weekly.

Machine failures occur in all stages of the process, from the pre-mixers to the flavour tanks and the conveyor belts. Data on machine performances at the mixing department is very poor. Therefore, further research is needed about how to deal with this problem.

Whenever modifications are necessary, the packaging planners usually get around 20-30 minutes to modify the schedules of the packaging lines. In academic terms, this is called re-scheduling of the packaging lines. This is based on 'expertise and common sense'. This time of 20-30 minutes comes from the time it takes for the pre-mixers to cook the next mix. Within this time window, the packaging planners try to make the best schedule possible (minimise total changeover time of the most important components). In total, during office hours (typically from 08:00 am until 04:30 pm) four packaging planners are only responsible for planning the packaging process.

Mixing scheduling

Thus, the scheduling of the mixing process is based on the schedules created for the packaging department. The goal of the mixing planners is to efficiently schedule jobs to minimize changeover times of the pre-mixers and pasteurization lines. The mixing planners create initial schedules in around two hours. The total planned utilisation of the mixing department is around 72.5%. This is calculated as follows:

$$\frac{Time\ Component\ A\ produces}{Theoretical\ capacity} = \frac{\begin{array}{c}Theoretical\ capacity - changeover\ time - planned\ stops - \\ the\ time\ no\ job\ is\ scheduled\end{array}}{Theoretical\ capacity}$$

As can be obtained, the planned utilisation differs from the planned utilisation of the packaging department by 'no job is scheduled'. Because of the excess capacity of the mixing department which will be explained later in this report, situations occur where it is not possible or wise to produce a base mix at the mixing department.

The realised utilisation of the mixing department is around 61.1%. the difference between the planned and realised utilisation is around 11.4% and is directly linked to the difference between the planned and realised utilisation of the packaging department. This means that, because of the 15.7%

less utilisation in the packaging department, the mixing needs to create 15.7% less jobs, which is around 11.4%. All jobs required by the packaging department can be processed by the mixing department because of its excess capacity.

In many situations, when alterations are made to the packaging schedules, the mixing schedules need to be altered as well. When the packaging schedule is altered, the mixing planners receive a new list of the production runs which is the input for the altered order list. Then, the mixing planners are responsible for re-scheduling, if necessary, within the time that the current batch has left to cook (to not miss available mixing time). It is necessary to alter a mixing schedule if, for example, jobs will be delivered to the packaging lines late or when all aging tanks of a packaging line will be filled up otherwise. Mixing planners have around 20 minutes to recreate schedules. Because of the complexity, it happens that 20 minutes is not enough. Then, a job will be assigned to a pre-mixer and while producing that job, the re-scheduling will continue. The average time it takes the mixing planners to re-schedule is around 40 minutes. On average, the mixing planners re-scheduled 5.8 times in 2021.

In 2021, around 87% of the time, the necessity of re-scheduling was the result of (i) Line breakdown at the packaging department, and (ii) re-scheduling of the packaging department.

The new packaging schedule that is made within the 20-30 minutes can be completely different from the previous, but the packaging planners try to maintain the original plan as much as possible.

The horizon of the modified schedules varies between 24 and 120 hours, depending on which day the modification is made. The modifications can contain changes in batch sizes, changes in sequences, or even the removal of batches.

In total, at a time, one or two mixing planners are both responsible for planning the mixing process and monitoring the mixing process.

Summarized research motivation

So, when initial scheduling, the initial schedules are proper for both packaging and mixing. However, in practice, the process is not as fluent as expected. Processes are interrupted by unpredictable activities, such as machine failures. Due to these unfortunate events, the initial schedule of the packaging lines does not hold up any longer. There is no consideration of those unfortunate events within the initial schedules. As a result, the mixing planners need to re-schedule very often as well.

Currently, the company is satisfied with the initial schedule-making process but is not with the process where modifications to the previous schedule are made. This is mainly because of the little time frame the planners must recreate schedules in and the complexity of re-scheduling.

To summarise, Ben & Jerry's has, currently, no structured ways of re-scheduling the mixing and packaging processes are designed when problems such as machine failures occur. This results in a lot of work for the mixing and packaging planners. This struggle (in combination with the desire to increase the capacity of both departments which will be discussed in the next chapter) could be an opportunity to improve efficiency by improving utilization. Therefore, the organisation has set an assignment.

1.3. Assignment of the organisation

The problem does not lie within the strategic or tactical level of the organisation. Ben & Jerry's works with a master production plan with a horizon of three months. At this level of planning, orders and production runs are created, and internal delivery dates are set. After this, an initial schedule is made for the packaging department and the mixing department, which has a time horizon of one week of production (Monday to Friday for the packaging department and Monday to Sunday for the mixing department). The problems arise at the operational level, within the scheduling phase of both departments.

In perfect production conditions with zero failures, there are not many issues with this initial schedule making. Also, when considering zero failures, the schedules made within this initial schedule making, the results of utilization are high. However, there are no production weeks with zero failures. Currently, the organisation does not require a solution to this problem.

The goal of the mixing planners when re-scheduling is to create a schedule within 20 minutes that maximises the utilization of the pre-mixers and pasteurization lines by minimising total changeover time. The mixing planners cannot come up with an optimal schedule for the upcoming period because there are too many variables and too many possible schedules that need to be evaluated and not enough time to consider all. Consequently, new schedules are made almost every day, sometimes even multiples per day (on average, around five per week).

Because of the complexity of this problem, the organisation has set this assignment. The main goal of the assignment is to maximise the utilization of the plant's bottleneck. The organisation desires to receive mainly two deliverables. (i) Whenever problems in the production process occur, the organisation wants a structured re-scheduling method (with corresponding supporting method) where the original or previous schedule is updated. (ii) There's the desire to determine the required capacity of the bottleneck of the production process whenever the capacity of other components of the production process increases. The company believes that with a proper re-scheduling method, it could be possible to evaluate existing capacity.

1.4. Core problem

Ben & Jerry's' production strategy is best described as a make- and assemble-to-stock (MTS) strategy for all its products. The strategy is based on a push strategy. Quantities per product are produced according to forecasts. The main problem, according to Ben & Jerry's, is that there is no structured method to re-schedule the mixing and packaging processes. The company does not desire a method to make an initial schedule because, within the initial scheduling process, there is enough time to come to a proper schedule.

However, the initial packaging schedules that are created momentarily are not robust because mainly of the frequent need for modifications. These schedules are based on the production cycles. Besides, the difference between the realised and theoretical utilization is high (15.7% for packaging and 10.8% for mixing), which indicates initial schedules are not built with the consideration of unforeseen events, like the consideration of probability distributions (for example, machine failures, in terms of mean time to failure). The frequent need of modifications of the packaging department leads to a higher necessity of re-scheduling the mixing process as well.

Whenever failures occur in the packaging department, the necessity of a modification of the previous schedule is around 80% of the time, and this happens around five times a week. These facts indicate that initial schedules of the packaging lines are not robust enough. Also, when a re-scheduling method is going to be created, this should be in line with the initial scheduling method. So, the initial scheduling method should be reconsidered as well.

Thus, the initial scheduling of the packaging lines is based on the production cycles, but this way is not robust. The re-scheduling of the packaging lines is based on ‘expertise and common sense’.

Currently, both scheduling and re-scheduling of the mixing lines are done by 'expertise and common sense' as well. The process of initial mixing scheduling is more structured because of the more available time than the re-scheduling process. Also, the overall belief is that the initial schedules are better. However, this could be a belief based on the high theoretical utilization, which is not quite relevant because it is never achieved. The poor structured (re-)scheduling processes and robustness of the schedules result in bad efficiency. The current overall efficiency of the plant is around 60%, compared to its theoretical capacity, and the company wants to improve this figure.

As mentioned, the difference between the theoretical and the realised utilization of the most important components (probably bottlenecks) is high. The organisation wants to improve its efficiency, so it must improve its bottleneck's utilization by improving the (re-)scheduling approach(es). However, the organisation does not have a clear view of its internal performances and is therefore not completely sure of its bottleneck. So, this unidentified but important component shall be the first topic of this research.

In the figure below (Figure 3), it is shown how poor robust initial scheduling and re-scheduling under high time pressure leads to many internal problems. Also, related problems have a reinforcing behaviour. The most important results of these two problems are low(er) efficiency, poor (internal) delivery reliability and extra production costs. Extra production costs are, for example, the result of having waste. Whenever planners plan more than processable, materials must be discarded. The estimated impact of waste is around five per cent of the profit margin, according to analyses of the focus time. Lower efficiency results in poorly reliable processes because the plant assumes batches are produced according to the initial plan. When this is not the case, the plans need to be modified, and processes like inventory management and delivery are not reliable. As a result, the plans are modified. For example, batches can be interrupted from production because other batches have higher priorities, which is called operational disturbance in Figure 2. Operational disturbance leads to situations where components must be rebooted/ restarted. Shortly after restarting, the process is slower, so the overall processing time is lower. Again, these data need validation (Chapter 2). Ben & Jerry's needs to be more competitive because of the growing pressure of the market and inflation.

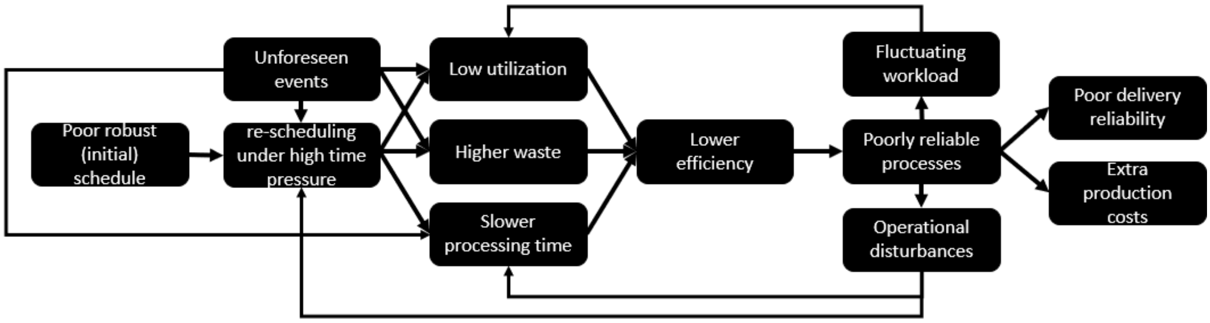

Figure 3 - Problem bundle

Capacity testing

At present, the organisation believes it does not make much sense to test whether the pre-mixers (and other components of the production process) have enough capacity when other components' capacity increase because of the poor current (re-)scheduling approaches. When proper (re-)scheduling approaches are created, the organisation believes that capacity requirements testing could be done. This capacity testing is a desire the organisation wants to achieve with this research. Capacity testing is not seen as the core problem. However, testing the capacity could be done whenever the scheduling and re-scheduling methods are defined and developed.

1.5. Problem statement

Ben & Jerry's currently has no structured way to re-schedule the production, changeovers, and planned stops, given the set of production runs of the packaging department that have been planned for the upcoming week(s). Besides, the initial scheduling and re-scheduling processes are time-consuming and do not provide robust solutions to deal with unforeseen events and the number of times schedules need to be modified is large. Therefore, the initial scheduling process needs to be reconsidered and should be in line with the re-scheduling approach.

Summarised, the problem statement is the following: *'the company has no optimal, structured and/ or robust methods for scheduling and re-scheduling the production, changeovers and planned stops'.*

1.6. Statement of research goal

To tackle this core problem the following goal for this research is set:

> *How should the scheduling and re-scheduling methods of production, changeovers, and planned stops be (re)designed to maximise the bottleneck's* utilization *of the production process?*

The contribution of this thesis to the solution of the core problem is defined by the following **deliverables**:

1. (Re-)scheduling prototype method
    a. The organisation works with the automation software 'Python'. Therefore, the organisation desires to be provided with solutions using this software.
2. Simulation models for testing purposes of the methods and capacity
    a. To test the (re-)scheduling methods' robustness by simulating actual production weeks in practice while using the created methods, and to eventually be able to study the utilization of the capacity of specific components of the production process.
3. Implementation report of new (re-)scheduling methods

1.7. Research questions and approach

To be able to answer the main research question, five research questions must be answered. Every question will have its chapter, where the question will be discussed. The sequence of the research questions is important since the information from previous research questions is needed to answer the next. Below every research question, a brief approach is given about how the question will be answered.

1. How are the current (re-)scheduling methods designed, what are the most important results and characteristics of the (components of the) production process, and what do these results and characteristics impose on the research?
    a. What are the most important flaws in the current (re-)scheduling?
    b. What are the most important key factors and components of the production?
    c. What are the characteristics of those key factors and components?
    d. What is the bottleneck of the production process?
    e. What utilization does the organisation desire to maximise?

The first research question is quite large and complex. Hence, this research question is divided into five sub-questions, which support the research question. Because the company is not completely sure about individual production components' results, it cannot be certain about the bottleneck of the organisation. First, this requires research before optimisation questions can be answered. The answer to this research question will be obtained by analysing empirical data given by the organisation's data software (LPI, Accos, SAP and Python). Analytical methods such as a bar chart will be used to answer this research question.

2. What (re-)scheduling methods are the most appropriate for this specific problem to be in line with the desires of the organisation?

By doing a literature review, the most relevant information about how (re-)scheduling approaches and their robustness under uncertainty can help to achieve goals, understanding constraints and goals themselves will be obtained. On the other hand, there are desires of the company. The goal of the methods should be chosen accurately, so the methods can be designed according to this goal.

3. How should (re-)scheduling methods be (re)designed to fulfil the requests and desires of the organisation according to obtained literature and own ideas and to be in line with the culture and philosophy of Ben & Jerry's?

This request question is the core of this thesis. The aim of this research question is, as the main research question, to (re)design the (re-)scheduling process. Within this chapter, the gap between the current situation and the desired situation will be filled with a proper solution. A solution where methods will be developed according to the desires of the organisation, the literature, and own ideas. The company desires a solution in Python because it is the program that is used at the plant.

4. What are the effects of the (re)designed (re-)scheduling methods in practice for Ben & Jerry’s?

To ensure the methods are as required by the organisation, three main aspects will be covered by this research: (i) the methods will be tested in a simulation model. This simulation model will be created in Python. (ii) With this simulation model, real situations will be created to be able to test the robustness of the methods and generate results. (iii), and lastly, a simulation model can help test what approach is best. The methods can be modified after this step when necessary. The results will be consulted with the organisation, and the organisation can give feedback for further adjustments or improvements.

5. How should the proposed methods be implemented in practice?

Finally, it is, of course, very important to successfully implement the methods, as described in research questions 3 and 4, such that the organisation can use them independently. To do so, implementation literature will be used. Also, observations, own ideas about implementation, and involvement of employees will be central in the problem-solving process.

Resources of the research

Mainly, seven types of resources will be used within this research to be able to answer all research questions and eventually to achieve the research goal.

Observations: observations will be mainly done at the beginning of the research to obtain information about the (information) systems Ben & Jerry's works with, like LPI, Accos and Python. Also, it is important to observe the (re-)scheduling process to find out how this process is structured.

Knowledge of employees: due to conducting interviews with Sybrand Heeres (focus group manager), Niek Morshuis (process engineer), planners and automation workers, information will be obtained, including information about constraints, data-accessibility, existing production processes, plant layouts, (re-)scheduling processes, and tactical planning processes.

Own ideas: sometimes it occurs that only literature, current knowledge of employees, and existing methodologies are not sufficient for a problem. Own ideas will be used, when possible, to bridge the gap between the existing knowledge and the desired situation.

Internal systems: the organisation works with the following systems that will be conducted within this research: LPI (manufacturing execution system), Accos (mix plan system), and Python for automation and data processing.

Literature: literature about scheduling, such as literature about job shop scheduling (scheduling method) and implementation techniques, will be used in this research to answer research questions.

Models and methods: (re-)scheduling methods will be created in Python because the organisation works with this program as well. Also, a simulation model will be created to test outcomes and verify them with the focus team.

In the table below (Table 1), a representation of the resources that will be used in this research is given.

Table 1 - Research resources per research questions

Research question	Observations	Knowledge employees	Own ideas	Internal systems	Literature	Models	Methods
RQ 1	X	X		X		X	X
RQ 2	X	X		X		X	X
RQ 3			X		X	X	X
RQ 4	X	X	X	X	X	X	X
RQ 5			X		X	X	X

1.8. Scope

According to (Alexander Howard, 1999) the MPC framework (Manufacturing Planning and Control systems plan and control the manufacturing process) consists of four levels of decision-making. Only the operational level will be included in this thesis, which can be divided into offline- and online operational. Also, four types of managerial areas are defined in the MPC. This research only includes resource capacity planning. All (around) 250 SKUs will be included, and all resources available at the moment of the research will be used. Given is a set of batches to be produced every week. This creation of batches is not within the scope.

Only the process from the raw materials (ingredients) until the flavour tanks will be considered, where assumptions are made that there are always enough ingredients, and the ingredients are always present. The process from the raw materials until the aging tanks is considered the mixing process. From the flavour tanks, it is considered as the packaging process. Later in this research, it will be clear why this scope is set. Also, whenever it is concluded in the research that there will be no need to investigate how new methods and models affect the performance of production components, these components can be disregarded in further research.

Empirical (historical) data on the characteristics of the SKUs will be used. Whenever there is no existing data, the data can be obtained by observing processes and will be logged. Also, it can be possible to use theoretical data, where distributions will be created to imitate the true characteristics of SKUs.

Some empirical data that will be used to develop methods are:

- Processing time
- Mean time to repair
- The number of machines
- Available machines

2. Context analysis and performance

The most important results and characteristics of the production process will be covered in this chapter. Also, an answer to the first research question will be given. This research question will be answered by answering five sub-questions. Each sub-question has a separate paragraph. Mainly, internal databases of Ben & Jerry's like SAP, ACCOSS, LPI and Python, together with interviews with the master planner of Ben & Jerry's, the head of production planning, stakeholders of the focus group, and the mix plan operators are used to answer the sub-questions.

2.1. Flaws of current (re-)scheduling methods

First the current situation will be stated, whereafter the greatest flaws will be described.

Current situation

As already can be concluded from chapter 1, there are problems with the current methods of (re-)scheduling. Because of the complexity of this problem, the specific problems and causes of this problem will be discussed in this paragraph.

The current planning and scheduling process is divided into four phases. All phases of planning have the goal of minimizing the changeover times. In phase one, production cycles are created. The cycles are created for the packaging lines. A production cycle is a sequence of orders (finished SKUs with quantities) to be produced, where some SKUs are produced multiple times in one cycle. Every production line (combination of mixing line and packaging line) has its own production cycle. The time horizon of a production cycle is around four weeks. All orders are produced in those four weeks. Whenever a cycle is completed, the cycle is repeated. These cycles are created and optimized by the supply chain manager as follows: first, orders are assigned to lines (around the same workload per packaging line), and then the sequence of those orders is optimized by an optimization method that minimizes the total changeover time per packaging line.

In phase two, GenPacked, a Polish logistics partner of the plant, is responsible for forecasting demand and planning production eight weeks ahead. This planning of eight weeks ahead is according to the production cycles of Ben & Jerry's. GenPacked uses a forecasting tool to forecast demand.

After phase two and before every production week (typically at the end of a previous production week), the packaging planners of Ben & Jerry's schedule production orders for the packaging department one week ahead. The planners consider information about all resources, like material and personnel. This is phase three. The packaging planners decides per packaging line the sequence and specific amounts of ice cream to be produced. The aim is to align the sequences of schedules as much as possible with the production cycles. Whenever changes to the initial schedules have to be made, the packaging planners change the schedules and communicate with GenPacked, the line managers, and the planning manager. The schedule horizon of the packaging planners is four weeks, but only schedules are created for one week. Namely, orders of SKUs that have a buffer can be postponed at most four weeks by the packaging planners.

In phase four, the mixing planners are responsible for distributing and sequencing base mixes and C&Ss to the ATs and to the FTs, which are the beginning of the packaging lines. The mixing planners receive a list with production runs of the packaging lines. Scheduling and sequencing of base mixes are done by common sense. When the packaging planners (phase three) change schedules, the mixing planners receive a new list with production runs of the packaging lines. The mixing planners need to analyse then differences and need to adjust the mixing schedule.

When a disturbance at the mixing department causes the necessity to change the week planning (of the packaging lines), which occurs infrequently, the mixing planners communicate with the packaging planners, and new week schedules for both departments are created. So, when necessary, the packaging planners alter the schedules that are made in step 3.

When orders are not met, the packaging planners communicate with GenPacked. GenPacked then takes these changes into consideration for the new week planning five to eight weeks ahead. Also, the packaging planners work 8.5 hours every day, at the same time. When there are major disturbances in the mixing department, the mixing planners need to re-schedule and make important decisions without consulting the packaging planners. This leads to logistic problems. For example, when there is less sugar processed than planned when the mixing planners are not on location, it happens that the next load of sugar cannot be delivered because of full storage tanks.

Summarized, mainly four activities of (re-)scheduling can be described. A visual overview of these four methods is given in Figure 4. Ci (i = 1,2,3) represents the transition of responsibility between two parties. The responsible party of the method is given next to the specific step. Isi (i=1,2,3,4) represent the Information Stream between two parties.

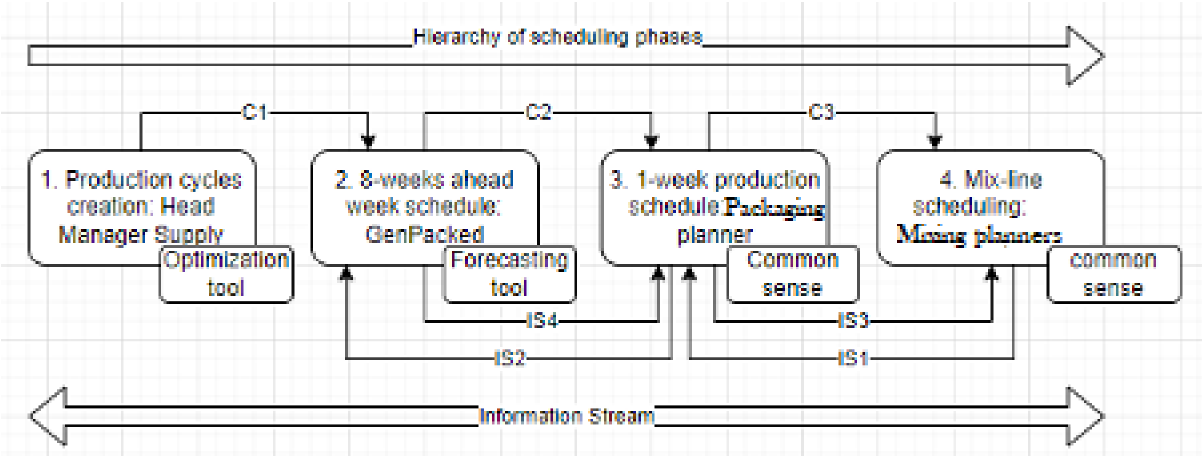

Figure 4 - Current (re-)scheduling activities

Flaws of the current (re-)scheduling methods

The current (re-)scheduling methods have multiple flaws that disadvantage results like the MP and OEE. Since results of planning outside the mixing department are out of scope, only results of the mixing department will be quantified.

Phase one: the production cycles are not optimal (not completely optimised, but an optimization method is used). The allocation of orders to lines and afterwards optimising per line could result in not having optimal production cycles. Also, the production cycles are created to minimize the total changeover time at the packaging department. In the future situation, with 24/7 operating packaging lines, the bottleneck will be at the mixing lines, so the production cycles should be based on the capacity of the mixing lines. However, since the research is devoted to the mixing department, this flaw is outside the scope.

Phase two: there are no flaws in the creation of orders based on forecasted demand.

Phase three: the creation of initial production plans is based on the not optimal production cycles and is therefore also not optimal. Production plans are altered on average 4.7 times per week. Currently, in almost all cases, the schedule of the mixing lines needs to be altered as well. This indicates the very low robustness of the plans. Also, changes in the packaging schedules are based on common sense and experience. Besides the creation of plans, there is a lack of communication between the mixing planners and the packaging planners, especially during night shifts. This is alarming because many changes to plans are made every week, and this requires more communication. In chapter three, scheduling and rescheduling will be discussed in more detail. In this chapter, the importance of reducing the amount of time a schedule needs modification will be clear. However, the schedules of the packaging department are out of scope and are considered as given. Contrary, the mixing department can consider disturbances in the production process at the packaging lines, and this could result in less re-scheduling at the mixing department.

Phase four: the mixing planners receive every week multiple lists with production runs. The mixing planners need to analyse how many to produce, and the progress is not digitally logged. Also, the mixing planners only receive information about to-be-produced CUCs and need to create an optimal schedule of producing base mixes. The scheduling of the mixing operators is based on common sense and experience. There is no optimization method used in this phase. Also, the communication between the packaging planners and the mixing planners is very poor.

Besides the flaws within the phases of the production planning process, there is another flaw that affects all phases. Namely, only once in the whole planning process, an optimization method is used. When it is necessary to alter plans, the new plans are not created using any optimization method.

Summarized, three main problems can be defined within the planning process, (i) not optimal production cycles, (ii) not optimal (re-)scheduling of the packaging lines, (iii) poor (re-)scheduling of the mixing lines, and (iv) little use of optimization methods.

2.2. Key factors and components production process

An answer to the first sub-question will describe the key factors and components of the production process. The focus of this research will be on these factors.

Critical Performance Indicators (CPIs)

The two most important overall efficiency and effectiveness figures of the plant are the Overall Equipment Effectiveness (OEE) and the Machine Performance (MP). The MP and OEE for every machine in the packaging department is known.

The figures are defined as follows:

$$OEE = \frac{Total\ amount\ of\ time\ producing}{Total\ available\ working\ time} = \frac{Total\ amount\ of\ time\ producing}{All\ time - holidays - weekend\ days}$$

$$MP = \frac{Total\ amount\ of\ time\ producing}{Total\ planned\ working\ time} = \frac{Total\ amount\ of\ time\ producing}{All\ time - holidays - weekend\ days - planned\ stops}.$$

Currently, the plant cooks base mixes 24 hours per day, seven days per week. Also, the plant packages products in two shifts daily, only on working days. The organisation desires to increase the capacity of the packaging department by implementing three shifts daily and, also, packaging at the weekends such that both departments produce 24/7. This is the so-called future production situation of the plant.

Only figures about the mixing department will be given in more detail in this report since the packaging department is out of the scope.

Later in this chapter, it will become clear that, currently, the mixing department's capacity is greater than of the packaging department. Therefore, the mixing department frequently does not need to produce any base mixes. This is called the idle time of the mixing department. therefore, the idle time is considered in the calculation of the OEE of the mixing department.

Since no data on the unplanned losses, auxiliary losses, and maintenance losses are available specifically on the mixing department, the same distribution of planned losses, unplanned losses auxiliary, losses, and maintenance losses as for the packaging department will be used.

