MASTER

Scheduling a multi-product multi-stage batch processing plant, with dissimilar parallel lines, and intermediate storage space and time restrictions

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Scheduling a multi-product multi-stage batch processing plant, with dissimilar parallel lines, and intermediate storage space and time restrictions

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in partial fulfilment of the requirements for the degree of

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in Operations Management and Logistics

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scheduling, hierarchical batch-sizing and production line-assignment, MILP, multi-product, multi-stage, batch plant, heterogeneous parallel lines, intermediate storage time restrictions

Preface

This thesis presents the results of a research project in partial fulfilment of the requirements for the degree of Master of Science in Operations Management and Logistics at the Eindhoven University of Technology. The project has been executed at Nutricia Advanced Medical Nutrition in Zoetermeer, The Netherlands.

During my previous study, I had a student job as a secretary on a chemical batch processing plant. At that time, an industrial engineer developed a plan to double the existing plant's capacity and build a new plant in China. By the time I graduated (three years later) both plants were running successfully. That experience was the inspiration to start studying Industrial engineering, and finally search a research assignment in a batch processing plant. When my dear neighbour Chris suggested a challenging project at Danone, I didn't hesitate. Although in times, the project was more challenging than I had foreseen, I have not rued my choice once. Danone's no-