The mixing department operators seven days a week, therefore, the OEE of the mixing department is stated as follows:

$\frac{Total\ amount\ of\ time\ producing}{All\ time - holidays - idle\ time}$, which is the same as:

$$\frac{Total\ amount\ of\ time\ producing}{Total\ available\ working\ time - (Total\ available\ working\ time - Total\ amount\ of\ time\ producing - losses)} = \frac{Total\ amount\ of\ time\ producing}{Total\ amount\ of\ time\ producing + Losses\ (in\ time)}$$

Material waste

Besides effectiveness and efficiency, the focus is on material waste (reduction). For material waste, the following categories can be defined: base mix, chunks, cups/ lids, sauce, and packaging. Waste is caused, for example, by having to discard material at the beginning of a run, at the end of the run, or whenever a base mix is already cooked and there is no place to process the product. Whenever a base mix is completely cooked and distributed to an aging tank, the mix needs to be processed within 72 hours. After this period, the mix must be discarded or needs a quality check and improvement.

Products and materials

To analyse the current situation, first, it is necessary to understand the product portfolio of the organisation. The current portfolio consists of 257 SKUs. These 257 SKUs consist of 20 base mixes, and these are packaged in four different packaging units (tubes, mini-tubes, buckets, and MAD packaging). MAD stands for Magnum After Dinner. This is a separate line, which becomes clearer after reading the next paragraph. In total, there are 80 CUCs[4]. One CUC consists of products that are the same but differ in packaging. For example, a tube of Cookie Dough ice cream for Spain and a tube of Cookie Dough ice cream for Asia are two different SKUs but are the same CUC. So, cookie dough 4.5L is not the same CUC as cookie dough 0.45L. The difference between these two examples is separated by clusters. In total, seven different clusters are supplied by the plant. Each cluster has its own package with different languages. Therefore, every cluster provides an extra CUC and, therefore, also an extra SKU per flavour.

Between these SKUs, there are many similarities. For example, the SKU 'cookie dough' and the SKU 'Cookie Dough Swich up' both have the base mix vanilla, cookie dough and chocolate chip cookies but the second SKU has an addition of an extra 'swirl' ('Chocolatey cookie swirl') to the original cookie dough flavour/ mix.

The production process is mainly dividable into three phases, the pre-mixing phase, the flavour adding phase, and the packaging phase. See in Table 2 the number of products to be divided per phase.

[4] CUC = Customer Unit Cluster

Table 2 - Division products

Phase one (pre-mixing)	Phase two (flavour adding)	Phase three (packaging and clustering)	
20 base mixes	48 flavours	80 CUCs	257 SKUs

So, phase two consists of adding additional flavours to the base mix, which results in having 48 flavours. This is done by adding C&S's. In total, there are 28 chunks and 35 swirls. The costs of the chunks and swirls are about the same and are therefore not included in this research.

In phase three, the ice creams are packaged. As mentioned, there are three (plus the MAD-SKU) packages, which result in having 80 CUCs. Every package has its own language for every cluster, which results in having 257 SKUs. As can be obtained, not all flavours are sold in all packaging units nor clusters.

In Table 3, the number of CUCs per specific packaging is given. For example, there are 11 different CUCs that have a volume of 0.1 litres.

Table 3 - Division CUCs

0.1 Litre CUCs	0.5 Litre CUCs	4.5 Litre CUCs	MAD
11 CUCs	48 CUCs	20 CUCs	1 CUC

Lines and machines

The complete production process is as follows:

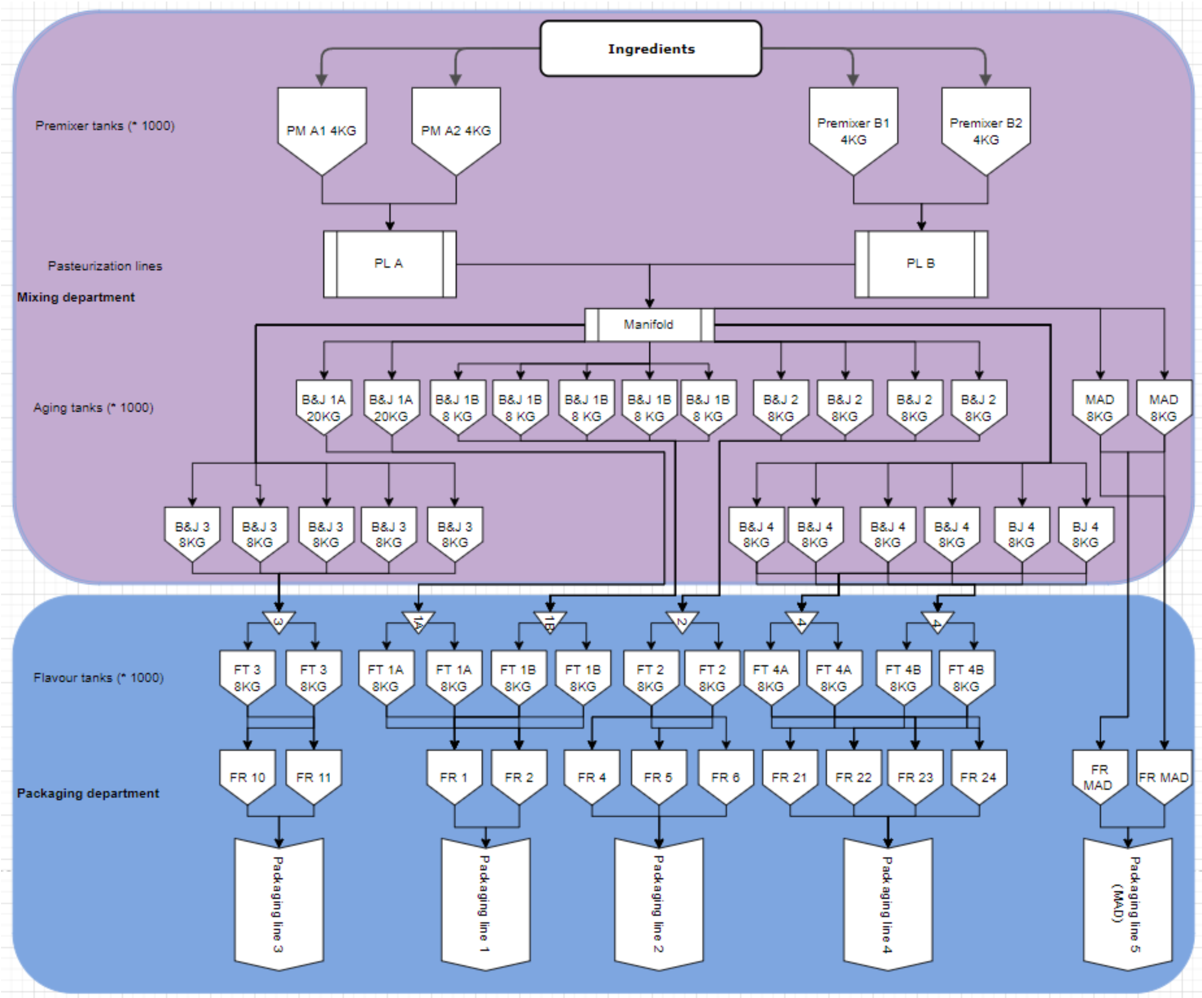

Figure 5 - Flowchart production process

The plant has a discrete distinction between the mixing department and the packaging department because of, for example, the possibility to produce allergen products at one and non-allergen products at the other. The distinction between the departments is clearly shown in Figure 5. The

As can be obtained from Figure 5, there are four pre-mixers where the base mixes are cooked, two pasteurization lines, and a manifold that directs the base mixes to the aging tanks (ATs). The capacity of the components of the production process is indicated (for example, the capacity of pre-mixer A1 is 12000 KG). The aging tanks are buffer tanks in front of the flavour tanks. In total, there are 24 aging tanks. The aging tanks with the name 'MAD' are buffer tanks specifically and only for the Magnum After Dinner-line. From the buffer tanks, the main mixes go to the flavour tanks (FTs). There are 12 FTs which are directly connected to the ATs. At the flavour tanks, the extra flavours are added, the chunks and swirls. This is done via sauce lines (SLs). From this phase, the ice cream is seen as a CUC. After the additive flavouring, the ice creams are cooled to minus five degrees. This is done by ammonia treatment. Each line has multiple freezers (FRs) for this treatment. So, in total, there are 13 Firs' After freezing the ice cream, the ice cream is packaged at the packaging lines. After this phase, the ice creams are considered SKUs. There are five packaging lines in total, where again, there is one line completely dedicated to the MAD product.

Mixing lines are the parts of the production process from the pre-mixers until the packaging lines. After this, it is considered packaging lines.

Currently, mixing line one produces 0.5-, and 4.5-litre tubes, mixing line two produces 0.5-litre tubes, mixing line three produces 0.1-litre tubes, mixing line 4 produces special products like products with extra restrictions due to allergens, such as peanuts and dairy. Mixing line 5, also called the MAD line, produces only one product, the Magnum After Dinner. It is not possible to change this set-up.

Planned stops

As mentioned above, the goal is to minimize changeover times by sequencing products in such a way the number of changeovers is minimized. However, mixing lines and packaging lines must be shut down for sequence-based changeover the lines. After every product change at a mixing line, the line needs to be cleaned. In Appendix A, a changeover matrix of the pre-mixers and the pasteurization lines is given. When for example, product '67408487' is going to be produced after product '67408485', then cleaning 'Pre mixer spoeling + X3' needs to be performed.

Disturbances and unplanned stops

The OEE and MP are strongly influenced by disturbances, shortages of employees, and (delayed) changeovers. The time lost due to the shortage of materials also influences the OEE and MP. Per line and per machine, it is known how many minutes of time each component has lost.

2.3. Characteristics of key factors and components, goals, and gaps

Important for further research is to know the characteristics of the key factors discussed in the previous paragraph. These key characteristics will be input for a model to be developed.

Critical Performance Indicators (CPIs)

Currently, the Year-To-Date (YTD) OEE is 58.3%, and the MP YTD is 76.5%. The goal of the OEE is 63.6%, and the goal of the MP is 81.1%. So, the gap between the current and desired situation is 5.3% for the OEE and 4.6% for the MP.

The main reasons for lower scores on OEE and MP figures are mainly caused by planned stops, unplanned losses, auxiliary losses, and maintenance losses. The percentages given below are the shares of the categories to the total time lost. The figures are obtained by analysing the performance of the whole plant over 2021. There is no accurate data available on the mixing lines specifically. Currently, the packaging department has determined efficiency and scrap figures per product, which are taken into consideration when creating schedules. These figures are fixed and are also the input for scheduling the mixing lines.

- Planned stops: for cleaning purposes, the lines are stopped after every product change (49.5%)
- Unplanned loss: breakdown and equipment failure time + minor stoppages and idling time + defects & rework + measurement & adjustment (14.8%)
- Auxiliary loss: process failure time + shortage of operators + material availability at line-side loss (21.2%)
- Maintenance loss: maintenance time + cutting blade change + shortage of utility + equipment process trial and modification time (14.5%)

In Figure 6 and Figure 7, the most important figures are visually represented.

As mentioned, not much accurate data on the performances of the mixing department are available, however, the total changeover time per week of the department and the total operating time per machine is known. The average total changeover time of all pre-mixers and pasteurization lines per week in 2021 was 6212 minutes. The average total combined operating time of all pre-mixers and pasteurization lines was 14885 minutes. The distribution of losses of the packaging department is used to determine the losses for the mixing department. The average total lost time (planned, unplanned, auxiliary, and maintenance losses) in 2021 was then 12549 minutes ($\frac{6212}{0.495}$).

Therefore, the OEE of the mixing department in 2021 was $\frac{14885}{60480-(60480-14885-12549)} = \frac{14885}{14885+12549} * 100\% = 54.3\%$.

The goal of the organisation is, as mentioned, 63.6%. Therefore, the gap between the current and desired OEE of the mixing department is 9.0%.

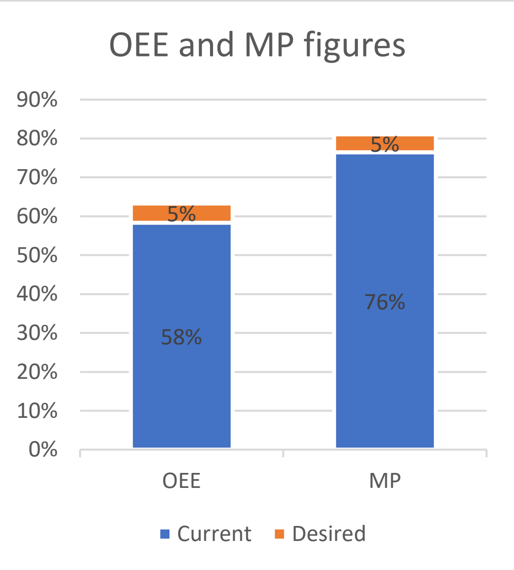

Figure 7 - OEE and MP figures

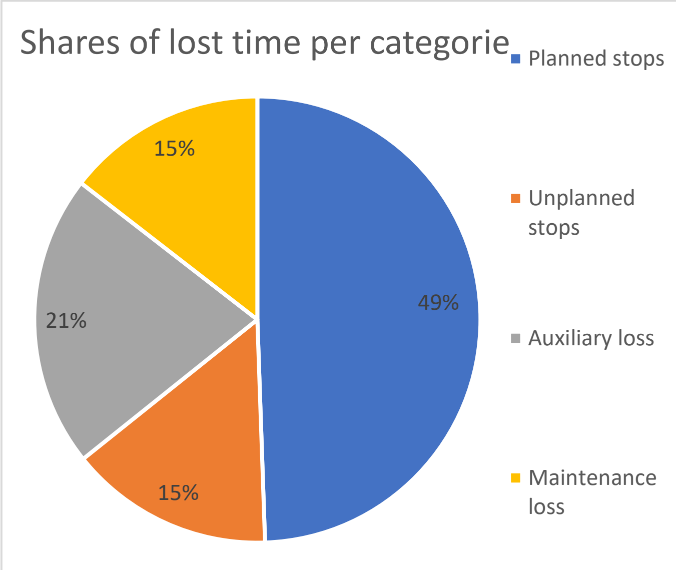

Figure 6 - shares of lost time per category

Material waste

To monitor the waste, Ben & Jerry's uses the term 'Zero Based Waste' (ZBW). This is the total waste compared to the total amount produced. The ZBW target is 5.70%, and the ZBW YTD is 6.46%, so there is a difference of 0.76%. In the next paragraph, this will be discussed in more detail.

Products and materials

The plant has different types of waste, namely mix, chunks, raw materials, sauce, and MAD chocolate. The amount of waste of these products is determined by comparing the input with the output (finished products). Within the production process, materials and (semi-finished) products are spilt. For example, when a mix is being poured into pints, then some part of the mix is spilt. In 2020 and 2021, it happened only twice that materials and (semi-finished) products were discarded because of exceeding the 72 hours limit. Therefore, waste of materials and (semi-finished) products is out of the scope of the research.

To be able to model properly, distributions of the following variables of products and materials will be used:

- Mixing time per mix per pre-mixer
- Processing time per mix per pasteurization line

Also, information about how products can be disaggregated is needed to model properly. Product disaggregation means that products are split up into base mixes and added C&Ss.

Ingredients

The total percentage of lost time due to shortage of raw materials (YTD) is 0.46%. Therefore, it is assumed in this research that raw materials are always present.

Lines and machines

To be able to find the bottleneck of the production process and to schedule properly, knowledge about the capacity of individual components of the production process is needed.

Capacity components mixing lines

The theoretical capacity of the machines of the mixing lines is given in Figure 5. Every machine has its own performance, which influences the true (realised) capacity. The pumping speed between all components is the same for all and is set at 12,000 litres per hour, and the pipes have never been subjected to disturbances. So, it is assumed as given that the pipes always work and can process 12 litons per hour.

Currently, there is no accurate data available on the machine performance of individual machines in the mixing department. For the sake of finding the bottleneck of the production process, the components of the mixing lines are set to 100%. When necessary, the MP of the components of the mixing lines can be adjusted to further evaluate the bottleneck of the production process. Hence, the true capacity of the mixing department is lower.

As can be obtained from Table 4, the total processing capacity of the mixing department is around 17.234,12 litres per hour on average. The total processing capacity is strongly affected by pasteurization line A (PL A) and pre-mixer B2 (PM B2). Those machines are the current bottlenecks of the production process because the capacity of other machines on the same lines is greater. Therefore, the sum of these components is the capacity of the mixing department. All products can be cooked in all mixers. All ice mixes can be stored in all flavour tanks, except for the MAD product. The total storage capacity is 184,000 litres. This is the sum of the aging tanks.

Table 4 - Capacity mixing department

Machine of mixing department	Tank capacity (litres)	Processing time per batch (minutes per batch)	Processing time (litres per hour)	Total actual capacity (without changeovers) (litres per hour) (assumed MP: 100%)
PM A1	4,000	20.77	11,555.13	11,555.13
PM A2	4,000	21.40	11,214.95	11,214.95
PM B1	4,000	31.44	7.633,59	7.633,59
PM B2	4,000	33.10	7.250,76	7.250,76
PL A	-	24,04	9.983,36	9.983,36
PL B	-	28,16	8.522,73	8.522,73
Manifold	-		12,000	12,000
B&J 1A (2x)	20,000		-	-
B&J 1B (2x)	8,000		-	-
B&J 2 (4x)	8,000		-	-
B&J 3 (5x)	8,000		-	-
B&J 4 (5x)	8,000		-	-
MAD (2x)	8,000		-	

Total processing capacity				7.250,76 + 9.983,36 = 17.234,12
Total storage capacity	184,000			

From Table 5, it can be stated that the total current processing capacity of the packaging lines is around 18,258.74 litres per hour. The total actual capacity per line is determined as follows: the quantity of one product (e.g., 0.465L) * units processable per hour * MP of the line * (1 + scrap of the line). So, the scrap is added to the capacity because the scrap is processed, and the mixing department needs to consider the scrap when supplying the packaging lines. All figures are averages. In the desired situation, after reaching the MP goals, the packaging lines can process a total of around 19,468.99 litres of ice cream per hour.

Table 5 - Capacity packaging department

Line	Package	Units processable (per hour): best case	MP of line	Scrap	Total actual capacity (per hour and without changeovers)	Total desired capacity (MP: 81.10%)
1	0.465L pints	10,800	73.9%	2.0%	3788	4150
	Four.5L bins	1,116				
2	0.465L pints	12,600	74.9%	1.9%	4467	4835
3	0.1L cups	18,000	76.9%	3.2%	1428	1505
4	0.465L pints	14,400	79.5%	1.5%	54034	5506
MAD	0.35L package	12,000	73.9%	2.1%	3171	3474
Total current processing capacity without scrap					18,259	
Total desired processing capacity without scrap (MP: 81.10%)						19,469

Planned stops

As discussed in Paragraph, 2.1, fixed changeovers are set for every product change per machine in the mixing department. In total, see Table 6, there are five different cleanings. These durations of cleaning are fixed.

Table 6 - Cleanings

Number	Name	Duration (seconds)
1	X5 benodigd	300
2	Pre mixer spoeling + X5 benodigd	360
3	Pre mixer spoeling + X3 benodigd	720
4	Complete installatie reiniging benodigd	5400
5	Complete installatie reiniging benodigd incl. handmatige reiniging mangaten/ mangatpakkingen *Z3 en premixcip)	7200

It is always allowed to perform cleaning with a higher number than needed but is not vice versa.

Disturbances and unplanned stops

Due to the late implementation of a data collection tool, there is currently no reliable data on disturbances and unplanned stops at the mixing department. Therefore, for verification purposes, the report will study distributions, random numbers, and different scenarios. However, it is known how many times the mixing schedules were altered in 2021. This was 302 times, which means the mixing planners re-scheduled, on average, 5.8 times per week.

In 2021, on average, there were 5.7 versions of packaging production plans per week. Hence, production plans are altered 4.7 times a week. In the next paragraph, it will be clear how these alterations affect the mixing department.

2.4. Bottleneck of the production process

when a research goal is to increase efficiency by increasing utilization, the goal normally is to optimize the utilization of the bottleneck. At the present time, the focus group is not completely sure about what the bottleneck of the production process is. The expectation is that the bottleneck is either the pre-mixers or the pasteurization lines. This uncertainty will be solved in this paragraph.

Capacity current situation:

- Mixing lines: $17.234 * 24 * 7 = 2.9 \text{ million litres}$ per week
- Packaging lines: $19{,}097 * ((24 * 5) + 16) = 2.6 \text{ million litres per week}$

Capacity desired situation (24/7 producing at the packaging lines and desired MP goals accomplished)

- Mixing lines: $17.234 * 24 * 7 = 2.9 \text{ million litres per week}$
- Packaging lines: $19{,}097 * 24 * 7 = 3.2 \text{ million litres per week}$

In the current situation, the capacity of the mixing lines is sufficient to supply the packaging lines because there is an excess capacity at the mixing lines relative to the packaging lines. However, in the future desired situation, the bottleneck will be within the mixing department because, in the desired situation, the packaging lines will have a greater total capacity than the mixing lines.

As described in Paragraph 2.2, the bottlenecks of the mixing department are pre-mixer B2 and pasteurization line A, with a processing capacity of 7.251 and 9.983 litres per hour, respectively.

2.5. Desired utilization optimization

The desired utilization optimization of this research will be the utilization of the mixing lines. The current bottlenecks are pre-mixers B2 and pasteurization line A. However, when only considering those two components, the total capacity of the mixing department could possibly not increase. This is because when only maximizing the utilization of those two components, the utilization of the other machines in the mixing department will be neglected.

An important note to the preferred objective is the consideration of the due dates of the mixing lines. The packaging lines are the most important and most costly components of the plant. Because of that, the goal of the mixing department should always be to ensure that the packaging lines can produce. When the flavour tanks attached to a packaging line are empty, the packaging line cannot produce.

The maximization of the utilization of the mixing lines' components will not affect the flexibility of the plant, nor will it result in very large queues because the (re-)scheduling horizon of the mixing lines will be less than four weeks, the mixing department will only produce what the packaging lines can process, and because the planning of the packaging lines will be constantly evaluated.

2.6. Conclusion chapter two

The board of the plant has set goals for desired figures like Machine Performance and Overall Equipment Efficiency. The gap between at the packaging department the current and desired situation is 5.28% for the OEE and 4.62% for the MP. The gap at the mixing department between the desired OEE and the current OEE is 9.0%. Only the OEE can be improved by improving the utilisations of machines.

Besides the current problems faced, the plant is going to increase the capacity of the packaging lines. This results in a future situation where the mixing lines will be the bottleneck of the production process. Since there is no optimization for (re-)scheduling the mixing lines, this is seen as the most important problem of the production process. Currently, the bottlenecks of the mixing department are pre-mixer B2 and pasteurization line A. Therefore, an optimization method to (re-)schedule the mixing lines will be created. The goal of this optimization method is a combination of ensuring delivery to the packaging lines on time and maximizing the utilization of the pre-mixers and the pasteurization lines.

Besides the flaws of (re-)scheduling, several flaws in the planning process are discovered. These flaws are (i) non completely optimized production cycles, (ii) not completely optimized (re-)scheduling of the packaging lines, and (iii) little use of optimization methods. Further, in this research, those flaws will not be considered since it is out of the scope.

For future notice, where the packaging lines will operate 24/7, the packaging planners will still make initial schedules for the next week. So, an initial schedule for the mixing department needs to be created after the packaging planning is done (typically on Friday) and before every Monday. For the re-scheduling of the mixing department, there is less time available. Therefore, it is important to consider and constantly evaluate running time in this research.

In the next chapters, relevant literature about (re-)scheduling will be studied. The next two chapters should contain information about:

- (Re-)scheduling model of maximizing the utilization of a component or multiple components of a production process
    - A model should consider decision variables like utilization, lateness, processing times, etc.
- Consideration of due dates
- Consideration of lateness
- Robustness of the schedules
    - By creating, for example, time buffers, which could be necessary since there are uncertainties in the production process
- Running time of the (re-)scheduling model
    - The available time when re-scheduling is a lot less compared to initial scheduling. Therefore, the consideration of running time is important. A simplified model for re-scheduling purposes can affect the solutions, and that affection should be evaluated.
- How disaggregation of SKUs can be incorporated in the making of schedules
    - Since there are many similarities among SKUs, and CUCs (base mixes are often similar), this should be incorporated into a model to be developed
- A model should make solutions where the following will be incorporated:
    - Job allocation to machines
    - Sequences of jobs on machines
    - Cleanings (changeovers) on machines: sequence-based and basic protocol

- Consideration of restrictions: e.g., non-dairy products cannot be produced on mixing line A

- A rescheduling method needs to be triggered to execute the new scheduling process. The trigger of when the scheduling process needs to be executed again needs to become clear. Examples are postponement of a production run at a packaging line, shortage of personnel, etc.

3. Literature review

In this chapter, literature research about the most important and relevant approaches of scheduling and simulation for this specific case will be conducted. An answer to research question two, 'What (re-)scheduling methods are the most appropriate for this specific problem to be in line with the desires of the organisation?' will be given.

3.1. Manufacturing planning and control framework

All planning and scheduling activities can be combined into an umbrella term of Manufacturing Planning and Control processes, short MPC processes. According to (Alexander Howard, 1999) , there are four different managerial areas, technological planning, resource capacity planning, material coordination and financial (which is omitted). Traditionally, scientists speak of three different hierarchical levels of control. Nowadays, the hierarchical levels of control are dividable into four categories, strategic, tactical, offline operational and online operational. This is mainly interesting for operations management, so also for this assignment. Figure 8 shows the responsibilities per hierarchical levels and managerial areas.

Strategic decisions have a horizon of usually one to two years, tactical planning concerns weeks/ months ahead, and operational activities usually capture decisions for the upcoming days/ weeks.

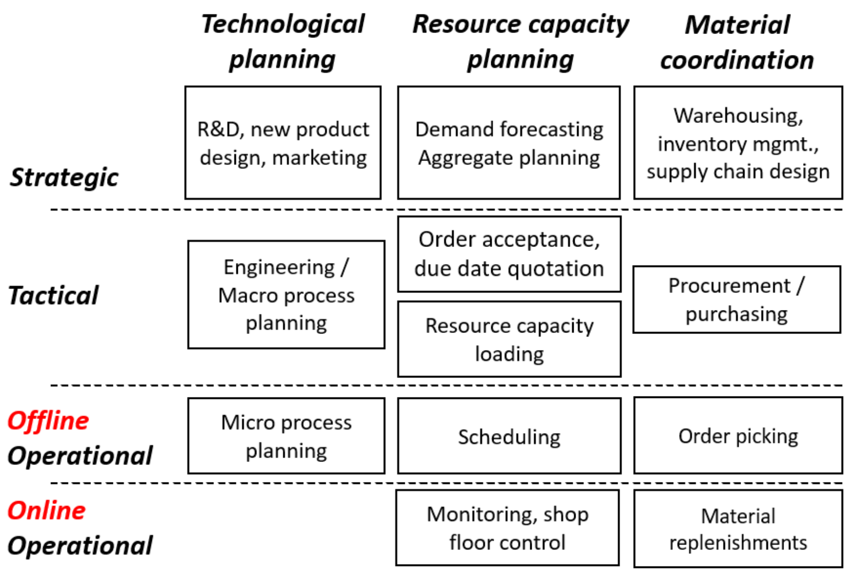

Figure 8 - Manufacturing Planning and Control framework

The scope of this research is within the offline and online operational levels in the resource capacity planning area.

Planning

Within the planning & scheduling philosophy, the distinguishment is made between planning and scheduling. In the literature, planning is used for strategic & tactical production control and scheduling for operational production control. Scheduling/ planning is the activity, and a schedule/ plan is the result.

Order acceptance is done at the tactical level of the company, where the planners are responsible for managing variability. (Pinedo, 2005) claims that planning is to create and cleverly use flexibility to deal with variability in demand and supply. In this research, the set of orders which need to be scheduled is considered as given.

Scheduling

When orders are assigned, the orders need to be scheduled. Given the assigned workload and given the available resources, the work needs to be planned within the given time frames. It is important to consider which objective for the scheduling process is most suitable for the company. As discussed in 2.5, the objective of scheduling for this research is to maximize utilization by minimizing the total changeover time. For this research, the available capacity is fixed and given.

Traditional scheduling methods do not have the possibility to split batches into base mixes and flavours, which is relevant to this research because Ben & Jerry's uses a clear distinction between base mixes, flavours, CUCs, and SKUs. When this splitting up of batches is not considered in this research, there will be a loss of utilization because of unnecessary changeovers.

Many scheduling methods are defined in the literature. In the literature, a distinction is made between offline and online operational scheduling. In paragraphs 3.7 and 3.8, this distinction will be discussed.

A schedule σ specifies for each operation O_{ij} a start time $S_{ij}(\sigma)$, for job j and machine i, a completion time $C_{ij}(\sigma)$, processing time p_{ij}, and the machine to which the operation is assigned to. Let Z denote the set of all possible schedules. Also, important constraints are setup times $s_{ij,ik}$, which will be the changeover times between operations O_{ij} and O_{ik}. When operation O_{ik} is scheduled after O_{ij} on machine *i,* then $S_{ik}(\sigma) = C_{ij}(\sigma) + s_{ij,ik}$. In the literature, release dates are often used. Because it is assumed ingredients are always present, there is no need to consider release dates now. However, when necessary, it can be added to the model.

Due dates d_j are typically considered hard constraints in the literature, but the importance of due dates can also be incorporated into the objective function to evaluate methods. This basically means that a schedule that causes lateness is feasible, but the schedule is worse than when no lateness occurs. For example, when a job is delivered late to a packaging line by the mixing department, a penalty can be given for every minute the job is late.

In this research, due dates are the time at which a job is planned at a packaging line. The processing times at both the mixing lines and the packaging lines are uncertain. However, because of the lack of accurate data on the performance of the mixing department and because the uncertainty of the processes of the packaging lines is out of scope, the processing times are considered deterministic. The average processing time ap_{ij} per job and per machine is investigated and will be used. Because of that, completion times of jobs are deterministic as well. So, processing times, completion times, and due dates are deterministic.

Since the goal of the model is a combination of ensuring delivery on time and maximizing utilization of the pre-mixers and the pasteurization lines, the objective of this research will also be a combination of these aspects. The objective function will be explained in chapter four.

The costs of changing over a machine or multiple machines are small and will not affect a solution. Therefore, it is not included in the objective function.

For future research, it will be assumed that the costs of downtime, because of lateness of the mixing department, at the packaging department are always higher than the costs of lower utilization at the mixing department.

Parallel machine scheduling problems are considered NP-hard[5], even in the strong sense. This means that it is even very unlikely that pseudo-polynomial algorithms can be created or found for these problems.

To cope with this problem, heuristics are created. A heuristic does not guarantee an optimal solution. One example of such a heuristic is Priority rule scheduling, which will be explained in 3.3.

3.2. Job shop machine environment

Four different basis typologies of machine environments can be described, (i) single-machine: a job consists of one operation to be processed on one machine, (ii) parallel-machine: a job with one operation can be processed on m machines, (iii) flow shop: a job consists of m operations, and there are m machines, where the sequence of operations are the same for all products, but an operation can only start when the previous operation is finished, and (iv) job shop: a job consists of m operations, and there are m machines, and the sequence of jobs can differ (H.C. Lee, 1997).

Because a pre-mixer can cook the next mix while another pre-mixer is already cooking and all products are to be produced by the mixing lines, it can be concluded that the machine environment of the mixing department of Ben & Jerry's is best described as a job shop machine environment. Generally, the sequence of operations can differ. For Ben & Jerry's, the sequence of operations is the same for all SKUs except for the MAD product.

3.3. Priority rule scheduling

Numerous heuristics are described in the literature. As mentioned, the costs of downtime of the packaging lines are way higher than the costs of lower utilization of the mixing lines. So, supplying the packaging lines on time has a way higher priority for the mixing department than having a higher utilization. Therefore, the priority value of an operation is based on the Earliest Due Date (EDD) rule (Haupt, 1989). The rule has the objective of minimizing lateness. The rule is local and static, which means only information about the current operation and the machine on which the operation is processed is used, and the priority values of operations do not change during the execution of the priority rule.

The priority value of P_j will be calculated as follows: $P_j = \min_i \{ d_i \}$, where *i* is part of a set of to-be-assigned jobs and is removed from this list once assigned a priority value.

This heuristic will find a solution with a little or possible zero lateness but possibly not an optimal one. However, the utilization of the mixing lines will probably be poor when using a heuristic that focuses on lateness. Therefore, optimization techniques will be used.

3.4. Generation scheme

A generation scheme is a method that creates schedules. In a parallel generation scheme, a job with the highest priority value that is not assigned to a machine is going to be assigned at the next available time slot. An addition can be made by restricting the choice of assigning jobs.

3.5. Optimization techniques

As mentioned in the previous section, it is not guaranteed that a heuristic will find an optimal solution. After finding a feasible solution with the heuristic, local search techniques can be used to

[5] NP-hard means Nondeterministic Polynomial hard problems, which basically means that it is suspected that there are no algorithms that can solve the problems in polynomial time because of infinite number of solutions

improve the initial schedule. A local search technique uses operators to make small changes to a solution to improve the solution step by step. Mainly, four operators can be described:

- Move operator: a job is moved to another machine or to another place in the sequence of jobs of a machine
- Swap operator: two jobs are swapped with each other
- Split operator: a job is split into two different jobs
- Merge operator: two jobs are merged as one job

Important when considering operators is to consider connectivity. An operator enables connectivity if the operator ensures that all possible solutions can be created. An example: consider a parallel machine scheduling problem where the current solution has scheduled 15 jobs on machine A and 15 on machine B. When using the swap operator, neighbour solutions will always have 15 jobs on machine A and 15 on machine B as well. So, a swap operator does not enable connectivity.

As mentioned, it is important to consider the fact that many SKUs consist of the same base mix. A move operator can be very beneficial because, when executed enough times, jobs can be clustered. This means that jobs with the same base mix can be process consecutively. A merge operator is not relevant because jobs consist of 4,000 litres. This will be explained more in detail in chapter five (Pinedo, 2005). A split operator cannot be beneficial because the processing time will not decrease when splitting.

A new schedule that is different from the previous, because an operator performed a change, is called a neighbour (solution) to the previous solution. At every performance of an operator, which is called an iteration, the optimization technique evaluates one or multiple neighbours, depending on the technique. The neighbour solution can then be accepted or declined according to some rule. This rule is based on the objective function of the model. The purpose of using an objective value is to compare schedules, where the goal is to find a schedule with the best objective value.

The two most used local search algorithms are simulated annealing and tabu search (Farnane et al., 2018). These are both advanced local search techniques because they can escape from a local optimum. This means that these techniques can accept worse outcomes to arrive at a better local optimum or a global optimum. Basic local search techniques do not have this feature. In the next paragraph, an explanation of simulated annealing will be given. Tabu search uses a tabu list which contains information about solutions that should not be considered again. This list grows rapidly, and many rules should be made to benefit from this technique. Simulated annealing is, according to Farnane et al. (2018), more efficient in most research. Therefore, simulated annealing is going to be used in this research.

3.6. Simulated Annealing

Simulated annealing is an algorithm that starts with a feasible solution X^c, which in this case would be the costs of lateness plus the total changeover time of the mixing lines. The objective value of the current schedule is then $E(X^c)$. The next step is where operators come in. By using one or multiple operators, a neighbour solution X^n is created, and the objective value of the neighbour solution is $E(X^n)$. So, for example, when a swap operator is used, the neighbour solution is the same as the current solution, except for two spots in the schedule, because two jobs have swapped positions.

Thereafter, the neighbour solution is evaluated: if $E(X^n) \leq E(X^c)$, then $E(X^c) = E(X^n)$, and $X^c = X^n$. This is called 'accepting the neighbour solution'. If $E(X^n) > E(X^c)$, then with a probability, the neighbour solution is still accepted. The probability is calculated as follows: $e^{\frac{(X^c)-E(X^n)}{T_i}}$, where T_i is a so-called temperature and operates as a control parameter. The worse solution is accepted when the probability function result is $> y$. Because the objective value of a solution is determined by combining two costs, the impact of setting the costs should be chosen and evaluated wisely.

So, the probability of accepting a worse solution depends on T_i, and T depends on i, where i reflects the current number of temperature changes. The temperature increases with every iteration until it reaches the end of the Markov chain length, m, at M. Then, the temperature cycle restarts. The next temperature is calculated as follows: $T_{i+1} = a * T_i, a \in (0,1)$.

The objective of the temperature is to balance the divergence and convergence function of the model. In the beginning, the model will accept with a greater probability a worse solution (divergence phase), and later the model will only accept better solutions (convergence). The probability of accepting a far worse solution is relatively small because it is still a neighbour solution, and a neighbour solution is very similar to the current one.

The model will run until a stopping criterium is met. Many stopping criteria are used in the literature, such as stopping the model when the temperature reaches a certain point or the number of iterations with no improvement. The stopping criteria should also be chosen and evaluated wisely.

In Appendix 0, a visual overview of the functioning of simulated annealing is given.

3.7. Offline operational scheduling

Offline operational scheduling means scheduling when the system is not running (Fohler, 2011).The basic is a given set of orders that need to be scheduled according to the objective to maximize utilization. When considering the current planning process of Ben & Jerry's, the initial schedules of the mixing lines (with the packaging plans as input) could be seen as the offline operational schedules.

Because there should be enough time to execute the model, the complete model, as described in the previous paragraph, will be executed to come to an optimal schedule.

3.8. Online operational scheduling

Online operational scheduling is when the system is running, and a scheduling decision needs to be made. Whenever a job arrives or a set of orders changes, an immediate decision must be made. The re-scheduling process of the mixing planners could be best described as online operational scheduling.

As already mentioned, the importance of time (urgency) is higher in online operational scheduling than in offline operational scheduling. Therefore, running time will be constantly considered. In situations where re-scheduling is necessary, and there is not enough time to execute the complete model as described in paragraph 3.6, the model should be reduced in complexity to be able to find a reasonable result in less time than needed. However, it could be possible that a reduction of the model's complexity will not be necessary. Then, the complete model, as described in paragraph 3.6 will be executed for re-scheduling purposes as well. For example, when a schedule needs to be modified, it is possible that already a part of the schedule is executed. Therefore, the complexity of the re-scheduling process is decreased. Also, when re-scheduling is necessary, and already a part of the schedule is executed, it is possible that the number of possible solutions is much less (e.g., Aging tanks could be full, due dates are changed, etc.).

To evaluate the performance of the (newly created) online operational schedules when using a simpler (reduced in complexity) model, the online operational schedules can be compared to the offline operational schedules.

3.9. Conclusion chapter three

The answer to research question two, 'What (re-)scheduling methods are the most appropriate for this specific problem to be in line with the desires of the organisation?', can be summarized as follows:

- A model will be developed that creates in the first step a reasonable schedule according to the priority rule 'Earliest Due Date (EDD)' for initial scheduling.
- The model will be optimized using simulated annealing.
    - In this step, optimization operators like 'swap' are used
    - The choice of which operator will be made when the model is ready for evaluations
    - Also, when the model is ready for evaluation, a choice must be made whether simulated annealing is also applicable for re-scheduling purposes.
- Further, it should become clear within this report, whether a scheduling method is also suitable for re-scheduling purposes.
    - When there is enough time to execute the scheduling method, the method will be executed completely
    - If it occurs that there is not enough time to execute the model completely in practice, a reduced model will be used. A model can be reduced in the number of iterations it can execute (further in this report, this will be explained).

In the next chapters, it will become more clear on how complexity and time will influence the model structure for re-scheduling purposes.

4. Model formulation

In this chapter, the problem formulation is described. This is done by explaining the core problem of this research qualitatively alongside the performance indicators. The detailed mathematical model is given in Appendix F. The reason that the mathematical model is not given in the main report is that it is too complex. Also, the problem is approached by using a heuristic and optimization techniques instead of using a MILP.

4.1. Problem context

The core problem of this research is to create (scheduling) and modify (re-scheduling) production schedules for the mixing department. Schedules for the pre-mixers and the pasteurization lines are the output of the scheduling and re-scheduling processes. Since the pre-mixers are directly connected with only one of the pasteurization lines, the schedules of the pasteurization lines should be successive to the pre-mixers that are connected.

As mentioned, the packaging lines far more important than the mixing lines since these are the more costly when not running. Therefore, the planners of Ben & Jerry's create schedules for the packaging department prior to a production week (from Sunday 10:00 pm to Friday 6:00 pm) and alter the schedules during the production week. The schedules for the mixing department need to be created in such a way that the production runs of the packaging lines can always be completed according to the schedules of the packaging department.

This means that the production runs of the packaging department need to be executed exactly as planned, both in size (number of products to be produced) and in the sequence in which it is planned. Thus, the sequence of production runs cannot be altered.

Translation from production plan into job list

As mentioned, the purpose of the mixing department is to supply the packaging department base mix such that the packaging department can produce the products as planned. This means that a production plan of the packaging department determines what product will be produced at what time and how many products will be produced. The production starts exactly at the time as planned. Also, the sequence of the production is fixed. Therefore, the production plan is the main input for the mixing department in terms of producing base mixes. An example of an actual production plan of the packaging department is given in Appendix D. To be able to produce the right (amount of) base mixes on time, the production plan needs to be translated into a job list that the mixing department can work with. This will be explained in this paragraph.

Time >	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00
Line 1	Cookie dough			Maintenance	Netflix & Chilll				
	base mix: vanilla ice cream				base mix: peanut ice cream				
Line 2		Karamel Sutra				Changeover	Cookie dough		
		base mix: caramel ice cream					base mix: vanilla ice cream		

Figure 9 - Example of the production planning of the packaging department

In Figure 9, an example is given of the production planning of two packaging lines for a part of the day. A complete production plan is a one-week plan. In the example, the following is given:

- Line one: the line starts at 08:00 am producing cookie dough ice cream until 11:00 am (so, three hours in total), whereafter there is one-hour maintenance scheduled. Finally, the line produces Netflix & Chill from 12:00 pm until 4:00 pm (four hours in total). The main mix of cookie dough is vanilla ice cream, and the main mix of Netflix & Chill is peanut ice cream.
- Line two: Karamel Sutra with base mix caramel ice cream will be produced from 09:00 am until 1:00 pm, whereafter a changeover will be necessary, and thereafter Cookie

Dough with vanilla ice cream as the base mix will be produced from 2:00 pm until 4:00 pm.

The time that a packaging line is producing a product is called a production run. The total amount of base mix required for one production run is considered an order. An order consists of the base mix, the quantity of the base mix, the time it needs to be ready to be further packaged (starting time + day), and the packaging line for which it is destined. The starting time is the time at which a packaging line starts producing a product. This is the maximum time at which the mixing department must supply the packaging line with the base mix needed for that product. Therefore, the starting time of a production run is considered the due date for the corresponding order.

The quantity of the base mix required is determined as follows: the amount of base mix required to produce one final product (SKU) * the speed of the line (in terms of the number of end products that can be processed per hour) * the total time of the production run in hours. An example (based on Figure 9): cookie dough ice cream will be processed on packaging line one from 08:00 am until 11:00 am. This production run needs the following amount of base mix:

$$0.370L\ of\ vanilla\ ice\ cream\ *\ 10{,}800\ products\ per\ hour\ *\ 3\ hours = 12{,}000L\ of\ vanilla\ ice\ cream$$

The part of the production plan as given in Figure 9, results in the order list given in Table 7:

Table 7 - Example of an order list

Order #	Base mix	Qty base mix	Start time (due date order)	Packaging line
1	Vanilla	12,000	08:00 (mon)	1
2	Caramel	16,000	09:00 (mon)	2
3	Peanut	16,000	12:00 (mon)	1
4	Vanilla	8,000	14:00 (mon	2

The example is only a part of the order list based on a part of a production plan. In practice, a production plan is a plan for a whole week. Therefore, a real order list contains orders for a whole week. The mixing department is responsible for producing the base mixes on time. A base mix is on time when the base mix is completely ready to be processed by a packaging line. When a base mix is completely ready, will be discussed later.

The first task is to translate the order list into a job list for the mixing department. Jobs are the base mixes that the mixing department needs to produce. The amount of base mix required by a production run of the packaging department is almost always much more than the capacity of the pre-mixers, which is 4,000 litres per tank. Therefore, the order needs to be split up into smaller pieces. A smaller piece of an order is called a job. So, a job can be at most 4,000 litres because it needs to be processed on a pre-mixer completely.

The production runs are set to ensure that the amount of base mix needed for a production run is always a multiple of 4,000 litres.

To set an adequate job list, some calculations must be made first and some information must be added to the job. So, the orders need to be split into jobs. The orders need to be split into jobs with quantities of 4,000 litres. This is the current way of working for the plant, and the organization desires to keep doing this. A job contains the following information: base mix, the quantity of the base mix, the due date, and the packaging line for which the base mix is destined.

The due dates of the jobs must be determined. For the first job, the due date is the same as the due date (starting time of the corresponding production run) of the order, see Table 8.

Table 8 - Example of one job

Job #	Base mix	Qty base mix	Due date	Packaging line
1	Vanilla	4,000	08:00 (mon)	1

Then the consecutive jobs of the same order can be determined. The due dates of the consecutive jobs are determined as follows: due date of the previous job of the same order + 4,000 litres / (the amount of base mix required to produce one SKU in litres * the speed of the line (in terms of the number of end products that can be processed per hour)). An example of the second job corresponding to the first order in Table 7.

$$08:00\ (mon) + \frac{4000}{0.370 * 10{,}800} \sim 09:00 (mon)$$

So, the due date of the second job (corresponding to the first order in Table 7) has a due date of 09:00 am on Monday. The complete job list translated from the order list is the following (Table 9):

Table 9 - Example of a job list

Job #	Base mix	Qty base mix	Due date	Packaging line
1	Vanilla	4000	08:00 (mon)	1
2	Vanilla	4000	09:00 (mon)	1
3	Caramel	4000	09:00 (mon)	2
4	Vanilla	4000	10:00 (mon)	1
5	Caramel	4000	11:00 (mon)	2
6	Peanut	4000	12:00 (mon)	1
7	Caramel	4000	12:00 (mon)	2
8	Peanut	4000	13:00 (mon)	1
9	Peanut	4000	14:00 (mon)	1
10	Vanilla	4000	14:00 (mon)	2
11	Peanut	4000	15:00 (mon)	1
12	Vanilla	4000	15:00 (mon)	2

The same applies to the job list as to the order list that a real job list contains jobs for a whole production week. So, the main goal of the mixing department is to supply the packaging lines with the jobs of a job list on time.

Planning process of the mixing department

Before the planning process can be explained in more detail, some assumptions must be made first.

Assumptions

The main assumptions made in this model are the following:

- The process of the mixing lines is considered fixed, and no downtime is considered.
- The sequence and the quantities of the batches made at the mixing department are adjustable
- The choice of which machine to process a mix on is adjustable
- Changeover times are fixed and given

Now it is clear that the purpose of the mixing department is to produce base mixes according to the job list, the way of mixing can be explained. Firstly, it should be explained when a job is delivered to the packaging line on time or too late. The due date of a job (see table …) is the time at which the base mix should be ready to be processed by a packaging line. A base mix is ready to be processed when it has aged for at least two hours in an aging tank. This basically means that the base mix should have been in an aging tank for at least two hours. In these two hours, no other batch can be added to the same aging tank. When it happens that an aging tank which already contains base mix is filled with another batch, the time at which the aging tank is ready is two hours later again (from the moment the second batch was added). It is possible that two or more batches of the same base mix are in the same aging tanks because the capacity of an aging tank is greater than the capacity (batch size) of a pre-mixer tank. So, the mixing department needs to consider aging time when planning and producing base mixes.

To clarify the process of the mixing department, a simplified overview of planning the mixing processes is visually given:

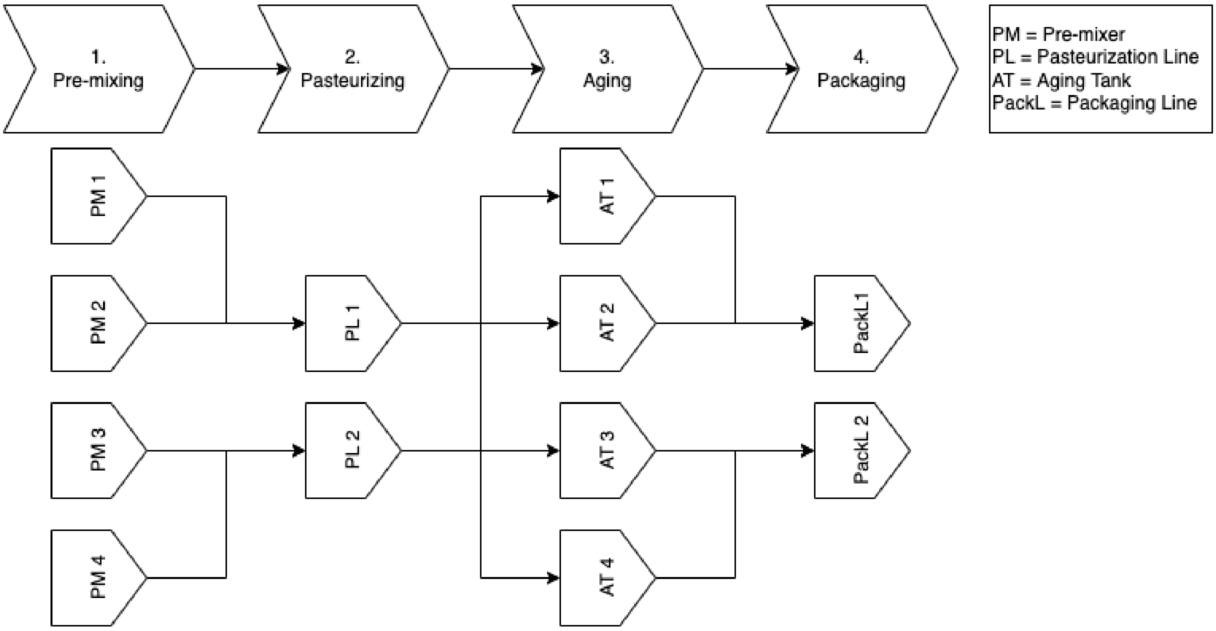

Figure 10 - Planning process mixing department

In the example given in Figure 10, for the sake of simplicity, only four aging tanks and two packaging lines are given. From the figure, the following can be obtained:
The mixing planning process consists of four steps. These four steps are the base of explaining the mathematical model later in this research.

Base mixes that are produced in pre-mixer one or two (this step is called cooking) will always be pasteurized by pasteurization line one. Base mixes that are cooked in pre-mixer three or four will always be pasteurized in pasteurization line two. When base mixes are pasteurized by either pasteurization line one or pasteurization line two, the base mix can be sent to all aging tanks. The aging tanks are linked to one of the five packaging lines and cannot be used by any other packaging line. Therefore, all aging tanks are completely dedicated to only one packaging line.

Steps of the planning of the mixing department

The process of the mixing department is now clarified. The next part to discuss is the degrees of freedom. The degree of freedom is the space of solutions in which decisions need to be made. Therefore, some basic rules and restrictions must be given first.

Step 1: The first step in the mixing process is the assignment of a job (base mix) to a pre-mixer. Therefore, some considerations and determinations must be made.

A pre-mixer can start cooking a base mix corresponding to a job when the destined aging tanks of that job have enough space left to 'receive' the base mix (corresponding to the job). So, before a pre-mixer can start cooking a base mix, it should be first determined whether there is enough space in the aging tanks. When there is enough space left in the aging tanks to send a base mix to, the aging tanks are 'available'. The availability of ATs will be discussed further in more detail in the mathematical model. Besides the aging tanks should be available, the pre-mixer must be available as well. Therefore, the pre-mixer should be empty. Also, when the previous cooked batch on the same pre-mixer is a different base mix than the current to-be-scheduled base mix, the pre-mixer needs to be cleaned.

When the corresponding aging tanks of an order are available, and the pre-mixer is available, the pre-mixer can start cooking a base mix if that base mix can be produced on that pre-mixer. The degree of freedom in this step is within what pre-mixer to choose for producing the base mix.

Step 2: When the cooking of the mixer is done, the attached pasteurization line withdraws the base mix from the pre-mixer tank. There is no choice in this step since all mixes from pre-mixers one and two go to pasteurization line one, and all base mixes from pre-mixers three and four go to pasteurization line two. However, the pasteurization line should be available as well. A pasteurization line is available when it is empty and cleaned (if necessary). When a pasteurization line is not available, the mix will stay in the pre-mixer until the pasteurization line is available again.

Step 3: After pasteurizing a base mix, again, a choice must be made. Now, the choice is what aging tank the base mix should be sent to. An overview of the aging tanks is given in Appendix E. The base mix must be sent to an aging tank of the corresponding packaging line. For example, job one of Table 9 has packaging line one as the destination. Given Figure 10, the base mix should be sent to either aging tank one or aging tank two because these two are attached to packaging line one. A base mix cannot be sent to an aging tank that is currently supplying a packaging line.

Step 4: When a packaging line needs a base mix from the aging tanks, it can happen that more than one aging tank (all attached to the same aging tank) contains the right base mix. Therefore, the last choice to be made is what aging tank is going to supply the attached packaging line. The difference between this step and step three is that in step three, the choice is which AT to fill (partially) with a job that comes from a pasteurization line and in step four, the choice is what AT will supply the attached packaging line. An AT can only supply one packaging line. However, situations occur where more than one AT belonging to the same packaging line is filled with the right base mix for that line. Therefore, a choice must be made about what AT is going to supply the packaging line.

Summarized

Summarising, the complete planning process with the corresponding considerations/ determinations, choices, and limitations are given in Table 10. This table is in line with the four steps of the planning process of the mixing department, as given in Figure 10. The decision number will be used later in 5.1. The numbers between brackets in the table below are included in the mathematical formulation by restrictions also indicated by the same number between brackets.

Table 10 - Decisions, determination, choices, and limitations of the planning process of the mixing department

Step	**Decision/ determination number**	**Choice (freedom)**	**Limitations**
1. Assigning a job to a PM	1. Determine the availability of PMs	All pre-mixers that can process the job	(1) A job can only be sent to a PM when the PM is empty and (2) cleaned if necessary. The job will be assigned to a pm, and then it will be evaluated whether the PM needs to be cleaned. If so, the starting time of which the job will be cooked will be postponed with the time of the cleaning that is necessary. (3) Not all base mixes can be processed on all machines.
	2. Determine the availability of ATs	All ATs that are dedicated to the packaging line corresponding to the job can be considered	A job can only be assigned to a PM when the corresponding ATs of the job are available. ATs, to where jobs can be sent, are either (4) empty or (5) filled with the same mix. (6) In the second case, the AT cannot already supply the attached packaging line.
	3. Decision 1: Assign a job to a PM	What PM to assign the job to	(7) A job must be completely assigned to only one PM. It cannot be split.
2. Pasteurizing the job of step 1	4. Determine starting time of pasteurizing a job	-	(8) When a job is assigned to a PM, the job will always be pasteurized by the attached PL. A job can only be sent to a PL when the PL is both (9) empty and (10) cleaned if necessary. If the PL is not ready to process a job, the job will stay in the PM until the PL is available again.
3. Sending a job to an AT	5. Decision 2: Send a (part of a) job to an AT from a PL.	What AT will the job be sent to? A job can be sent to more than one AT if necessary. It is possible to send a job to an AT before it is needed by the packaging lines.	(11) A job can only be sent to an AT that is attached to the destined packaging line. (12) Also, a job cannot be sent to an AT that is currently supplying a packaging line. (x) It is not allowed to have a job in an AT for more than 72 hours.
4. Supplying the packaging lines	6. Determine the aging tank volumes	-	(13) The total volume withdrawn by a packaging line is equal to the demand over time – the total volume that could not be withdrawn because of late jobs. (14) when a job is late, the demand over time by a packaging line is altered, and so are the (15) due dates of the jobs that will be supplied later.
	7. Decision 3: Send a (part of a) job from an AT to a packaging line	What AT will supply the packaging line	(16) A base mix should be ready to be sent to the packaging lines. (17) Only one AT can supply the packaging line at a time.
	8. Determine if the job is late	-	(18) A job is late when the delivery time exceeds the due date. When a job is late, the packaging line cannot produce any products. Therefore, the due dates of all jobs that are required by the same

			packaging line after the late job need to be updated.

So, it can be concluded that three main decisions need to be made by the mixing department for planning the mixing process. These three decisions are reflected in the mathematical model by three decision variables. The goal is to make these three choices such that the best schedules for the pre-mixers and pasteurization lines are created in terms of lateness and utilization and consider the schedules of the packaging lines as fixed and given.

Lateness

Lateness is when a job is ready (finished aging) to be further processed by a packaging line after its due date. The costs of providing a packaging line with a job late are the same for all packaging lines and are measured in minutes.

Changeover

The organisation desires to optimize the utility of the pre-mixers and pasteurization lines. Typically, utilization means the amount of time that a machine is producing. To determine a proper utilization, this determination is not applicable because the complete order list of a week must be produced. Therefore, it does not matter in what way this order list is planned because all orders must be planned, and the total production time of the machine will be around the same for different solutions. A better way to determine the utilization for this research is to consider the total changeover time. These changeover times are measured in minutes.

4.2. Goal function

Feasible solutions that the model will create are measured by the objective value. As mentioned, the goal is to minimize the total lateness of the jobs and the total changeover time of all machines. How these variables are measured will be discussed next.

Lateness

A job is considered late when the delivery time of the job exceeds its due time: $DeliveryTime_j > DueTime_j$. The total lateness *TotalLateness* of all jobs on the job list is then: $TotalLateness = \sum_{j=1}^{J} max\{DeliveryTime_j - DueTime_j, 0\}$

Currently, lateness in the mixing department occurs almost never because of the excess capacity compared to the packaging department. In 2021, it happened only twice that a job was delivered to the packaging department late.

The reason lateness is used in the model is if it is not considered, then the model will create solutions where many jobs will be delivered late, and a very little total changeover time will be realized. So, lateness in the model can be considered as a penalty to the objective value.

Changeover time

All mixers, pasteurization lines, and aging tanks have the same rules for cleaning, also called changeovers. This is according to the changeover matrix in Appendix …. When a pasteurization line needs cleaning, this needs to be done before producing the next job. It is possible to start cooking a batch in a pre-mixer while the other pre-mixer attached to the same packaging line is being cleaned. Also, it is possible to start cooking a batch in a pre-mixer when the attached packaging line is not yet available to pasteurize that batch.

Costs of cleaning are measured in minutes and are considered fixed and deterministic. The costs of cleaning the machines of mixing line ‘A’ are 1.5 times higher than the costs of cleanings at mixing line B since this line is 1.5 times faster and, therefore, 1.5 times more important. Mixing line 'A' consists of pre-mixers one and two and pasteurization line one. Mixing line 'B' consists of pre-mixers three and four and pasteurization line two.

The total changeover time per pre-mixer is measured as follows: $TotalChangeOverTimePM_{pm} = \sum_{i=1}^{J}\sum_{j=1}^{J} ChangeOverTimePM_{i,j,pm} * x_{i,j,pm}$, where $ChangeOverTimePM_{i,j,pm}$ represents the changeover time between job *i* and *j* on pre-mixer *pm*, and $x_{i,j,pm}$ represents a binary variable which indicates whether job *i* and *j* are produced, successively, on pre-mixer *pm*. The total cleaning time of pasteurization line *pl* is measured as follows: $TotalChangeOverTimePL_{pl} = \sum_{i=1}^{J}\sum_{j=1}^{J} ChangeOverTimePL_{i,j,pl} * a_{i,j,pl}$, where $ChangeOverTimePL_{i,j,pm}$ represents the changeover time between job *i* and *j* on pasteurization line *pl*, and $a_{i,j,pm}$represents a binary variable which indicates whether job *i* and *j* are produced, successively, on pasteurization line *pl*, respectively.

Cost relation between lateness and cleaning

Since the feasible schedules will be evaluated and compared to each by one objective value, the relation between the two types of costs must be set. The comparison of the cost is made as follows: first, the costs of having to stop a packaging line for one minute due to a late job (exceeded due date) is ten times more costly than having to stop a pre-mixer or a pasteurization line of mixing line 'B' for one minute due to changeovers. This determination comes from research of the focussed improvement department. So, the cost relationship between these two costs is as follows: one minute of lateness = 10 minutes of changeover time at pre-mixers three and four = 10 minutes of changeover time at pasteurization line two. Secondly, the cost relationship between the pre-mixers of mixing lines 'A' and 'B' can be set. As mentioned, the costs of cleaning the pre-mixers and the pasteurization line of mixing line A are 1.5 times higher than the pre-mixers and the pasteurization line of mixing line 'B'. Therefore, the cost relation between cleaning the pre-mixers of mixing line 'A' and the pre-mixers of mixing line 'B' is the following: one minute of changeover time at pre-mixers one and two = one of changeover time at pasteurization line one = 1.5 minutes of changeover time at pre-mixer three and four = 1.5 minutes of changeover time at pasteurization line two.

For the sake of simplicity, the term total weighted changeover time will be used further. This means that the total changeover time of pre-mixers three and four and pasteurization line two are multiplied by 1.5.

4.3. Mathematical model

After explaining the main variables of the model, the mathematical model can be discussed in detail. Since the goal of this research is to optimize schedules for the mixing department in terms of both lateness and utilization, the objective function will also be a combination of the two. The minimization of this objective value should lead to (i) less unplanned stopping time at packaging lines due to late orders of the mixing department and (ii) less total changeover time at the mixing department. The objective function of the model is given below, and the successive constraints are set to obtain feasible solutions. As mentioned, only a qualitative description will be given in the main report. The detailed mathematical model is given in Appendix F.

Objective value

The objective value is measured in minutes

$$\min 10 * TotalLateness + TotalWeightedChangeoverTime$$

Subject to:

Step 1 - Assigning a job to a pm:

- A job can be assigned to a pre-mixer when (i) the job can be processed on the pre-mixer (yes or no), (ii) the previous job scheduled on the same pre-mixer is completely cooked and withdrawn by the attached pasteurization line, and (iii) the pre-mixer is cleaned if necessary.
- A job must be assigned to a pre-mixer completely. It is not allowed to split up jobs.
- A job can only be assigned when the corresponding aging tanks of the job are available to send the job to. The aging tanks are available if there is enough capacity left to send the job to.
    - The capacity left in an aging tank is considered available when it is (i) empty, and not supplying the packaging department, or (ii) full and consists of the same base mix as the current to be assigned job, and not supplying the packaging department

Step 2 - Pasteurizing the job of step 1:

- All jobs that are assigned to pre-mixer one or two will be processed by pasteurization line one. All jobs that are assigned to pre-mixer three or four will be processed by pasteurization line two. All jobs must be pasteurized at once. It is not possible to split a job in this phase.
- A pasteurization line can start pasteurizing a job when (i) the previous job scheduled on the same pasteurization line is finished pasteurizing, (ii) the pasteurization line is cleaned, if necessary, and (iii) the job is cooked completely.
- Since both pasteurization lines have two attached pre-mixers, it can happen that both pre-mixers contain a job that is ready to be pasteurized. Whenever this happens, the pre-mixer job that was first ready will be pasteurized first.

Step 3 - Sending a job to an AT:

- A job can only be sent to an AT that is attached packaging line destined for the job.
- The complete job must be sent to the ATs at the same time, but the job can be sent to multiple ATs (splitting).
- A job cannot be sent to an AT that is supplying the attached packaging line at that moment.
- The starting aging time of an AT is the time at which the last job was sent to the AT. So, when an AT has already started aging, and another job is sent to the AT, the aging process must start over again.
    - The delivery time of the jobs in an AT is the starting aging time plus 120 minutes.

Step 4 - supplying the packaging lines

- Packaging lines withdraw base mixes from the attached ATs according to the production plan of the packaging department. Therefore, the content of the ATs is equal to the total base mix sent to an AT minus the total base mix withdrawn by the packaging line.
- The packaging line withdraws base mix from the AT that is (i) finished aging and (ii) the emptiest of all ATs that contain the right base mix.
- When a job is late (the end of aging time is later than due time) and the packaging line has not received the job yet, the packaging line does not withdraw any base mix.
    - The lateness of a late job is the delivery time minus the due time.
    - The due times of all jobs line following the late job with the same destined packaging line must be increased with the difference between the due time and the delivery time of the late job

- The demand of the packaging lines must be altered according to the lateness of the job; all demand of a packaging line after the due time of a late job is shifted with the difference between the due time and the delivery time of the late job.

5. Solution design

In this chapter, the solution design phase of the research will be discussed. An answer to research question three 'How should (re-)scheduling methods be (re)designed to fulfil the requests and desires of the organisation according to obtained literature and own ideas and to be in line with the culture and philosophy of Ben & Jerry's?' will be given. For clarification reasons, first, only questions regarding initial scheduling will be answered. Thereafter, in chapter seven, questions regarding re-scheduling will be answered.

As mentioned, the model uses the schedules of the packaging lines to create schedules for the mixing lines. These schedules for the mixing department consist of jobs. For initial scheduling, the model starts with empty aging tanks, and jobs should be scheduled to complete a production week of the packaging department. This model works the same for initial schedule making as for re-scheduling. However, for initial scheduling, the beginning situation is that there are no jobs produced yet, and all ATs are empty. When re-scheduling, the ATs can be filled, and some jobs will already be produced. Therefore, there are fewer possible solutions available when re-scheduling. The difference between these approaches will be described in paragraph 0.

Several techniques to create schedules will be discussed in this chapter. The model will first create a feasible solution by using a constructive heuristic, and whereafter the solution will be improved by simulated annealing.

5.1. Constructive heuristic

The organisation desires no changes in the sequence of production at the packaging lines. Thus, the mixing department needs to schedule mixes in such a way the sequence of the jobs at the packaging lines needs no alterations. Besides the sequence of production runs at packaging the packaging lines, the length and quantity of production runs of the packaging lines cannot be changed. Therefore, the job list, as mentioned in the previous chapter, will be considered fixed and given. The mixing department is responsible for supplying the packaging lines according to the job list.

The freedom of alterations of the mixing department is within the sequence and quantities of the mixing and pasteurization process. Also, the mixing department can choose what mixes are mixed on what pre-mixers and pasteurization lines.

The constructive heuristic will be used to fulfil step one (as described in the previous chapter), the assigning of a job to a pre-mixer.

Complexity

A randomly chosen week planning results in 300 orders to be produced at the mixing department. Four different pre-mixers, two pasteurization lines, and 23 aging tanks are available.

The number of possible schedules for only one pre-mixer is 300 factorials (!), which is already astronomically large, and therefore it is impossible to evaluate all schedules. Therefore, a constructive heuristic and optimization techniques will be used.

Feasibility

A heuristic should provide a feasible solution. A feasible solution is a solution that does not violate constraints. So, a feasible solution is a solution that meets all constraints mentioned in chapter four.

Priority rule scheduling

Since the costs of being late are far higher than the costs of stopping the mixing lines due to cleaning, the priority rule should be based on the due date of the jobs. Two priority rules that focus on the due date are the Earliest Due Date (EDD) priority rule and the min-slack priority rule.

As described in Chapter three, the EDD rule is a static rule, which means that the values assigned before scheduling will not alter. The EDD rule assigns values to jobs based on the due date. The job that has the earliest due date and has not been assigned a priority value receives the highest priority. This process is repeated until all jobs have a priority value. Then, from all jobs on the job list that are not scheduled, the job with the highest priority value will be scheduled first. This process is repeated until no more jobs are left to be scheduled.

The min-slack rule is also investigated to create feasible solutions. The min-slack rule works almost the same as the EDD rule. The min-slack rule chooses a job to schedule that has the least slack. Slack is calculated by the due date – the total processing time to process the job. Because the differences in total processing time between all jobs are relatively small, the schedules created by this rule will not differ much from the schedules created by the EDD rule.

Therefore, the Earliest Due Date (EDD) priority rule will be used. Besides the fact that the due date is the most important aspect of the job allocation process, this priority rule also provides a feasible solution. This is very important because the probability of creating infeasible solutions with other priority rules seems high. For example, when jobs processed by the mixing lines with a later due date are produced before jobs with an earlier due date, it can happen that the packaging lines cannot produce in the exact sequences and quantities as planned.

Again, the planning process of the mixing department consists of four steps. A model needs to execute all four steps. The priority rule will be used to execute step one. For clarification reasons, the heuristic and the model will be explained step by step. The steps, as explained below, are briefly explained. Of course, within all steps, the restrictions of chapter four need to be met.

Step 1 - Assigning a job to a PM:

1. Priority values to all jobs need to be assigned, which is based on the earliest due date. The priority value is based completely on the due date. So, the job with the earliest due date, gets the highest priority. Successively, the job with the second earliest due date gets the same priority value minus one. This is repeated until all jobs have a priority value.
2. In every iteration of assigning a job, the volumes of the ATs need to be determined. This is done by evaluating the demand of the packaging line, the jobs that are processed by the pasteurization lines and the lateness of jobs.
3. The second step is to assign jobs to pre-mixers. In every iteration, a job will be assigned to the available PM. As mentioned in the previous chapter, there are many restrictions that need to be met. A job will only be assigned to a PM when all restrictions for this step are met. So, the job with the highest priority value that meets all restrictions is assigned to an available PM

Step 2 - Pasteurizing the job of step 1:

4. Determine the starting time of pasteurizing a job. A job will be processed by the attached pasteurization line when it is available. A pasteurization line is available when the previously scheduled job on the same pasteurization line has been processed, and the pasteurization line is cleaned if necessary.

Step 3 – Sending a job to an AT

5. A job will be sent to the best AT. The best AT is the AT that is currently the fullest and not supplying the packaging line. Also, filling an AT with a job should not jeopardize the production plan of the packaging lines. When a new job is sent to an AT, the AT must be completely aged for another two hours again. Hence, it should be evaluated whether sending a job to an AT will jeopardize production.

Step 4 – Supplying the packaging line

6. The best AT will supply the packaging line. The best AT is the AT that is finished aging and contains the right base mix that is needed by the attached packaging line. It happens that more than one AT that is part of the same packaging line contains the right base mix for the attached packaging line. Therefore, a choice must be made of which AT is going to supply the packaging line at what moment.

The model, as explained above, is the model that is used in the research. How the model is realized in detail is explained in Appendix G.

Because the combined processing time of mixing and pasteurizing a mix will always be greater than cleaning an AT, the cleaning of an AT is not considered in this research

5.2. Optimization techniques

When the model creates feasible solutions, the optimization part of the model can be constructed. As discussed, the solution of the heuristic will be improved by using the optimization technique Simulated Annealing. Besides the working of simulated annealing, the settings of the technique will be discussed.

Implementation of Simulated Annealing

Now the constructive give proper schedules, the improvement part of Simulated Annealing can be created. As mentioned in paragraph 3.6, simulated annealing is an optimization technique and a continuous iterative process where neighbour solutions are created and evaluated until some stopping criterium is met. A cooling schedule will be used to reach the stopping criterium. A cooling schedule controls the possibility of accepting worse solutions (schedules). In every iteration, the Temperature increases, and the possibility of accepting worse solutions gets smaller.

Neighbour selection

The neighbour selection process consists of two parts, the possible neighbour operators, and the neighbour selection process.

Neighbour operators

In Paragraph 3.5, four different operators are discussed. These four operators are move, swap, split, and split. In this research, only the move operator will be used and evaluated.

Neighbour selection process

An optimization technique is used to increase the objective value and improve the schedule. Because the model running time is quite high, not all options can be evaluated. Therefore, the neighbour solutions should be selected carefully. In this research, infeasible solutions will not be considered. In paragraph 5.1, infeasibility is discussed.

Move operator

A move operator randomly picks a job of the schedule of one of the pre-mixers and moves the job to a different position of the schedule of the same pre-mixer or a different one. A different position of the schedules can imply that the job is scheduled, earlier or later, on the same or different pre-mixer.

Swap operator

Basically, a swap operator works the same as a move operator. Two jobs will be randomly picked, and the jobs will be swapped positions. It is possible that two jobs are scheduled on the same pre-mixer swap.

Merge operator

A merge operator merges two or more jobs. In this research, merging two jobs is not possible, and therefore this operator will not be considered. Merging is not possible because it is not possible to assign two jobs at the same time to one pre-mixer. The volume of the job is, namely, already the maximum volume that can be processed by a pre-mixer at once.

Neighbour evaluation

When the neighbour schedule is created, the neighbour can be evaluated. As mentioned in paragraph 3.6, based on the objective value of the neighbour, and the current temperature of the iteration, the solution will be accepted or rejected. When the neighbour solution has a better objective, the neighbour solution will be accepted, and the current solution becomes the neighbour solution. If the neighbour solution is worse, the neighbour solution will only be accepted according to a change equal to: $e^{\frac{(X^c)-E(X^n)}{T_i}}$. For explanation, see Paragraph 3.6.

Cooling schedule

Important for the evaluation of the neighbour is setting the parameters of the cooling schedule. First, the starting temperature needs to be set. Afterwards, the decreasing factor, end temperature, and Markov chain length parameters can be set.

The establishment of the best settings for the cooling schedule of simulated annealing is described in Appendix H. The best settings for the experiments with a time difference limit of six and 12 hours are:

- Starting temperature: 152
- Decreasing factor: 8
- End temperature: 0.85
- Markov chain length: 95

The first two experiments work properly when using the settings as stated above. However, because of the use of penalties when performing simulated annealing with a time difference limit of 24 hours, the settings are possibly not the best for the third experiment. The procedure of determining the best settings for the experiment is repeated. The best settings for the experiment with a time difference limit of 24 hours are: (i) a starting temperature of 168, (ii) an end temperature of nine, (iii) a decrease factor of 0.85, and (iv) a Markov chain length of 100.

5.3. Validation and verification

Now several optimizations and experiments are evaluated, the model can be validated and verified. There are differences within the process of the initial scheduling and re-scheduling. So, the model needs to be validated and verified for both processes.

Verification

To verify the model, some extra tables are created, like the consumption intervals (the amount and type of base mix that is withdrawn from the ATs in every period between a mix was sent to the ATs) of the packaging lines and the time a mix was sent to an AT. These tables are compared with each other in combination with the schedules of the pre-mixers and the pasteurization lines with the operators and the head of planning. The conclusion is that the model works as it should and meets all restrictions. Therefore, the model is verified.

For re-scheduling purposes, a complete production week with seven re-scheduling points is analysed. At every re-scheduling point, the status of the ATs is analysed and compared to the plan. With the help of the created tables, it was possible to check whether the model works as it should and meets all restrictions for re-scheduling purposes. The conclusion is that the model is also verified for re-scheduling purposes.

Validation

The results of the heuristic and the optimization technique are discussed in chapter six in more detail. However, for validation reasons, the outcomes of the methods are analysed now.

First, the actual executed production schedules are compared to the actual created production schedules (by the mixing planners of Ben & Jerry’s). In this phase, only the data of the practice is used. So, the models (constructive heuristic and simulated annealing) are not used yet. The differences below represent the percentual differences between the actual executed production schedules and the actual created production schedules per production week. The difference of 0.7% (week 10) means that the actual total changeover time in practice was 0.7% more than was planned in the schedules created in production week 10. In Appendix J, an example is given of how several schedules contribute to the actual created schedules.

- Week 10: 0.7%
- Week 11: 0.3%
- Week 12: 0.4%
- Week 13: 0.9%

The differences as stated above are relatively small. So, the actual created production schedules are very similar to the actual executed production schedules. Therefore, the schedules that are created by the constructive heuristic and simulated annealing will be compared to the actual executed production schedules. This comparison is done because the organisation desires to know what improvements can be made to the actual executed production schedules rather than the improvements to the actual created production schedules.

Now, the comparison between the constructive heuristic and the actual executed production schedules can be made. The differences below represent the percentual differences between the actual executed production schedules and the schedules created by the constructive heuristic per production week. The difference of 1.3% (week 10) means that the actual total changeover time in practice was 1.3% more than the total changeover time in the schedules when performing the constructive heuristic in production week 10.

- Week 10: 1.3%
- Week 11: 0.2%
- Week 12: 4.3%
- Week 13: 2.5%

The average percentual difference of the evaluated weeks is around 2.1%. As can be obtained from the figures above, the differences between the constructive heuristic and the actual executed production schedules are relatively small. Also, when comparing the actual executed production schedules to the schedules created by the constructive heuristic, there are many similarities in terms of sequences of the jobs. So, the conclusion is that the constructive heuristic creates schedules that represent the way of scheduling in practice very well. Therefore, the model is validated.

5.4. Conclusion chapter five

In the conclusion of chapter six, an answer will be given to research question three. Since there is a clear distinction in the report between initial scheduling and re-scheduling, in this chapter, only an answer will be given to the question regarding the initial scheduling part of the question.

The first question to answer, is what the desires are about scheduling methods of the organization. This part of the research question has been discussed in chapters three and four. The answer to that question can be stated as follows: the organization desires a method that creates schedules for the pre-mixers and pasteurization lines before a production week, in which (i) the total lateness and (ii) the total changeover time of the pre-mixers and pasteurization lines is minimized, and (iii) can create the schedules within 20 minutes.

The second question is, how this method should be (re)designed. Because there is not a real method that is currently used, it should be designed. Therefore, a model is built that creates schedules for both the pre-mixers and the pasteurization lines. This model considers all important steps in the planning process of the mixing department. A constructive heuristic has been created that creates schedules for both pre-mixers and pasteurization lines. Thereafter, simulated annealing is performed to improve the solutions of the constructive heuristic. The methods can improve the performance of the mixing department. Whether it will improve the performance will be discussed in the next chapters. The model is verified and validated for both initial scheduling and re-scheduling.

6. Experimental design and results

This chapter discusses the experimental set-up that Is used to test the created models. As mentioned, only the initial scheduling part of the research will be covered in this chapter.

6.1. Testing environment and settings

The testing environment should be described for both initial scheduling and for re-scheduling. In both situations, the model will first run the constructive heuristic. Afterwards, the simulated annealing part will be executed. Several experiments of the simulated annealing part will be performed and analysed.

Testing environment

To evaluate the performance of the designed algorithms for scheduling purposes, four entire production weeks are considered. Weeks 10, 11, 12 and 13 are considered. Because the production weeks are based on production cycles of around four weeks, these four weeks represent a production cycle of Ben & Jerry's. As mentioned in chapters four and five, the mixing department must deliver a complete job list in a week. It is only relevant to evaluate a complete production week and not just a part of a week because the choices made in the model affect the complete production week. Within the model, the assumption is made that the demand from the packaging department is fixed and given (deterministic).

Test settings

For both initial scheduling and re-scheduling, the constructive heuristic and the optimization part will be executed and evaluated. In total, four tests will be done with the constructive heuristic and the optimization technique. Namely, the constructive heuristic itself will be executed, and the optimization technique will be tested with three different settings.

The experiments that will be done are moving jobs to a point in time with a difference of at most 6, 12, and 24 hours (three different settings). The reason to evaluate these time restrictions, is that moving jobs to a point in the schedule of a random machine less than six hours, does not improve the objective value much. Moving jobs to a point in the schedule of a random machine with a difference of more than 24 hours results in many infeasible schedules. This is a change in the neighbour selection decision, called 'moving jobs with time restriction'. Also, the department desires to know whether it is beneficial to schedule jobs that are due much later than when scheduled because it is a risk to schedule many days ahead. It is a risk to schedule ahead much because it can happen that mixes need to be discarded when a production run at the packaging line is removed from the planning.

For the simulated annealing part, it is important to set a penalty for infeasible solutions. An infeasible solution can only be fixed by accepting more alterations to the schedule. An infeasible solution will receive the following penalty: the objective value of an infeasible solution is 10% higher than the last feasible solution. Hence, infeasible solutions will be accepted more in the beginning phase of the simulated annealing and less in the end phase.

6.2. Results

This chapter discusses the most important results of the construction heuristic as discussed in chapter five, and the results of the experiments of simulated annealing will be given, both discussed in chapter six. Finally, some examples of the outcomes are given.

Output of the constructive heuristic and simulated annealing compared to actual practice

The constructive heuristic and the optimization technique will be both compared to the actual total changeover time in practice and the actual total planned changeover time. First, the comparison to the actual total changeover time in practice will be made. In total, four experiments are done, one with the constructive heuristic and three with the simulated annealing. The three experiments are simulated annealing experiments with a move operator that moves jobs to a point in time with a time difference of at most (i) six, (ii) 12 and (iii) 24 hours.

The evaluation of the heuristic and the simulated annealing is done by discussing the objective value and the running time. Four weeks are tested and evaluated. The objective value consists of the total changeover time and the total lateness per solution. As mentioned before, lateness almost never occurs and, also, in the weeks evaluated below, no lateness occurred in both the actual production week and in the created solutions. Therefore, the actual total changeover time will be compared to the total changeover time when using the constructive heuristic and optimization techniques. All total changeover times are given in minutes. The improvement is given in percentages and is an improvement to the actual total changeover time in practice. In the table below, F(x) improvement represents the percentual objective value improvement obtained by the experiments. So, 'F(x) heuristic (min.)' represents the objective value improvement of the constructive heuristic measured in minutes compared to the actual total weighted changeover time in practice.

Table 11 - Results constructive heuristic and SA compared to actual practice

Week	Total weighted changeover time actual in practice (min.)	F(x) improvement heuristic (min.)	F(x) improvement (min.) SA < 6h.	F(x) improvement (min.) SA < 12h.	F(x) improvement (min.) SA < 24h.
10	7212	8.4%	18.3%	22.3%	21.6%
11	7900	11.9%	16.6%	23.5%	18.5%
12	8088	10.3%	19.0%	23.4%	20.1%
13	7468	10.4%	19.2%	24.0%	20.9%

As can be obtained from the table above, the schedules generated by the constructive heuristic are much better than the actual total weighted changeover times of the evaluated weeks, with an improvement between 8.4% and 11.9%. The results of the schedules generated by using simulated annealing are even more promising. In all experiments of simulated annealing, the total running time of the model was between 18 and 20 minutes. The total running time of the constructive heuristic was around five seconds for all weeks. This is acceptable for the organization.

However, the total weighted changeover times of the schedules generated by the constructive heuristics are very similar to the actual plans made by the planners. When comparing the schedules with each other, it can be concluded that the constructive heuristic creates schedules in the same way the planners do.

Output of the constructive heuristic and simulated annealing compared to actual planned

Since it is clear what the improvements of the used techniques are compared to the actual total changeover time in practice, it can be analysed what the improvements are compared to the actual planned. So, how do the techniques improve the schedules created by the planners of weeks 10, 11, 12 and 13.

Table 12 - Results constructive heuristic and SA compared to actual planned

Week	Total weighted changeover time actual planned (min.)	F(x) improvement heuristic	F(x) improvement SA < 6h.	F(x) improvement SA < 12h.	F(x) improvement SA < 24h.
10	6598	-0.1%	10.7%	15.1%	14.3%
11	7101	2.0%	9.2%	14.9%	9.3%
12	7402	2.0%	11.5%	16.3%	12.7%
13	6698	0.1%	9.9%	15.3%	11.8%

In Table 12, it is shown that the constructive heuristic does not improve the schedules significantly. After analysing the schedules created by the constructive heuristic and comparing them with the schedules of the planner, it can be concluded that the constructive heuristic works almost the same as how the planners create schedules. Therefore, the constructive heuristic is a good reflection of the current way of scheduling the mixing department.

The simulated annealing part is more interesting for this research since, in this part, the objective value gets improved. It can be obtained from Table 12 that the simulated annealing experiment with the move operator that moves jobs to a point in time with a time difference of at most 12 hours (SA < 12h.) is the most beneficial experiment. The average improvement to the actual total planned changeover time of this experiment over the four evaluated weeks is 15.4%

These improvement of 15.4% can be explained by the fact that the model can consider jobs with a lower priority easier than the mixing planners. When comparing the actual executed schedules with the schedules created by simulated annealing, the difference is a result of smarter scheduling. The size of the difference is mainly caused by the fact that in the actual schedules, a job for a packaging line is mainly processed alternately (so, for example, first, a job is processed for packaging line one, and then a job is processed for packaging line two), while in the schedules of simulated annealing mainly similar mixes are made one after the other.

6.3. Model analysis

To evaluate the trend of the experiments of simulated annealing, the experiments are investigated in more detail in Appendix I. in this appendix, the three experiments of simulated annealing are executed for one production week. The trend of the objective value within the experiment is given by graphs. It can be concluded that the second experiment (SA < 12h.) is the best for this research. Also, it can be obtained that, in the first and third experiment, the objective value decreases more steadily than in the second experiment and a good result is achieved slower than in the second experiment. The first experiment improves slower because of the smaller depth of neighbourhood. The third experiment improves slower because of the increased infeasible solutions; because of the greater depth of neighbourhood, the model creates more infeasible solutions.

6.4. Conclusion chapter six

In the conclusion of chapter six, an answer will be given to research question four 'What are the effects of the (re)designed (re-)scheduling methods in practice for Ben & Jerry's?'. Again, only the initial scheduling part is covered in this chapter, and therefore only this part of the research question will be answered.

For initial scheduling, it can be concluded that the mixing department should use the simulated annealing algorithm to create schedules for the pre-mixers and pasteurization lines. The best setting for initial scheduling is to move jobs to a point in time with a time difference of at most 12 hours. This setting resulted in an average improvement of 15.4% compared to the actual total changeover time planned. The improvements of simulated annealing can be explained by the fact that, when performing simulated annealing, similar base mixes are schedules consecutively. The improvement of 15.4% leads to a total lost time due to planned losses of 5255 minutes, which is an improvement to the total lost time (Losses) of 957 minutes (6212 – 5255).

The organisation desires to improve the OEE of the mixing department. The current OEE of the mixing department is 54.3%. this is calculated by: $\frac{Total\ amount\ of\ time\ producing}{Total\ amount\ of\ time\ producing + Losses} = \frac{14885}{14885+12549} * 100\% = 54.3\%$. The improvement in total changeover time leads to an improved OEE of 55.9%: $\frac{14885}{14885+12549-957} * 100\% = 55.9\%$.

The implementation of the new methods will result in weekly saving 120 minutes initial scheduling time for one operator.

7. Re-scheduling

In this chapter, the additions to chapters five and six for re-scheduling purposes will be discussed. In chapter five, the model was already validated and verified for re-scheduling. So, the additions to the solution design and the experimental design and results will be explained in this chapter. First, the causes of re-scheduling are discussed.

7.1. Causes of re-scheduling

Since the situation when re-scheduling differs from the initial scheduling, the optimization part of a model differs as well. As discussed before, it can be possible that only infeasible solutions can be created when re-scheduling because of full ATs. Therefore, it should be first investigated what events are the cause of the necessity of re-scheduling. Afterwards, it will be investigated how the necessity of re-scheduling, because of these events, can be decreased.

The mixing department needs to make alterations to its schedules when unforeseen events at either the packaging department or the mixing department result in a situation where it will not be possible to supply the packaging lines with jobs according to the production runs of the packaging department. It is not possible to supply the packaging lines according to the production runs when (i) the sequence of the production run cannot be followed and/ or when (ii) the jobs are delivered late to the packaging lines. In total in 2021, the mixing planners re-scheduled 302 times (5.8 times per week). The following three causes of re-scheduling are investigated (these three events cause 95.1% of the necessity of re-scheduling in 2021. The percentages represent the share to the total number of times re-scheduling was necessary):

i. Machine breakdown at the mixing department: 20 times (8.2%)
ii. Line breakdown at the packaging department: 86 times (28.5%)
iii. Altered production plan of the packaging department: 196 times (64.9%)

(i) Whenever a machine breaks down at the mixing department, it will be analysed whether a breakdown of one hour of that machine will result in lateness. This breakdown of one hour is set because around 80% of the duration of a machine breakdown in the mixing department is less than one hour (in 95% it was less than 71 minutes, and the average duration of a machine breakdown of the last 5% was 78 minutes). When a breakdown takes more than one hour, 96% of the situations it is necessary to re-schedule. The scheduled jobs on the other machines will just be executed as planned. So, only the jobs that are scheduled on the machine with the breakdown will not be processed. When the breakdown of one hour simulation results in lateness, it is considered that re-scheduling is necessary. When re-scheduling is necessary, it is called a re-scheduling trigger.

(ii) When a packaging line breaks down, the ATs of the attached packaging line will fill up. Therefore, it is not possible to assign jobs for the same line to a PM. So, re-scheduling is always necessary.

(iii) Jobs are almost always created far before needed (up to 24 hours). Whenever the production plans of the packaging department are altered, jobs will already be processed by the mixing department. When the sequence of the production runs of the packaging lines is altered, the mixing department always has to re-schedule as well. When only the quantities of the production runs are altered (and thus the starting time of later production runs are altered), it can happen that re-scheduling is not necessary. Examples of reasons to re-schedule are (a) not enough raw materials, (b) unexpected delay in maintenance, and (c) defects & rework. 45.6% of the alterations are in terms of quantities. In the other 54.4%, also the sequences are altered.

The reason why the last two events result in having to alter a schedule more frequently is that planners of the plant desire to execute the production plan of the packaging department as much as possible.

Summarized, re-scheduling is necessary when (i) jobs will be delivered late because of a machine breakdown at the mixing department, when (ii) aging tanks will be filled up due to breakdowns at the packaging department, and it can be necessary when (iii) alterations are made to the production plan of the packaging department. Only when alterations to the production plan are made in terms of quantities (and thus starting times) can it be possible that re-scheduling is not necessary.

When all attached aging tanks of a packaging line are full of jobs that are not required first by the packaging line, the packaging line cannot receive the right jobs. Therefore, base mixes should be discarded. Again, the penalty for discarding a job is 240 minutes.

7.2. Solution design

The additions to the solution design for re-scheduling purposes will be given for both the constructive heuristic and the optimization techniques.

Constructive heuristic

As mentioned, the goal is to create a model that generates schedules for the mixing department before the packaging department starts producing (scheduling) and while the packaging department is producing (re-scheduling).

The approach for both cases (scheduling and re-scheduling) is the same. However, the starting situation is not the same for both cases. The differences in the starting situation between both cases are given in the introduction to Section 5. When re-scheduling, the starting situation must be evaluated first. For example, the job list is different than when scheduling. When re-scheduling, the schedules that were created when initial scheduling are removed. The aging tanks are evaluated and considered when determining the due dates of the jobs that need to be delivered to the packaging lines. Then, the jobs on the new job list will be scheduled again according to the new job list.

It can be possible that when the department needs to re-schedule, only infeasible schedules can be created. The only way this is possible is when all ATs of a packaging line (so, all ATs that are attached to a packaging line) are not available to send a job to, and the ATs do not contain the base mix that is first needed by the packaging line. This will be solved by discarding all mixes that are in the ATs.

The differences in the starting situation per case (scheduling and re-scheduling) are the following:

Table 13 - Differences in the heuristic between (the approach of) scheduling and re-scheduling

Aspect	Initial scheduling	Re-scheduling	Difference in approach
(i) Machine breakdown at the mixing department	All PMs, PLs, and ATs are available	PMs or PLs can be down	If a machine has a break down when re-scheduling, no jobs can be scheduled on this machine. When the machine starts working again, another re-scheduling is executed, and the machine is considered again.
(ii) Line breakdown at the packaging department	No packaging line is down	Packaging line(s) can be down	When a packaging line is down, the corresponding ATs will get full. Then, no more jobs for this packaging line can be produced by the mixing department. Re-scheduling is necessary when the

			first AT of the same packaging line gets available to send a job to again.
(iii) Altered production plan of the packaging department	Production plans for the packaging lines are available prior to the production week	Production plans for the packaging lines can be altered, therefore the jobs, due dates and sequences can alter	Production plans for the packaging lines should be considered completely again
PMs, PLs, ATs	Always empty	Can be not empty	The content of PMs, PLs, and ATs should be determined
Jobs	Complete list of jobs based on complete production week of the packaging department	Jobs can already be processed. If this is the case, there are fewer jobs to schedule	Completed jobs should be removed. Due dates of jobs should be altered according to the changes in the production plan of the packaging department. whenever a job is being processed by a machine that breaks down, the job is added to the job list again because it is not finished.

Optimization techniques

To optimize the schedules created by the constructive heuristic for re-scheduling, again, simulated annealing will be used. The same settings of simulated are used for re-scheduling as for initial scheduling. This means that simulated annealing is performed with only the use of a move operator (again, with time limitations of six, 12, and 24 hours), and the running time of the model can be at most 20 minutes.

7.3. Testing environment and settings

The testing environment and settings for re-scheduling purposes will be discussed next.

Testing environment

Within the model, it is possible to simulate the production week (all pre-mixers, pasteurization lines, aging tanks, and packaging lines). It is possible to simulate the demand from the packaging department. Within the model, jobs are processed by the pre-mixers and the pasteurization lines as planned, jobs are sent to aging tanks, and aging tanks are emptied by the packaging lines. All these processes are deterministic in the model.

To evaluate the algorithm for re-scheduling purposes, the model will simulate a complete production week according to the plan of the packaging department and the created schedules of the mixing department. Empiric data on the evaluated production weeks are used. The data on the following is used for evaluation (called events):

- Machine breakdowns (moment and duration) in the mixing department
- Line breakdown (moment and duration) at the packaging department
- The re-scheduling points (moments of re-scheduling in a production week),
- All schedules of the mixing department
- All schedules of the packaging department

Evaluation method

The simulation model runs one production week using the methods and all aspects as mentioned above. In Appendix J, an example of re-scheduling one pasteurization line during a production week is given. In this example, three times the schedule (so, three rescheduling points) is altered. So, in total four schedules were created for this production week. From this figure, it can be obtained how the schedules contribute to the 'Final schedule of a method', see second last column. Also, in the figure, three re-scheduling points (RS) and two other events are given. To evaluate a method (constructive heuristic or simulated annealing), the simulation model runs deterministically to the first event. At every moment of an event, the content of the PMs, PLs, and ATs (when using a new method) are not known, and the demand from the packaging lines and the status of the packaging lines are known. The contents of the PMs, PLs, and ATs are not known because the contents of the components depend on the created schedules. Therefore, the contents of all components of the mixing department are determined by the model, and all other aspects are known. Successively, at every event, it can be evaluated whether re-scheduling is necessary or not.

An example: the model runs until the first even (machine breakdown at 08:45 and the machine cannot be used for 10 minutes). At this moment, it is evaluated whether re-scheduling is necessary for the current schedule. In this example, it was not necessary to re-schedule. Thereafter, the model runs until 10:00 am where re-scheduling was necessary in practice for the first time (RS 1) due to altered packaging planning. In this example, it was necessary to re-schedule at this event.

When re-scheduling is necessary, the first step is to execute the constructive heuristic again, considering the status of all aspects mentioned before. Secondly, the optimization part (simulated annealing) will be used to improve the heuristic. The schedules made during a production week are compared to schedules created by the constructive heuristic and the simulated annealing algorithms. Besides, the schedules created by the algorithms will be compared to the actual total changeover times. Also, the running time will be constantly evaluated.

A production week is completely simulated, and the results will be analysed. In the example, in one production week, four schedules are created and only a part of the schedules is executed (because of re-scheduling). For example, the part of the initial schedule that is executed is the part from 08:00 am until 10:00 (jobs A – D). The parts of the schedules that are executed are together the Final schedule of a method. Finally, the Final schedule of a method can be compared to the actual executed production schedule of a week. This is done by comparing the actual total changeover time in practice to the total changeover time of the Final schedule created by a method. In total four production weeks and four methods are evaluated (so, 16 experiments in total).

Summarized, the evaluation of one method for one production week works as follows: (i) first, a method creates a schedule, (ii) the simulation model runs until the first event, (iii) it is determined whether re-scheduling is necessary, (iv) if re-scheduling is necessary, a new schedule is created with the same method. This is repeated until the end of the production week.

Test settings

The test settings when executing the constructive heuristic and simulated annealing are the same for re-scheduling as for initial scheduling. Thus, the constructive and the three settings (six-, 12-, and 24-hour time limitations) of simulated annealing will be executed, and an infeasible solution will receive the following penalty: the objective value of an infeasible solution is 10% higher than the last feasible solution.

At a re-scheduling point, infeasibility can occur; when ATs are filled with jobs that are not required first by a packaging line, the packaging line can never receive the right job first. Whenever a situation occurs where no feasible solution can be created at a re-scheduling point, jobs need to be discarded to fix the infeasibility. Per job that is discarded (even if it is partly processed), a penalty of 240 minutes will be added to the objective value. This comes from the costs of having to discard, which is based on the lost minutes of operating time at the mixing department (at least 40 minutes) + the costs of the base mix itself. To fix the infeasibility, all jobs of the two oldest (finished aging first) aging tanks of the packaging line that causes the infeasibility will be discarded.

To execute simulated annealing, the process of setting the parameters is executed again for re-scheduling purposes (both for the experiments with time difference limits of six and 12 hours, and 24 hours). The results of this process for the experiments with a time difference limit of six and 12 hours are:

- Starting temperature: 152
- End temperature: 8
- Decrease factor: 0.825
- Markov chain length: 118

The best settings for the experiment with a time difference limit of 24 hours are:

- Starting temperature: 168
- End temperature: 9
- Decrease factor: 0.875
- Markov chain length: 82

7.4. Experimental design and results

Now the additions to the solution design and the experimental design and settings are given, the experimental design for re-scheduling can be explained, and the results can be analysed.

Output of the constructive heuristic and simulated annealing compared to actual practice

In Appendix K, an analysis is done on the differences between the actual executed production schedules and the actual created production schedules. It is concluded that the differences are relatively small. Thus, the actual total changeover time in practice (result of actual executed production schedule) are used for further analysis.

The evaluation of the heuristic and the simulated annealing is done by discussing the objective value and the running time. Four weeks are tested and evaluated. The objective value consists of the total changeover time and the total lateness per solution. As mentioned before, lateness almost never occurs and, also, in the weeks evaluated below, no lateness occurred in both the actual production week and in the created solutions. Therefore, the actual total changeover time will be compared to the total changeover time when using the constructive heuristic and optimization techniques. All total changeover times are given in minutes. The improvement is given in percentages and is an improvement to the actual total changeover time in practice. In the table below (Table 14), F(x) improvement represents the percentual objective value improvement obtained by the experiments. So, ‘F(x) improvement heuristic’ represents the objective value improvement of the constructive heuristic measured in minutes compared to the actual total weighted changeover time in practice. ‘F(x) improvement SA < 6h.’ represent the objective value improvement of the simulated annealing with the move operator and a time difference limit of six hours, measured in minutes compared to the actual total weighted changeover time in practice.

Table 14 - Total actual changeover time in practice compared to total changeover time when using the constructive heuristic and SA to re-schedule

Week	Actual total weighted changeover time in practice (min.)	F(x) improvement heuristic	F(x) improveme nt SA < 6h.	F(x) improvement SA < 12h.	F(x) improvement SA < 24h.
10	7212	1.3%	8.4%	11.3%	9.6%
11	7900	0.2%	7.6%	10.9%	9.3%
12	8088	4.3%	8.8%	11.0%	8.9%
13	7468	2.5%	7.5%	10.8%	9.2%

The results of the experiments do not differ much per week. However, it does per experiment. The experiment with the best improvement is again the one with a time limit of 12 hours. The average improvement of the simulated annealing experiment with a time limitation of 12 hours is 11.0%. In only two experiments, infeasibility occurred. To overcome this, jobs were discarded from the aging tanks. This was with the experiment with a time limit of 24 hours for weeks one and three. In all weeks, the number of re-scheduling points was equal to the actual number of re-scheduling points.

In all experiments, the total running time of the model was between 18 and 20 minutes. This is acceptable for the organization.

Buffers

When using the constructive and the simulated annealing, the number of re-scheduling points did not decrease, and in two situations, it was necessary to discard jobs. Since an organization can benefit from less re-scheduling, the possibility of decreasing the number of re-scheduling points is investigated. The use of aging tank buffers will be investigated. The effects of causes (ii) 'Line breakdown at the packaging department' and (iii) 'Altered production plan of the packaging department' of Paragraph 7.1 can be limited with the use of tank buffers.

An aging tank buffer is an aging tank that will not be used until it is necessary to use. It is necessary to use an aging tank when a job is delivered to the packaging department late otherwise (when the aging tank is not used). All packaging lines will have at most one aging tank buffer. This means that, for example, when re-scheduling, all packaging lines have at least one aging tank available to send jobs to. In this example, the attached aging tanks will fill up less fast, and therefore the number of re-scheduling points can be decreased.

The evaluation of the use of buffer tanks will be done the same as for the evaluation of the methods as described in the previous paragraph; (i) first, a method creates a schedule, (ii) the simulation model runs until the first event, (iii) it is determined whether re-scheduling is necessary, (iv) if re-scheduling is necessary, a new schedule is created with the same method. This is repeated until the end of the production week.

The differences between the approaches of using all aging tanks and using aging tank buffers are:

- In step (i), one aging tank per packaging line is not used to send jobs to; this is the aging tank buffer. The specifics of the aging tank buffer per packaging line can be found in Appendix L.
- In step (iii), the aging tank buffer that is not used in step (i) can be used to prevent re-scheduling, so, when determining whether re-scheduling is necessary, this should be considered
- In step (iv), if it is useful to use the aging tank buffer to send jobs to, the aging tank buffer can be used. If not, one aging tank per packaging line is not used to send jobs to.

The use of tank buffers is analysed for both the constructive heuristic and simulated annealing (four experiments per evaluated production week in total, so, 16 experiments in total).

In Table 15, two aspects are given, the number of re-scheduling points and the improvement of the objective value. The improvement is percentual and is a comparison with the actual total weighted changeover time in practice. For example, 'F(x) impr. SA < 6h.' represent the percentual improvement in total weighted changeover time when using the method simulated annealing with a time limit difference of at most six hours. The number of re-scheduling points represents the number of times it is necessary to re-schedule using a method.

Table 15 - Total actual changeover time in practice compared to total changeover time when using the constructive heuristic, SA, and tank buffers to re-schedule

Week	# RS-points heuristic	F(x) impr. heuristic	# RS-points SA < 6h.	F(x) impr. SA < 6h.	# RS-points SA < 12h.	F(x) impr. SA < 12h.	# RS-points SA < 24h.	F(x) impr. SA < 24h.
1	4	0.4%	4	5.3%	4	7.2%	4	6.0%
2	4	-0.7%	4	4.8%	4	6.9%	4	5.8%
3	4 (-1)	1.3%	4 (-1)	6.0%	5	7.3%	5	6.7%
4	6 (-1)	0.8%	6 (-1)	5.0%	7	6.7%	7	5.8%

As can be obtained from the table, in only four experiments (of a total number of 80 re-scheduling points), the number of re-scheduling points decreased when using the buffer tanks in combination with constructive heuristic and simulated annealing, which is a reduction of 5.0%. Again, the simulated annealing experiment with a limitation to moving jobs within a range of 12 hours is the most promising. The improvement for this experiment is 7.0% compared to the actual total weighted changeover time in practice.

The reason that the number of re-scheduling points has not decreased much is investigated. When analysing the schedules and the re-scheduling points, it can be concluded that the organisation does not benefit much from the use of buffer tanks in terms of re-scheduling points because in the current way of (re-)scheduling, very often, there is enough capacity in the aging tanks left to send jobs to. This is because it is often not efficient to send a job to an aging tank because the complete aging tank then needs to age for 120 minutes again.

7.5. Conclusion chapter seven

Research questions three and four are partially answered in chapters five and six, respectively. The parts that are answered are the parts concerning initial scheduling g. In this chapter, the re-scheduling part of the research is covered. Therefore, in this paragraph, answers will be given to the parts of research questions three and four corresponding to the re-scheduling part.

Answer to research question three regarding the re-scheduling part

Firstly, an answer will be given to research question three about the design of the methods regarding the re-scheduling part.

The first question to answer is what the desires are about re-scheduling methods of the organization. This part of the research question has been discussed in chapter three. The answer to that question can be stated as follows: the organization desires a method that creates schedules during a production week for the pre-mixers and pasteurization during a production week, in which (i) the total lateness and (ii) the total changeover time of the pre-mixers and pasteurization lines is minimized, and (iii) can create the schedules within 20 minutes.

The second question is then how this method should be (re)designed. Because there is not a real method that is currently used, it should be designed. Therefore, a model is built that creates schedules for both the pre-mixers and the pasteurization lines during a production week. This model considers all important steps in the planning process of the mixing department. A constructive heuristic has been created that creates schedules for both pre-mixers and pasteurization lines. Thereafter, simulated annealing is performed to improve the solutions of the constructive heuristic. Also, the method considers (i) the content of PMs, PLs, and the ATs, (ii) the status of all machines in the mixing department and the status of the packaging lines, and (iii) the production plan of the packaging department where alterations can have been made.

Answer to research question four regarding the re-scheduling part

Finally, in this chapter, an answer will be given to research question four about the outcomes and achievements of the methods regarding the re-scheduling part.

As applies to initial scheduling, the same applies to re-scheduling. The mixing department should use the simulated annealing algorithm to re-create schedules for the pre-mixers and pasteurization lines when necessary. Again, the best setting is the one that forces the move operator to move jobs to a point in time that is within 12 hours. The department desires to re-schedule within 20 minutes, and the algorithm can create good schedules within this period. This setting resulted in an average improvement of 11.0% compared to the actual total weighted changeover time in practice. An improvement of 11.0% means a decrease of 638 minutes total changeover time.

The organisation desires to improve the OEE of the mixing department. The current OEE of the mixing department is 54.3%. this is calculated by: $\frac{Total\ amount\ of\ time\ producing}{Total\ amount\ of\ time\ producing+\ Losses} = \frac{14885}{14885+12549} * 100\% = 54.3\%$. The improvement in total changeover time leads to an improved OEE of 55.5%: $\frac{14885}{14885+12549-638} * 100\% = 55.5\%$.

The use of tank buffers does not seem to be very interesting for the organisation to implement since the necessity of re-scheduling will not be decreased much by using tank buffers (5.0%). Also, the improvement of simulated annealing compared to the actual total changeover time is far less when using buffers than when not using buffers (11.0% improvement compared to 7.0%).

The expectation is that the created method can achieve improvements in terms of reducing the total changeover time but not in terms of reducing the number of re-scheduling points. As described in the previous paragraph, the model has been validated and verified for both initial scheduling and re-scheduling purposes.

The implementation of the new methods will result in weekly saving 200 minutes re-scheduling time for one operator.

8. Implementation, conclusions, limitations, and recommendations

In this final chapter, the final research question, '*How should the methods of research questions three and four be implemented in the approach of (re-)scheduling?*' will be answered. Also, the final conclusions and recommendations resulting from this research will be given in this chapter.

8.1. Implementation

To benefit from this research, the organization needs to implement a method. The created method for this research is a prototype method that can be used as a guideline for creating a method that will be used by the organisation. The method is created in Python because the organisation works with Python as well. Within the method, pseudo-code is given to understand the code.

Linkage method and databases

For the research, several databases are used to collect and evaluate data. To execute the experiments, several data had to be inserted into the model. It is possible to connect all databases to the model. Therefore, it is important to understand what database provides what data.

SAP-, PowerBI-, and SQL database

These databases were used to evaluate the processing times of the pre-mixers and the pasteurization lines. When new products need to be processed, these new products need to be inserted into the model.

Excel-tool and LPI

These tools are used by planners to create schedules for the packaging department. The output of these tools, the schedules for the packaging department, is the input for the schedules for the mixing department. Whenever alterations are made to a schedule of the packaging department, the new schedule needs to be inserted (manually or automatically) into the model.

ACCOSS

This tool is used by the planners of the mixing department to monitor the process of the department. This tool collects data about the progress, the status, and the content of all machines at the mixing department. This tool should be linked to the (re-)scheduling tool because then, re-scheduling can be executed automatically.

LPI

This tool is used by the planners of the packaging department to monitor the process of the department. This tool collects data about the progress, the status, and the content of all machines in the packaging department. Again, this tool should be linked to the (re-)scheduling tool because then, re-scheduling can be executed automatically.

Dashboard

Currently, no accurate dashboards are used to monitor the planning process of the mixing department. This means that the planners of the mixing department monitor the progress of the planning process by monitoring the progress, the status, and the content of all machines at the mixing department together with the schedule. Now, there is no dashboard that presents the progress of the complete planning of the mixing department. Therefore, the status of jobs is not known by other departments, such as the packaging department.

A dashboard must represent the current progress of the complete planning of the mixing department. Within the dashboard, it should be possible for all relevant departments to evaluate the progress of all jobs. For example, it should be easily possible for a packaging department planner to evaluate the status of the mixing department such that the planner can consider re-scheduling properly.

At the present time, decisions of the planners of the packaging department are made without the planners having the required knowledge about the status of the mixing department. A dashboard can prevent this. Finally, when the scheduling is created properly, the mixing department operators must follow these schedules.

Training operators and planners

When the method is linked to the databases and a dashboard is created, the mixing planners, the packaging mixing planners, and the operators need to be trained to understand and work with the system. Important in the training is the consideration of freedom for all employees. An important aspect to consider, for example, is what the responsibilities of all stakeholders.

Conclusion of the implementation

The answer to the final research question 'How should the proposed methods be implemented in practice?' is, therefore, the following: the method that is created in the previous chapters should be linked with the required databases, a dashboard should be created to properly monitor the planning process of the mixing department, and the mixing department operators need to follow the schedules.

8.2. Conclusions

The stated goal of this research is to maximize the utilization of the bottleneck of the organization. In accomplishing this, first, the bottleneck of the organization needed to be stated. Currently, the bottleneck of the organization is not within the mixing department. However, the organization desires to expand the packaging line. Successively, the mixing department can become the bottleneck. To prevent the mixing department from being the bottleneck, the current process of scheduling is analysed.

> *How should the scheduling and re-scheduling methods of production, changeovers, and planned stops be (re)designed to maximise the bottleneck's* utilization *of the production process?*

The current process of (re-)scheduling can be categorized as a process based on knowledge and experience, and jobs are scheduled in order of earliest due time. No optimization techniques are used in this stage. Also, no dashboards are used which leads to much communication between departments.

The organization desires methods where schedules for the pre-mixers and pasteurization lines can be created either before a production week (scheduling) or during a production week (re-scheduling), in which (i) the total lateness and (ii) the total changeover time of the pre-mixers and pasteurization lines is minimized.

Therefore, two methods are created, namely a constructive heuristic and simulated annealing. The schedules created by the constructive heuristic based on the priority rule 'Earliest Due Date' represent the current way of scheduling jobs. Three different experiments are used for performing simulated annealing (simulated annealing with a move operator and a time difference limit of (i) six, (ii) 12, and (iii) 24 hours.

A method for (re-)scheduling can have a running time of at most 20 minutes. Besides, the use of buffer aging tanks is analysed to potentially benefit in terms of decreasing the necessity of re-scheduling and changeover time. The use of buffer tanks is analysed for all four experiments: one with the constructive heuristic and three with the simulated annealing. The results of these experiments obtained the following insights:

1. **The best simulated annealing experiments result in an improvement of the OEE of 1.6% for initial scheduling and 1.2% for re-scheduling.** The improvement is measured in total weighted changeover time since there is no lateness in any of the evaluated production weeks and the experiments. The best average improvement, for initial scheduling, is 15.4% compared to the actual total planned changeover time. The best average improvement of, for re-scheduling, is 11.0% compared to the actual total changeover time in practice. Also, the use of a method will save time for the mixing planners. The expected time that will be saved is around two hours for initial scheduling and 200 minutes for re-scheduling, so, 320 minutes weekly.
2. **The test with the use of buffer aging tanks resulted in having to re-schedule one time less in four experiments**: two weeks when using the constructive heuristic, and two weeks when performing the simulated annealing with the move operator and a time limitation of 6 hours. The total number of re-scheduling points in four weeks in all four experiments is 80. So, the average number of re-scheduling points per week was five. Which means the number of re-scheduling points has decreased slightly (5.0%, four against 80). Again, the best setting for simulated annealing, when using buffer tanks, is the setting with a move operator and a time limitation of 12 hours. The average improvement of this experiment is 7.0% compared to the actual total weighted changeover time in practice. The number of re-scheduling points did not decrease in any experiment.

8.3. Limitations

During the research, assumptions and simplifications are made that resulted in a set of limitations:

1. The demand of the packaging department is considered fixed and given. Because it is out of the scope of the research, the uncertainty in this aspect is not considered. The schedules created with the model are based on deterministic demand of the packaging lines. This demand comes from the production plans of the packaging department When the demand differs from the plans, it can happen that the starting time of a job can differ as well.
2. Because the production plans of the packaging department are considered given and the packaging department needs to schedule jobs corresponding to these plans, the results of schedules of the mixing department are limited to these plans. There is less space to schedule jobs because the department needs to supply the packaging department in the sequence as given by the production plans of the packaging department.
3. Due to the absence of accurate data of the performance of the machines in the mixing department, the investigation of decreasing the number of re-scheduling points was not extensive. When creating schedules, the processes of the machines in the mixing department are considered fixed and deterministic because there is no accurate data available on the performance of the machines. Therefore, no breakdown of machines is considered in the process.
4. In the model, the absence of raw materials is not considered. It happens almost never that absence of raw materials leads to problems in the planning process. However, the increase of the capacity of the packaging department can lead to less raw materials in stock. Therefore, the absence of raw materials can become more relevant.
5. Despite the constructive heuristic representing the current performance in terms of total weighted changeover time, the created schedules created by the simulated annealing

algorithm are just indications of the expected performances. Because of the determinism of the demand of the packaging department, the simulated annealing algorithm performs very good compared to the existing schedules. However, the demand is not deterministic, and therefore, the actual performance of the schedules created by the algorithm should be tested in practice. This is not covered in this research.

8.4. Scientific relevance

This research is strongly focussed on the production processes at Ben & Jerry's. However, the specific situation of Ben & Jerry's is relevant for all similar production plants. This research is one of the first to consider all (four) steps of the planning process of the mixing department. The addition of this research to the literature is:

1. A scheduling method that is much more efficient than existing heuristics and that considers (i) the assigning of a job to a pre-mixer, (ii) the assigning of a job to a pasteurization line, (iii) the sending of a job to an aging tank, and (iv) the sending of a job from an aging tank to a packaging line. Also, additional rules within these steps are considered. For example, the consideration of the availability of aging tanks when assigning a job to a pre-mixer (step one of the planning processes).
2. A method that can test the use of aging tank buffers and that, again, considers all (four) planning steps of the mixing department.

These subjects have been thoroughly analysed and used for the improvements planning process of the mixing department. The same approach could be used for other situations. The analysis of the constructive heuristic and EDD-rule, and simulated annealing are not new and can already be found in literature.

8.5. Recommendations

Finally, the recommendations to the organization are given in this paragraph. The recommendations based on the research are:

1. **Create and implement a (re-)scheduling method that can automatically create schedules within 20 minutes, minimizes the total weighted changeover time, and without any lateness.** The experiments with the simulated annealing algorithm show improvements to the current schedules of 11.0% and 15.4% for initial scheduling and re-scheduling, respectively. To automize the (re-)scheduling process, several databases need to be linked to the method, see Paragraph 8.1. If these improvements will be realized, the capacity of the department will increase. Because of the desires of the organization, the capacity needs to increase. The organization needs to consider whether it wants to invest in a (re-)scheduling method or to increase the capacity in a different way.
2. **Collect and analyse performance data of the mixing department and use the data for decision-making.** The organization is currently working on the data collection of the mixing department. The advice to the company is to create a database in such way the data can be easily used in the planning process. When the data are implemented in the model correctly, the model should be able to (re)create schedules without the interference of an employee. Besides, for optimizing machine performance reasons, the data about the machines are required to make accurate analyses.
3. **Investigate other buffers.** Because of the lack of data on the mixing department, the investigation on buffers to decrease the number of re-scheduling points is limited. Therefore, the created methods are not more robust than the existing ones. Whenever more data on the mixing department are collected, it can be possible to investigate the use of

buffers more accurately. The organization can benefit from this in terms of less necessity of re-scheduling. The use of tank buffers, as discussed in chapter seven, is not recommended since the improvement of simulated annealing is less than when no tank buffers are used.

4. **Improve the communication between the mixing department and the packaging department by creating a dashboard that displays the progress of the planning of the mixing department.** Currently, much communication is needed because of the lack of a dashboard to monitor the mixing planning process. A dashboard can help to make decisions faster and the communication more structured.
5. **Optimize the production cycles and production schedules of the packaging department along with the schedules of the mixing department.** Currently, the production cycles of four weeks are set, the schedules of the packaging department are created according to these cycles, and successively, schedules for the mixing department are created. In the design of this process, all steps should be considered to optimize the overall performance instead of the individual performance of a department.
    a. The schedules of the packaging lines should be optimized completely. Currently, the schedules of the packaging department are not optimal because the products that need to be produced in a production cycle are divided over the packaging lines. Then, the schedules of the individual packaging lines are optimized. When an optimization method will be used to improve the overall performance of the department, instead of optimizing packaging lines individually, the expectation is that the overall performance will be improved.

Appendix

All appendices used in the report are given below.

A. Changeovers

In Table 16 and Table 17, the changeover matrix and the explanation are given, respectively.

Table 16 - Changeover matrix base mixes

Pre mixer / pasteur spoelingen																				
Van ---------> Naar	67408485	67408487	67413412	67413413	67560337	67576335	67604182	67611366	67862954	67862955	67920001	8214323	8247132	8499301	8517629	8602508	8854395	8978927	9247848	9247863
67408485	1	4	4	4	4	4	4	6	6	4	4	4	4	4	4	4	4	4	7	7
67408487	2	1	4	4	4	4	4	6	6	1	4	4	4	4	4	4	4	4	7	7
67413412	4	4	1	4	4	4	4	6	6	4	1	4	1	4	4	4	3	1	7	7
67413413	4	4	2	1	4	4	4	6	6	4	2	4	2	1	4	1	3	2	7	7
67560337	2	4	4	4	1	4	4	6	6	4	4	4	4	4	4	4	4	4	7	7
67576335	2	4	4	4	4	1	4	6	6	4	4	4	4	4	4	4	4	4	7	7
67604182	4	4	4	4	4	4	1	6	6	4	1	4	4	4	4	4	3	4	7	7
67611366	2	4	4	4	4	4	4	1	6	4	4	4	4	4	4	4	4	4	7	7
67862954	2	2	4	4	4	4	4	6	1	4	4	4	4	4	4	4	4	4	7	7
67862955	2	2	4	4	4	4	4	6	6	1	4	4	4	4	4	4	4	4	7	7
67920001	4	4	2	4	4	4	4	6	6	4	1	4	1	4	4	4	3	1	7	7
8214323	4	4	4	4	4	4	4	6	6	4	4	1	4	4	4	4	4	4	7	7
8247132	4	4	2	4	4	4	4	6	6	4	1	4	1	4	4	4	3	1	7	7
8499301	4	4	2	1	4	4	4	6	6	4	2	4	2	1	4	1	3	4	7	7
8517629	4	4	4	4	4	4	4	6	6	4	4	1	4	4	1	4	4	4	7	7
8602508	4	4	2	1	4	4	4	6	6	4	2	4	2	1	4	1	3	4	7	7
8854395	4	4	2	4	4	4	4	6	6	4	2	4	2	4	4	4	1	1	7	7
8978927	4	4	2	4	4	4	4	6	6	4	1	4	1	4	4	4	3	1	7	7
9247848	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	1	4
9247863	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	2	1

Table 17 - Explanation per changeover

1.		Geen spoelingen benodigd.
2.		X5 benodigd.
3.		Pre mixer spoeling + X5 benodigd.
4.		Pre mixer spoeling + X3 benodigd.
5.		Premixer + containerleiding spoeling + X3 benodigd
6.		Complete installatie reiniging benodigd.
7.		Complete installatie reiniging benodigd incl. handmatige reiniging mangaten / mangatpakkingen. (Z3 en premixcip)
Er mag ten aller tijde een hoger genummerde spoeling worden gebruikt, nooit een lager genummerde spoeling.		

B. Optimization methods

In the figure below, the process of the optimization method is given.

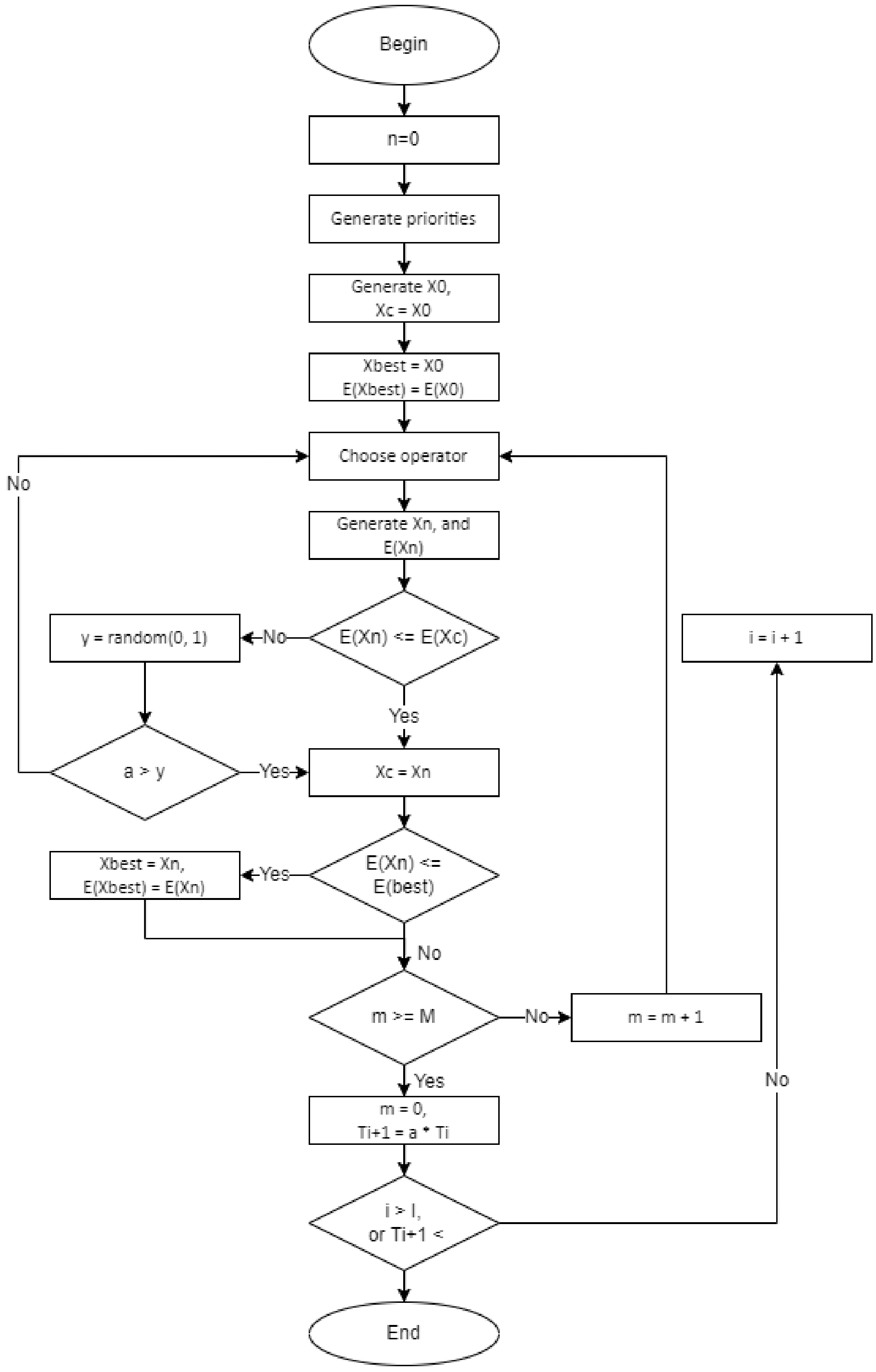

Figure 11 - Simulated annealing flow chart

Where $a = e^{\frac{E(X^c)-E(X^n)}{T_i}}$

C. Distributions analyses

In this appendix, distributions of processing times per machine are given.

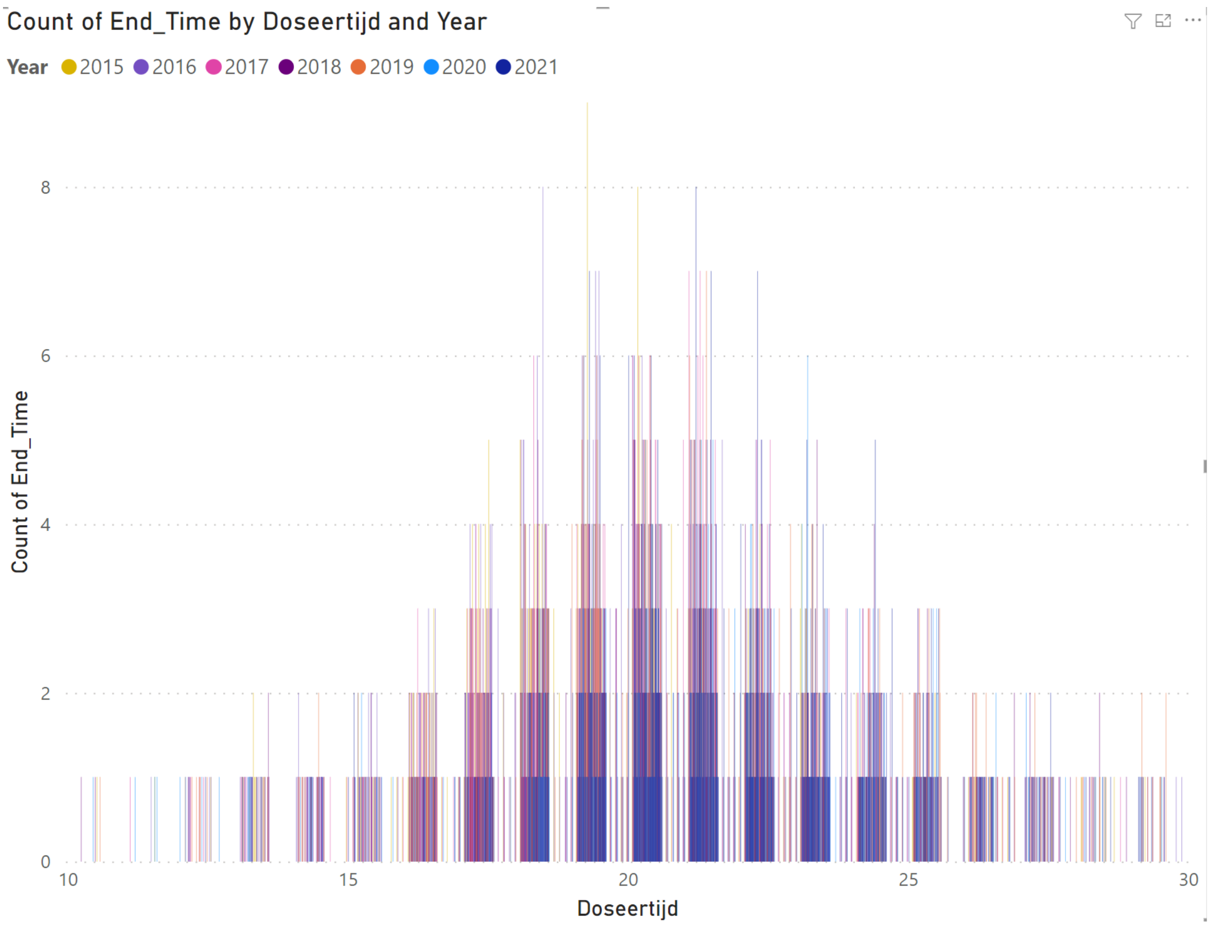

Figure 12 - VS350 (pre-mixer A1) mix 8237132

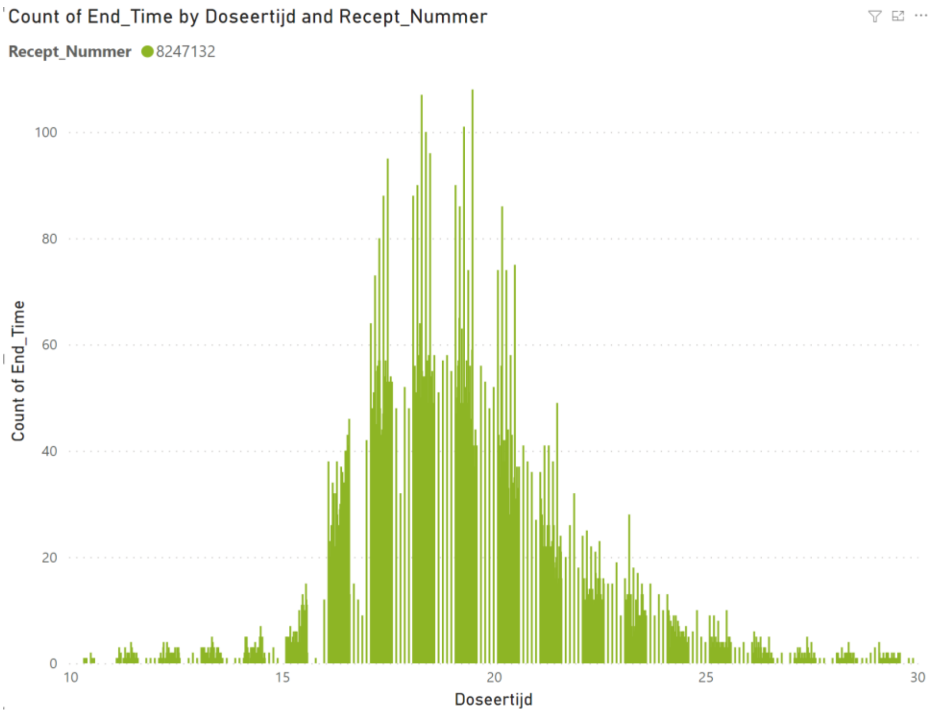

Figure 13 - VS370 (pre-mixer A2) mix 8247132

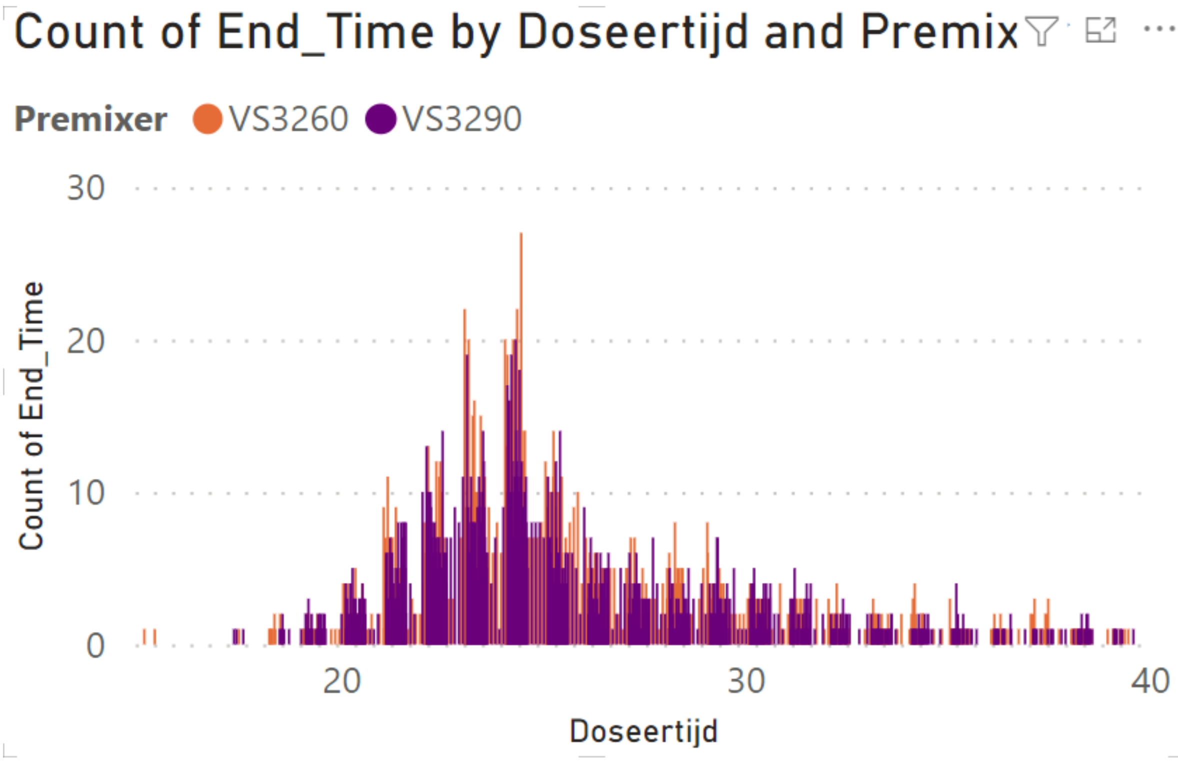

Figure 14 - VS3260 and VS3290 (pre-mixer B1 and B2) mix 8247132

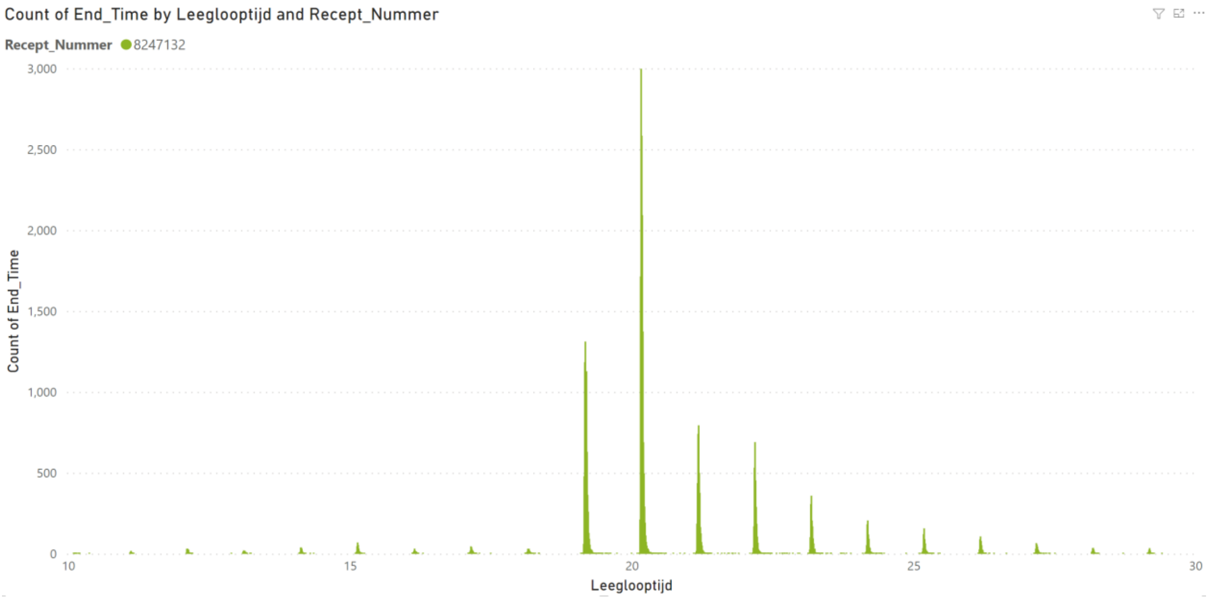

Figure 15 - Pasteurizer A (PL A) mix 8247132

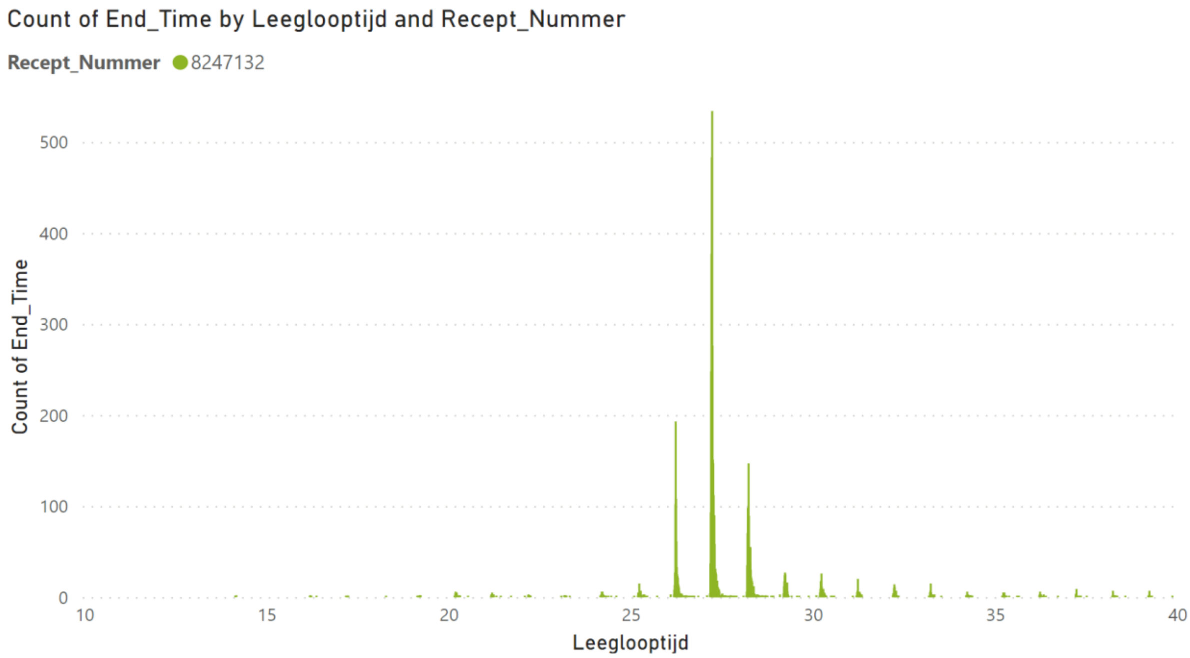

Figure 16 - Pasteurizer B (PL B) mix 8247132

D. Week planning

In Table 18, an example of a planning of the packaging department can be found.

Table 18 - Example of a week planning of the packaging department

-16											900/920			90%
4.0	sauzen		B&J Line 2	L501										
18.6	x8x210DB	14384000	B&J Line 2	68484991	106.5	Chep	C210	22,365	178,921	8499301	50,000			3+A
9.0	Onderhoud		B&J Line 2	LM10							50,000			
4.5	Lijncip + sauscip		B&J Line 2	L002										
11.7	NZ x8x210DB	14378283	B&J Line 2	68528168	63.0	Chep	C210	13,230	105,840	8247132	34,105			3
0.3	Verpakkingsovergang		B&J Line 2	L005										
13.5	CL3x8x180EB	14378379	B&J Line 2	68814817	85.0	Euro	E180	15,299	122,392	8247132	39,439			3
5.4	CL4x8x180EB	14378268	B&J Line 2	67919946	34.0	Euro	E180	6,120	48,960	8247132	15,777			3
13.0	Breakdowns and stoppages		B&J Line 2	D003										
21.0	CL5x8x180EB	14378409	B&J Line 2	68692291	132.0	Euro	E180	23,760	190,080	8247132	61,249			3
7.0	CL7x8x180EB	14378461	B&J Line 2	68814823	44.0	Euro	E180	7,925	63,400	8247132	20,430			3
2.0	Waterspoeling lijn		B&J Line 2	L011							171,000			
6.2	MoopSaltCaramBrownCL1x8x18	14378427	B&J Line 2	68593318	39.0	Euro	E180	7,020	56,160	67413412	13,722			3
8.2	MoopSaltCaramBrownCL2x8x21	14378438	B&J Line 2	68593314	51.9	Euro	E180	9,351	74,804	67413412	18,278			3
5.5	72-uurcip		B&J Line 2	L004							32,000			
10.2	CL3x8x210DB	14378378	B&J Line 2	68725424	55.0	Chep	C210	11,560	92,480	8247132	33,043			4+A
2.2	CL5x8x180EB	14378428	B&J Line 2	68824277	14.0	Euro	E180	2,520	20,160	8247132	7,203			4+A
18.1	VanilaPecanBlondieCL2Ax8x180E	14378284	B&J Line 2	68788407	114.2	Euro	E180	20,555	164,444	8247132	58,754			4+A
			B&J Line 2								99,000			

E. Aging tanks

In Table 19, the capacity per aging tank can be found.

Table 19 - Capacity of aging tanks

Line	Tank	Capacity	0 = A, 1 = B
0	0	4000	0
0	1	4000	0
1	2	20000	0
1	3	20000	0
1	4	4000	1
1	5	4000	1
1	6	4000	1
1	7	4000	1
1	8	4000	1
2	9	8000	0
2	10	8000	0
2	11	8000	0
2	12	8000	0
3	13	4000	0
3	14	4000	0
3	15	4000	0
3	16	4000	0
4	17	8000	0
4	18	8000	0
4	19	8000	0
4	20	8000	0
4	21	8000	0
4	22	8000	0

F. Detailed mathematical model

Sets, parameters, and variables

Focusing on the mathematical formulation, the following sets can be defined: jobs j, pre-mixers pm, pasteurization lines pl, aging tanks at, packaging lines x, and time t.

Additionally, the following parameters can be described: processing times $a_{j,pm}$ and $a_{j,p;}$ per job j and pre-mixer pm and pasteurization line pl, the quantity of a job j referred to as q_j, the total amount of base mix corresponding to job j that is processed on packaging lines x and withdrawn from aging tank at at time t, A_{agx} $C_{ag,j,t}$ for the current volume in aging tank at available for job j to be sent to at time t, C_{agmax} for the capacity of an aging tank at, and finally the cleaning time on pre-mixer pm and pasteurization line pl between two jobs, is given by $E_{pm,j,j+1}$ and $E_{pl,j,j+1}$

Sets

j = {1, …, |J|}	Set of Jobs
$pm = \{1, \dots, \lvert 4 \rvert\}$	Set of the four pre-mixers
$pl = \{1,2\}$	Set of the two pasteurization lines
$at = \{1, \dots, \lvert AT \rvert\}$	Set of aging tanks
$x = \{1, \dots, \lvert 5 \rvert\}$	Set of the five packaging lines
$t = \{1, \dots, \lvert T \rvert\}$	Set of time periods

Parameters

$ap_{j,pm}$ = the processing time of job j at pre-mixer pm in minutes

$$apx_{j,pm} = \begin{cases} 1, \text{if possible to process job } j \text{ on pre} - \text{mixer } pm \\ 0, \text{otherwise} \end{cases}$$

$al_{j,pl}$ = the processing time of job j at pasteurization line pl in minutes

$$atpack_{j,at} = \begin{cases} 1, \text{if aging tank } at \text{ belongs to the destined packaging line corresponding to job } j\,. \\ 0, \text{otherwise} \end{cases}$$

mix_j = the corresponding base mix number of job j

o_j = the due date of job j

$CMax_{at}$ = the maximum capacity of aging tank at in litres

$EP_{i,j,pm}$ = the cleaning time on a pre-mixer *pm* between jobs *i* and *j* in minutes, where *i* and *j* represent two consecutive jobs processed on a pre-mixer. It is the same cleaning time for all pre-mixer for all cleanings.

$EL_{i,j,pl}$ = the cleaning time on a pasteurization line *pl* between jobs *i* and *j* in minutes

$InitDemand_{j,x,t}$ = the initial amount of base mix corresponding to job j required by the packaging line x at time t

Variables

$sm_{j.pm}$ = the starting time of cooking job j on a pre-mixer pm.
$sp_{j,pl}$ = the starting time of pasteurizing job *j* on pasteurization line *pl.*
$sa_{j,at}$ = the starting time of aging job *j* in aging tank *at.*
u_j = the delivery time of job *j* coming from pasteurization line *pl.* It resembles the time at which job *j* is ready (finished aging) to be processed by a packaging line
$C_{at,j,t}$ = the amount of space left in aging tank at for job j at time t in litres

$$PLJ_{j,pl} = \begin{cases} 1, \text{if job } j \text{ is or will be processed on pasteurization line } pl \\ 0, \text{otherwise} \end{cases}$$

Mix_j = the corresponding base mix of job *j*

$$MixR_{j,at,t} = \begin{cases} 1, \text{ if the corresponding base mix of job } j \text{ is the same as the base mix that is in aging tank } at \text{ or the volume of aging tank } at \text{ is equal to zero at time t} \\ 0, \text{otherwise} \end{cases}$$

$MixI_{at,t}$ = the base mix that is in aging tank *at* at time *t*

$$ATX_{at,t} = \begin{cases} 1, \text{if the aging tank } at \text{ is supplying the attached packaging line at time } t \\ 0, \text{otherwise} \end{cases}$$

$$ATPL_{j,at,x,t} = \begin{cases} 1, \text{if job } j \text{ is being supplied by the aging tank } at \text{ to the attached packaging line } x \text{ at time } t \\ 0, \text{otherwise} \end{cases}$$

$$q_j = \begin{cases} 1, \text{if } \mathrm{u_j} > o_\mathrm{j} \\ 0, \text{otherwise} \end{cases}$$

$$l_{j,pm,t} = \begin{cases} 1, \text{if job } j \text{ is assigned to pre} - \text{mixer } pm \text{ at time } t \\ 0, \text{otherwise} \end{cases}$$

$$k_{j,t} = \begin{cases} 1, \text{if the aging tanks corresponding to job } j \text{ are available at time } t \\ 0, \text{otherwise} \end{cases}$$

$Demand_{j,x,t}$ = the amount of base mix corresponding to job *j* required by the packaging line *x* at time *t*

Decisions

For clarification reasons, the decision variables are labelled in Table 10. and the following decision variables resemble the decisions as mentioned in table ….

$d_{j,pm,t}$ = the assignment of a complete job j to pre-mixer pm at time t in litres

$m_{j,at,t}$ = the part of job *j* sent to aging tank *at* at time *t* in litres

$n_{j,at,x,t}$ = the part of job *j* sent to the attached packaging line (*x)* from aging tank *at* at time *t* in litres

$$\min_{j,t} 10 * (\sum_{j=1}^{J} (u_j - o_j) \ * q_j) + \ 1.5 * \left(\sum_{t=1}^{T} \sum_{pm=1}^{2} \sum_{j=1}^{J} EP_{j-1,j,pm} + EL_{j-1,j,1} \right) + \sum_{t=1}^{T} \sum_{pm=3}^{4} \sum_{j=1}^{J} EP_{j-1,j,pm} + EL_{j-1,j,2}$$

Subject to:

Step 1 - Assigning a job to a pm:

1. Determine availability PMs

- $sm_{j,pm} \geq sm_{j-1,pm} + ap_{j-1,pm} + EP_{j-1,j,pm}$ (1) (2) starting time of cooking job *j* on pre-mixer *pm* is at least the time at which the previous job (*j – 1)* on that pre-mixer *pm* started + the processing time of job *j – 1* + the cleaning necessary between jobs *j-1* and *j* on pre-mixer *pm.*
- $sm_{j,pm} \geq sp_{j-1,1} + al_{j-1,1} + EP_{j-1,j,pm}$ for pm = 1,2 (1) (2) starting time of cooking job *j* on pre-mixer *pm* is at least the time at which the previous job (*j -1)* started pasteurizing by pl 1 for pre-mixers 1 and 2 + the processing time of pasteurizing job *j-1* + the cleaning necessary between jobs *j-1* and *j* on pre-mixer *pm.*
- $sm_{j,pm} \geq sp_{j-1,2} + al_{j-1,2} + EP_{j-1,j,pm}$ for pm = 3,4 (1) (2). starting time of cooking job *j* on pre-mixer *pm* is at least the time at which the previous job (*j -1)* started pasteurizing by pl 2 for pre-mixers 1 and 2 + the processing time of pasteurizing job *j-1* + the cleaning necessary between jobs *j-1* and *j* on pre-mixer *pm.*
- $if\ apx_{j,pm} = 1\ then\ \sum_{t=0}^{T} d_{j,pm,t} \geq 0$, else $\sum_{t=0}^{T} d_{j,pm,t} = 0$ (3) a job *j* can only be sent to a pre-mixer *pm* if the job can be processed on that pre-mixer *pm*
- $4000 * apx_{j,pm} \geq \sum_{t=0}^{T} d_{j,pm,t}$
- $MixI_{at,t} = \sum_{j=1}^{J} \sum_{x=1}^{5} mix_j * (\frac{m_{j,at,t} - n_{j,at,x,t}}{m_{j,at,t} - n_{j,at,x,t}})$ (5) the base mix that is in aging tank *at* at time *t* is determined by evaluating all jobs that have been sent to the aging tank and all the jobs that are sent to the attached packaging line from the same aging tank.
- $if\ MixI_{at,t} = mix_j\ and\ ATX_{at,t} = 0\ (at\ does\ not\ supply\ pack\ line)\ or\ CC_{at,t} = 0\ (= (4)), then\ MixR_{j,at,t} := 1, else\ MIXR_{j,at,t} = 0$ (5) (6) a job *j* can be sent to an aging tank *at* if the base mix in the aging tank *at* is the same as of job *j* and the aging tank *at* is not supplying the attached packaging line at time *t*. Also, the job *j* can be sent to an aging tank *at* if it is empty.
- $if\ (1 - MixI_{at,t} - Mix_j > 0, and\ 1 - ATX_{at,t} > 0)\ or\ CC_{at,t} = 0\ then\ MixR_{j,at,t} = 1$
- $C_{at,a,t} = \sum_{t=0}^{t} \sum_{j=1}^{J} \sum_{x=1}^{5} (CMax_{at} - m_{j,at,t} + n_{j,at,x,t}) * MixR_{j,at,t} * atpack_{j,at}$ (4) (5) (6) the amount of volume space for job *j* available in aging tank *at* at time *t* depends on the maximum capacity of the aging tank, the volume of all jobs that were sent to the AT and the volume of all jobs that were sent to the attached packaging line from the AT.

2. Assign a job to a PM

- Decision number 1: $if\ C_{at,j,t} \geq 4000, then\ d_{j,pm,t} \geq 0, else\ d_{j,pm,t} = 0$
- $\sum_{t=0}^{T} \sum_{pm=1}^{4} l_{j,pm,t} = 1$
- $d_{j,pm,t} = 4000 * \mathrm{l}_{j,pm,t}\ \forall y \in Y, j \in J, m \in M, g \in G, t \in T$ (7) A job *j* must be sent completely or not to a pre-mixer *pm* at time *t*

Step 2 - Pasteurizing the job of step 1:

3. Determine starting time of pasteurizing a job

- $PLJ_{j,1} = \sum_{t=0}^{T} \sum_{pm=1}^{2} l_{j,pm,t}$ (8) Whether a job *j* will be processed by pasteurization 1 depends on whether it is cooked in pre-mixer 1 or 2
- $PLJ_{j,2} = \sum_{t=0}^{T} \sum_{pm=3}^{4} l_{j,pm,t}$ (8) Whether a job *j* will be processed by pasteurization 1 depends on whether it is cooked in pre-mixer 1 or 2
- $sp_{j,pl} \geq + \sum_{t=0}^{T} \sum_{pm=1}^{4} (sm_{j,pm} + ap_{j,pm}) * l_{j,pm,t} + EL_{j-1,j,pl}$ (9) (10) starting time of pasteurizing job *j* on pasteurization line *pl* is at least the time at which job *j* was cooked in

pre-mixer *pm* + the processing time of job *j* on pre-mixer *pm* + the cleaning necessary between jobs *j-1* and *j* on pasteurization line *pl.*

- $sp_{j,pl} \geq sp_{j-1,pl} + al_{j-1,pl} + EL_{j-1,j,pl}$ (9) (10) starting time of pasteurizing job *j* on pasteurization line *pl* is at least the time at which the previous job (*j – 1)* was pasteurized at pasteurization line *pl* + the processing time of job *j – 1* on pasteurization line *pl* + the cleaning necessary between jobs *j-1* and *j* on pasteurization line *pl.*

Step 3 - Sending a job to an AT:

4. Send a job to an AT from a PL

- $if\ atpack_{j,at} = 1\ then\ \sum_{t=0}^{T} m_{j,at,t} \geq 0, else\ \sum_{t=0}^{T} m_{j,at,t} = 0$ (11) a job *j* can only be sent to an aging tank *at* if the aging tank is attached to the destined packaging line
- $\text{if } \mathrm{CC}_{at,t} - \mathrm{CC}_{\mathrm{at,t-1}} > 0 \text{ and } \mathrm{CC}_{\mathrm{at,t}} > 0; \text{thus if } (\mathrm{CC}_{at,t} - \mathrm{CC}_{at,t-1}) * \mathrm{CC}_{at,t} > 0 \text{ then } \mathrm{ATX}_{at,t} = 1, \text{and } \mathrm{ATPL}_{j,at,x,t} = 1, \text{else } \mathrm{ATX}_{at,t} = ATPL_{j,at,x,t} = 1$. (12) an aging tank at is supplying the attached packaging line at time t when the difference between tank volume at time $t\text{-}1$ and time t is greater than 0
- $If ATX_{at,t} = 0, then\ m_{j,at,t} \geq 0\ , else\ m_{j,at,t} = 0$ (12) when an aging tank at is supplying the attached packaging line at time t, no other job j can be sent to the aging tank at at time t
- $sa_{j,at} \geq \sum_{pl=1}^{2} (sp_{j,pl} + al_{j,pl}) * PLJ_{j,pl}$ (12) the starting aging time of job *j* is the starting pasteurizing time of job *j* + the pasteurizing processing time of job *j* at pasteurization line *pl*
- $u_j = sa_{j,at} + 120$ (16) the delivery time of job *j* is the starting time of aging job *j* in aging tank *at* + 120 minutes

Step 4 - supplying the packaging lines

5. Send a job from an AT to a packaging line

- $\sum_{at=1}^{AT} \sum_{t=0}^{t} n_{j,at,x,t} = \sum_{t=0}^{t} Demand_{j,x,t}$ (13) the total volume of all jobs j that is sent from all aging tanks at to packaging line x until time t is the same as the demand of job j by packaging line x until time t
- $if\ Line_i - Line_j = 0\ then\ SLine_{i,j} = 1\ else: SLine_{i,j} = 0$ (14) (15) SLine gives a 1 as a value when the destined packaging line of jobs i and j are the same
- $Demand_{b,x,t} = Demand_{b,x,t+\sum_{j=1}^{b-1}(u_j - o_j)*q_j*SLine_{b,j}}$ (14) when a job j is late, all demand from packaging line x after the due date of job j is moved to the point in time $u_j - o_j$, which is the demand of all jobs b required after job j
- $o_b = o_b + \sum_{j=1}^{b-1} (u_j - o_j) * q_j * SLine_{b,j}$ (15) a due date of job b is changed with the difference between the delivery times and due dates from all jobs prior to job b that were late and have the same destined packaging line
- $if\ t \geq u_j, then\ n_{j,at,x,t} \geq 0; thus\ t - u_j > 0, else\ n_{j,at,x,t} = 0$ (16) a job *j* can only be sent to the attached packaging line (x) when the time *t* is larger or equal than the delivery time of job *j*
- $\sum_{at=1}^{AT} \sum_{j=1}^{J} ATPL_{j,at,x,t} \leq 1$(17) > only one job *j* can be sent from one aging tank *at* to the attached packaging line *x* at time *t*

6. Determine if job is late

- $if\ u_j > o_j; thus\ u_j - o_j > 0, then\ q_j = 1$ (18)
- $\sum_{t=0}^{T} \sum_{pm=1}^{4} d_{j,pm,t} = \sum_{t=0}^{T} \sum_{at=1}^{AT} m_{j,at,t} = \sum_{t=0}^{T} \sum_{at=1}^{AT} \sum_{x=1}^{5} n_{j,at,x,t} = 4000$ all jobs j must be sent to a pre-mixer pm, an aging tank at and to a packaging line x

G. Improving heuristic

First, a feasible solution is created, whereafter, changes to the heuristic to improve the schedules are investigated. This should be possible because the objective value of the heuristic is very high. This is done by communicating with the operators and managers of the planning department. Possible improvements are indicated by comparing the heuristic's schedules with the current way of planning. Also, possible efficiency improvements of the model are evaluated to minimize running time. The differences between the heuristic's solution and the current way of planning (the way operators plan) are the following:

Table 20 - Improvements in the creation of the constructive heuristic

Component	Heuristic	Operators	Difference
Updating order list	In the previous model, the order list was not updated, and now it is. Orders that are produced are removed from the list		In the new situation the model does not have to consider the whole order list, which results in a lower running time
Orders	A run of a SKU at packaging is seen as one order	A run of a CUC at packaging is seen as one order	One production run at packaging can contain of several different SKUs to be made, but all are the same CUC. The operators consider this as one run, the heuristic considers it as multiple runs
Aging strategy	A mix is available to consume by the packaging lines if the AT meets the restrictions of aging	When a mix is more than 120 minutes in the tank and no other mix is added to the AT, the mix is available to be consumed by packaging	In the heuristic, it happens that a mix was already over 120 minutes in an AT without another mix added, but the aging restrictions were not met
Mixing before production runs of packaging lines	Mixes are made according to the EDD-priority rule	ATs are filled as following (all tanks are filled with the mix that will be consumed by packaging fist) * 1000: Line 1: 1 tank (20L) full Line 2: 3 tanks (8L) full Line 3: 3 tanks (4L) full Line 4: 4 tanks (8L) full Line MAD: 1 tank (4L) full The sequence of these jobs is based on the lowest total changeover time. This means that the lightest in colour is produced first, then the darker one, etc.	The result of the way of planning before the runs start, is that this method probably results in less changeover time.

Table 21 - Improving the heuristic

Schedules

In Table 22, a part of the schedules of the pre-mixers is given. Every pre-mixer has two columns in the table, where the first is the product that the pre-mixers need to produce or a cleaning, and the second is the starting time of which at the pre-mixer must start cooking the mix. For example, the third job of the first pre-mixer (A1) is cleaning number two, which is cleaning 'X5' and takes five minutes. So, the next job, mix 5247130, can start at -524.968 minutes before 10:00 pm on Sunday, which is around 1:15 pm on Sunday.

Table 22 - Schedule pre-mixers

Prod Pre-mixer A1	Starting Time Pre-mixer A1	Prod Pre-mixer A2	Starting Time Pre-mixer A2	Prod Pre-mixer B1	Starting Time Pre-mixer B1	Prod Pre-mixer B2	Starting Time Pre-mixer B2
8499300	-569.968	8247130	-1440	8499300	-720	9247850	-314.968
8499300	-549.968	8247130	-1421	8499300	-694	9247850	-287.968
2	-529.968	8247130	-1402	2	-668	9247850	-260.968
8247130	-524.968	8247130	-1383	8247130	-663	7	-233.968
8247130	-505.968	4	-1364	8247130	-638	8499300	-143.968
8247130	-486.968	8499300	-1343	4	-613	8499300	81.0323
8247130	-467.968	8499300	-1323	8499300	-592	8499300	107.032
8247130	-448.968	8499300	-1303	8499300	-566	8499300	133.032
4	405.161	8499300	-1283	4	-540	8499300	159.032
8499300	426.161	8499300	-1263	8517630	-519	8499300	185.032
8499300	485.161	8499300	-1243	8517630	-517	8499300	484.032
8499300	505.161	2	-1223	4	-515	7	510.032
8499300	730.455	8247130	-1218	8499300	-494	9247850	600.032

In Table 23, a part of the schedules of the pasteurization lines is given. As can be obtained from this table and the previous, is the direct link between the schedules. For example, the starting time of the first job of pre-mixer A2 is 19 minutes before the starting time of the same job at pasteurization line A.

Table 23 - Schedule pasteurization lines

Mix produced PL A	Starting Time PL A	Mix produced PL B	Starting Time PL B
8247130	-1421	8499300	-694
8247130	-1401	8499300	-667
8247130	-1381	2	-640
8247130	-1361	8247130	-633
4	-1341	8247130	-606
8499300	-1302	4	-579
8499300	-1282	8499300	-545
8499300	-1262	8499300	-518
8499300	-1242	4	-491
8499300	-1222	8517630	-470
8499300	-1202	8517630	-443
2	-1182	4	-416

Lateness

In the table below, an overview is given of all late orders per packaging line. As can be obtained from the table for example is that packaging line 3 had the line stopped because mix 8247130 was not available at time 2508 (minutes after Sunday 10:00 pm), and that mix finished aging 190 minutes later (2698 - 2508). Since that is the only late order on the list for that line, the total lateness of packaging line 3 = 190 minutes.

The total lateness of the heuristic per line is as following:

Packaging line	Total lateness (minutes)
1 `	0
2	1212
3	195
4	70
5	1007
Total	2482

This results in the following total costs of lateness:

$$10 * 1642 = 24820$$

Table 24 - All late orders per packaging line

Packaging line 2			Packaging line 3			Packaging line 4			Packaging line 5		
Mix	Start time mix late	Mix available time	Mix	Start time mix late	Mix available time	Mix	Start time mix late	Mix available time	Mix	Start time mix late	Mix available time
8.25E+06	-141	521.755	8.25E+06	2508.4	2703.7	8.60E+06	3855	3925.4	9.25E+06	120	1124.79
8.25E+06	573.355	839.382	0	0	0	0	0	0	9.25E+06	1403.19	1405.79
6.83E+07	4990.18	5117.7	0	0	0	0	0	0	0	0	0
8.25E+06	8490.9	8647	0	0	0	0	0	0	0	0	0

Changeover times

In Table 22 - Schedule pre-mixers, the changeovers between products are indicated by a single figure. For example, in the fourth row and the first column the figure 2 represents changeover 2. As can be obtained from A, this represents the changeover 'X5', which takes 11 minutes.

The total changeover times of the heuristic are as following:

Machine	Changeover time (minutes)
Pasteurization line 1	1657
Pasteurization line 2	1078
Pre-mixer 1	1238
Pre-mixer 2	586
Pre-mixer 3	718
Pre-mixer 4	769

These changeover times result in the following total costs of changing over:

$$1.5 * (1657 + 1238 + 586) + (1078 + 718 + 769) = 7787\ minutes$$

Objective value

Finally, the result of the heuristic is measured according to the objective value:

$$24820 + 7787 = 32606\ minutes$$

Running time

Since the model will be used to re-schedule, the time it takes to run the model, the running time, is important. The running time of the heuristic is 10.7 seconds.

Output of the improved heuristic

In paragraph G, the improvements of the heuristic are discussed. Summarized, the following improvements are executed:

- Updating the order list: when a job is allocated to a machine, the job is removed from the order list, which results in fewer jobs to pick from
- Orders: the previous model considered every different CUC (and the same SKU) as one run, as it is seen by the operators as one
- Sequence of batches: instead of producing one batch at a time on a machine for a specific line, multiple batches for the same line can be processed simultaneously.
- Aging strategy: some mixes were in the previous heuristic already ready to be processed by the packaging lines, while the restrictions of aging were not met. The aging strategy has changed
- Mixing before production runs of packaging lines: the first few batches before the production runs of the packaging lines at the beginning of a week is optimized according to the current strategy of the operators.

First, the first two components are included in the model. This results in the following:

1. The new running time is 4.3 seconds (which is a reduction of 59.8%)

Thereafter, the next two components are included. This results in the following:

2. Lateness: there is no more lateness at any line
3. The total 'weighted' changeover time of the machines at the mixing department is 7522
4. Objective value: 7522

After adding the fifth component, the total 'weighted' changeover time was reduced to 6692 and the total lateness remained zero, so an objective value of 6692 is obtained. Weighted means that the total changeover time of mixing line A is multiplied with 1.5. This last objective value was used in the determination of the simulated annealing settings and will be used further in this research.

Idle time

The heuristic picks in every step a job to produce when an AT for that job is available to send a mix to. This results in the situation that a cleaning will be done when a mixer can start cooking the next job. In practice, it works the same way, operators start cleaning the mixing lines when it is sure what product will be produced next. In the first iteration of simulated annealing, it is chosen to not alter the initial schedule at all, to check whether this could be improved. This is indeed the case, the model schedules cleanings between jobs before a job can be processed, because it already knows what job will be processed next. This results in a total idle time (on all machines of the mixing department) reduction of 264 minutes. This component is not included in the objective value. However, this component does improve the solution because the true goal is to improve utilization. All solutions that are evaluated have zero idle time, because it is in all situations already known what product will be produced next.

H. Settings of Simulated annealing

Simulated annealing is performed using a move operator. Three experiments are set:

1. Using a move operator that moves jobs to a point in time with a time difference of at most six hours
2. Using a move operator that moves jobs to a point in time with a time difference of at most 12 hours
3. Using a move operator that moves jobs to a point in time with a time difference of at most 24 hours

First, the best settings of the second experiment are investigated. Thereafter, it is analysed whether these settings are the best for the other experiments.

Starting temperature

There are multiple ways to determine the start temperature for simulated annealing. We use the method that is recommended by Ledesma, Aviña, & Sanchez (2008). We set the start temperature, Ts, in such a way that during the first cooling stage, the probability of accepting a worse solution is roughly equal to 80%. This first cooling stage is equal to the number of possible neighbours. Because this number is excessively large, we choose a cooling stage of 250 iterations. Further in this research, some experiments are set to be evaluated.

Table 25 - Probability of accepting worse per starting temperature

Start temperature	Probability of accepting worse
400	0.921739
360	0.909297
320	0.864143
280	0.856813
240	0.844978
200	0.844098
160	0.819383
120	0.736383
80	0.746445

The average increase of the objective value when accepting a worse solution is 34.01. With this value, the starting temperature can be determined. This is $T_s = \frac{-\Delta}{\ln(0.8)} = \frac{-34.01}{\ln(0.8)} = 152$. So, the starting temperature is set at 152.

Decreasing factor, end temperature and Markov chain length

The running time is around two thirds of a second per iteration. For both initial scheduling and re-scheduling, the model can take at most 20 minutes. The operators are willing to wait (when re-scheduling) for 20 minutes for the model to come up with a solution, which is equal to the average time one batch can be processed on mixing line A, and the time the operators can wait until the decision has to be made which batch need to be cooked next. For the sake of simplicity, the maximum time for initial scheduling is also set at 20 minutes. Because it can take the model at most

20 minutes to run, around 1800 iterations ($\frac{60*20}{\frac{2}{3}}$) can be executed. The settings of the simulated annealing model need to be modified to the availability of time.

The decreasing factor is the factor a with which the temperature is decreased after m number of iterations (length of Markov chain). The decreasing factor is often set between 0.8, and 0.99. The end temperature is the temperature at (below) which the model will stop running. So, when the temperature drops below the end temperature, the model stops running. To verify what end temperature is best, it will be investigated after what temperature no significant improvements are obtained (improvement is considered significant when it improves the objective value with at least 1%). Several experiments with different decreasing factors are set, see Table 26. All have the same starting temperature of 152.

Table 26 - Decrease factor and end temperature with no significant improvement

Decrease factor	End temperature after which no significant improvement
0.8	8.36
0.825	15.11
0.85	29.92
0.875	34.99
0.9	42.93
0.925	64.48
0.95	91.01

With a decrease factor of 0.8, the solution will not be significantly improved at a temperature of 8.36. Therefore, the end temperature is set at 8.

Successively, the best decrease factor and Markov chain length can be set. This will be done simultaneously because they are correlated. As mentioned, for initial scheduling, the model can execute around 1,800 iterations. So, first the best settings for initial scheduling will be determined. To do so, several settings are evaluated twice. This is done twice, because there is some randomness in the simulated annealing process, and to execute the model twice, the probability of finding the right settings is higher. The length of the Markov length is based on the set decrease factor. The length of the Markov chain length can be calculated as follows: $\frac{maximum\ number\ of\ iterations}{\log_{decrease factor}\frac{end\ temperature}{start\ temperature}}$. So, when the decrease factor is 0.8, the start temperature is 152, and the end temperature is 8, the Markov chain length is: $\frac{1800}{\log_{0.8}\frac{8}{152}} = 136$.

Table 27 - Experiments to set simulated annealing for initial scheduling

Start temperature	End temperature	Decrease factor	Markov chain length initial scheduling	Best objective I (1)	Best objective I (2)
152	8	0.8	136	17.8%	17.9%
152	8	0.825	118	18.7%	18.9%
152	8	0.85	99	18.9%	18.8%
152	8	0.875	82	18.9%	18.9%
152	8	0.9	64	18.9%	18.9%
152	8	0.925	48	11.8%	12.5%

152	8	0.95	31	7.4%	7.8%

As can be obtained from the table above (Table 27), there are some differences in the objective value of the experiments. This is the result of the randomness of simulated annealing: simulated annealing searches for a random job to move to a random place of a sequence of a random machine. Not all moves are evaluated, and therefore there are differences in the outcomes.

Although the results are partly based on randomness, the best settings of the simulated annealing for initial scheduling purposes are a decrease factor of 0.85, and a Markov chain length of 99. The results of the first five experiments do not differ much. These settings are used to determine next parameters. Whenever necessary, additional experiments with different parameters can be executed. These parameters will be used for the experiments further in this research.

For re-scheduling purposes, the model can execute around 1,800 iterations as well. To be able to set proper experiments, one real example of re-scheduling is used. The real example is a moment where it was necessary to re-schedule. The following data is altered or set according to the real time data at the first time a re-scheduling was necessary: the current volumes and the mixes per aging tank are set, the jobs that are already processed are removed from the order list, and the alterations of the planning department are considered. First, the heuristic for re-scheduling is executed. Successively, the simulated annealing is performed. In Table 28, the results of the different settings are given. The improvements in the last two columns are improvements compared to the objective value of the heuristic for re-scheduling. The objective value of the heuristic for re-scheduling was 5886. This comes from the cleanings from the moment the re-scheduling was executed until the end of the production runs of the packaging lines.

Table 28 - Experiments to set simulated annealing for re-scheduling

Start temperature	End temperature	Decrease factor	Markov chain length re-scheduling	Best objective R (1)	Best objective R (2)
152	8	0.8	136	12.6%	11.5%
152	8	0.825	118	13.2%	13.4%
152	8	0.85	99	11.7%	12.1%
152	8	0.875	82	10.1%	10.1%
152	8	0.9	64	8.4%	5.9%
152	8	0.925	48	3.8%	5.6%
152	8	0.95	31	4.8%	4.7%

The best settings of simulated annealing, given the solutions are partly based on randomness, for re-scheduling are a decrease factor of 0.825, and a Markov chain length of 118.

In Appendix I, the trend of the objective value when performing simulated annealing is shown. The first two experiments work properly when using the settings as stated above. However, because of the use of penalties when performing simulated annealing with a time difference limit of 24 hours, the settings are possibly not the best for the third experiment. This will be investigated next.

Settings of simulated annealing with the move operator and a time difference limit of 24 hours

The same procedure to determine the best settings for simulated annealing is repeated. The best starting temperature for this experiment was 168. Thereafter, the end temperature can be set.

Table 29 - Decrease factor and end temperature with no significant improvement (24h.)

Start temperature	End temperature after which no significant improvement
168	9.2
168	11.4
168	10.6
168	15.2
168	25.2
168	41.3
168	66.7

The best end temperature was 9, according to Table 29.

Successively, the best decreasing factor, end temperature and Markov chain length can be set (Table 30).

Table 30 - Experiments to set simulated annealing for initial scheduling (24h.)

Start temperature	End temperature	Decrease factor	Markov chain length	Best objective (1)	Best objective (2)
168	9	0.8	137	12.2%	12.0%
168	9	0.825	118	13.3%	13.8%
168	9	0.85	100	15.9%	15.7%
168	9	0.875	82	15.5%	15.4%
168	9	0.9	65	13.8%	14.0%
168	9	0.925	48	12.0%	11.9%
168	9	0.95	32	11.9%	12.1%

So, the best settings for the experiment with a time difference limit of 24 hours, when initial scheduling, are: (i) a starting temperature of 168, (ii) an end temperature of nine, (iii) a decrease factor of 0.85, and (iv) a Markov chain length of 100.

Also, the best settings for this experiment when re-scheduling is investigated. The best settings are:

- Starting temperature: 168
- End temperature: 9
- Decrease factor: 0.875
- Markov chain length: 82

The best improvement for this experiment was (1) 11.4% and (2) 11.3%.

I. Sensitivity analysis simulated annealing

As mentioned, three different experiments are set to be evaluated: move jobs to a point in the sequence of jobs at a random machine with a difference in time of at most 6, 12, and 24 hours. To illustrate the effect of the settings, a figure per experiment is given. This is the simulated annealing part for initial scheduling purposes. From the figures, the progression of the objective value is given. The blue lines represent the objective value per iteration of the simulated annealing. Again, the output of the simulated annealing will be discussed for both initial scheduling as for re-scheduling purposes. Besides the effect of simulated annealing on the objective value, the effect of the number of re-scheduling purposes is evaluated. At every re-scheduling point it is evaluated whether re-scheduling is necessary or not. It has been decided that it is necessary to re-schedule when at least one job will be late when the current schedule will be followed. On the y-axes of the figures below, the objective value per schedule is given, and on the x-axes the iteration number is represented.

Output of simulated annealing for initial scheduling purposes

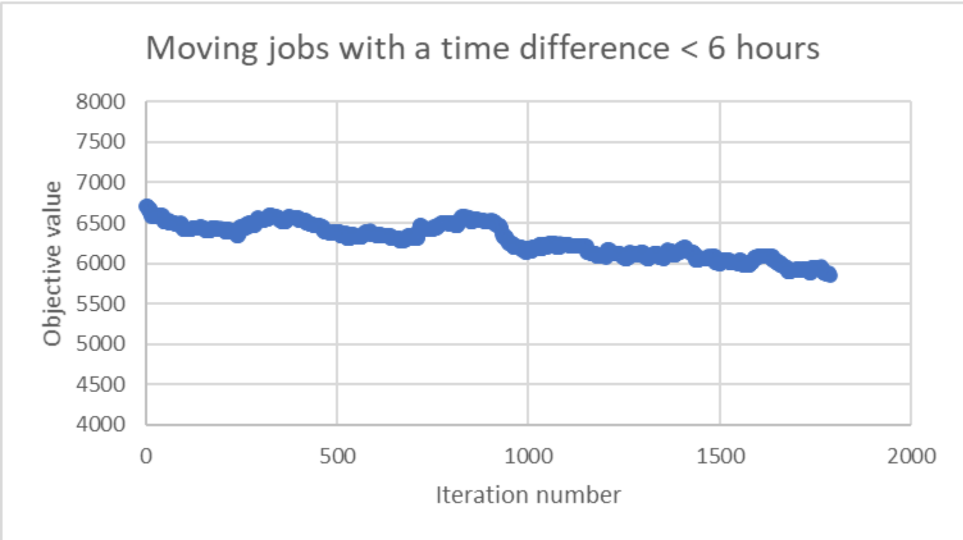

Figure 17 - Moving jobs with a time difference < 6 hours

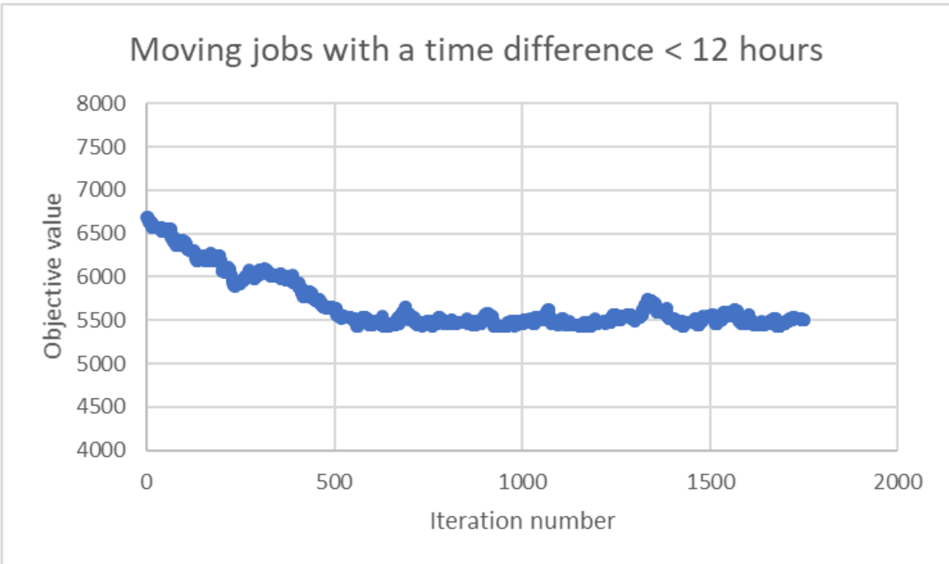

Figure 18 - Moving jobs with a time difference < 12 hours

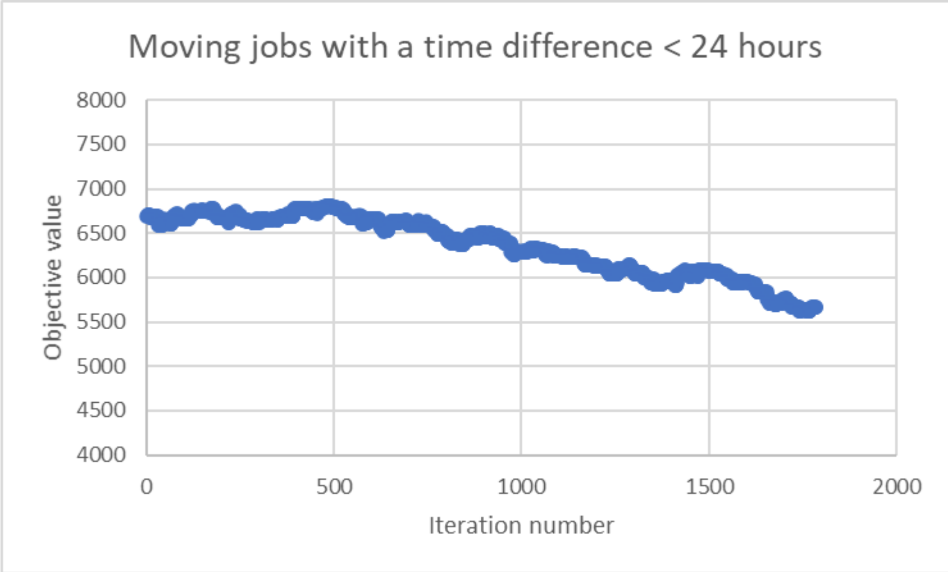

Figure 19 - Moving jobs with a time difference < 24 hours

In all experiments, the objective value has improved. In the first experiment (< 6 hour's time difference), the improvement per iteration is relatively small, which is logical since there are not many neighbours to evaluate. The total improvement of the first experiment is (13.6%). The second experiment (< 12 hour's time difference) has the best improvement of all experiments (18.9%). In the beginning of the simulated annealing (until 500 iterations), there are many improvements, whereafter the objective value does not improve much. The last experiment, there are many fluctuations in the objective value. This is because in the last experiment many infeasible solutions were created. The improvement of the last experiment is 10.0%.

J. Re-scheduling

From the picture below, it can be obtained how schedules created before or during a production week result in the actually executed production schedule.

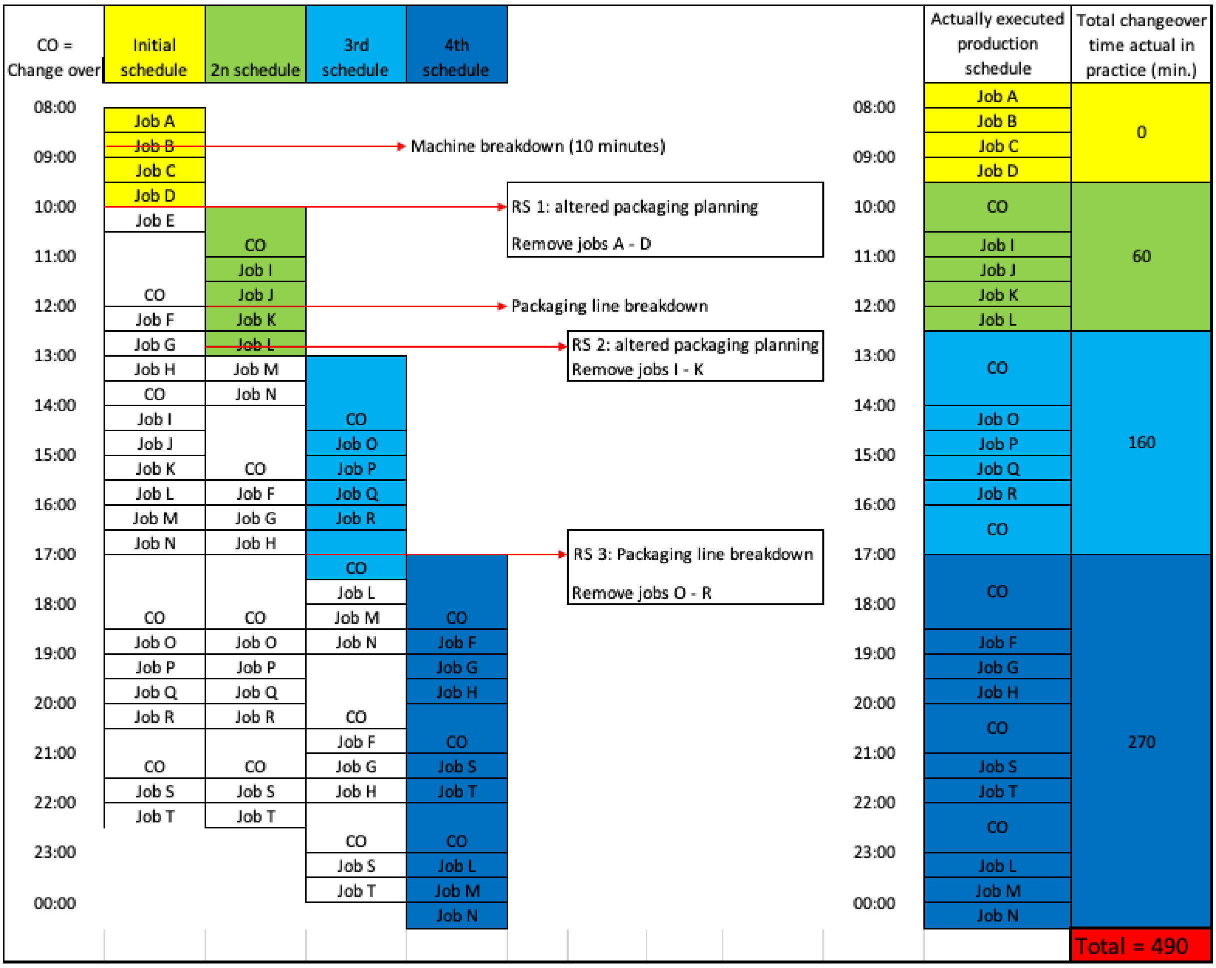

Figure 20 - Re-scheduling activities example

K. Analysis on actually executed and actually created production schedules

First, it is important to compare the actually created production schedules created when initial scheduling and re-scheduling to the actually executed production schedule changeovers during a production week. As mentioned, all schedules created in a production week (actually created production schedule) are known. The result of the actually created production schedule is the actually total planned changeover time. Also, the actually executed production of the mixing department is known. This means that how jobs are really executed is known, both the sequence and the times at which the jobs are executed are known. The result of the actually executed production schedule is the actual total changeover time in practice. There can be some differences between these schedules because it can happen that a mistake is made in the process, and it leads to an extra changeover. The differences below represent the percentual differences between the actually executed production schedules and the actually created production schedules in a production week which is the difference between the actually total changeover time in practice and the actually total planned changeover time. The difference of 0.7% (week 10) means that the actual total changeover time in practice was 0.7% more than was planned in the schedules created in production week 10.

- Week 10: 0.7%
- Week 11: 0.3%
- Week 12: 0.4%
- Week 13: 0.9%

The actual total changeover time in practice will be used further to analyse the constructive and the simulated annealing. These total changeover times are the same as used in chapter six.

The evaluation of the heuristic for re-scheduling for one complete production week is done as follows (the production week that will be used as an example had seven alterations to the initial schedule) according to the example given in Appendix J: first, the constructive heuristic will be used to make an initial schedule. Then, the simulation will run until the first event in time where re-scheduling was necessary (RS 1); a re-scheduling point.

Then, the status of all relevant components (PMs, PLs, ATs, demand packaging lines) will be evaluated, and the necessity of re-scheduling is determined. If re-scheduling is necessary, the constructive heuristic will create a new schedule for the remaining part of the production week; so, from the moment in time where re-scheduling was necessary until the end of the production week. This process is repeated until the end of the production week.

The total changeover time of week 13 when using the constructive heuristic is 7283 minutes. The actual total changeover time in practice of this production week (week 13) was 7468 minutes. Therefore, the schedules created by the constructive heuristic result in 2.5% less changeover time. This improvement is not very significant. However, the schedules created while using this method for re-scheduling are very similar to the actual executed production schedule.

The running time of the executions of the constructive heuristic is given in the third column. In the table, RS stands for re-scheduling point. As mentioned before, the maximum time a model can take to run is about 20 minutes. Therefore, the running time of all the executions of the constructive heuristic is very acceptable.

This evaluation process is executed three more times for weeks 10, 11, and 12; see results in Table 14. Week 13 represents the production week as mentioned in the previously given example. The number of re-scheduling points represents the number of times it was necessary to re-schedule in a production week, and the average running time represents the average time it took the model to run the constructive heuristic.

As is done for the evaluation of the constructive heuristic for re-scheduling, also the output of simulated annealing for re-scheduling purposes will be evaluated. This is done in a comparing way. That means that simulated annealing is executed to create a schedule, whereafter, the simulation model runs until the first event, the necessity of re-scheduling is determined, re-scheduling is executed if necessary, and this is repeated until the end of the production week. In, an overview is given of the results of the constructive heuristic and the simulated annealing for re-scheduling purposes. The improvements in columns four, five, six, and seven are percentual improvements compared to the actual total weighted changeover time in practice.

L. Aging tank buffers

Since there are differences in the number of aging tanks per packaging line, the buffers per line differ:

- Packaging line MAD: zero buffer tanks. This will not improve the objective value because this packaging line produces only one product
- Packaging line 1: one buffer tank of 4,000 litres
- Packaging line 2: one buffer tank of 8,000 litres
- Packaging line 3: one buffer tank of 4,000 litres
- Packaging line 4: one buffer tank of 8,000 litres

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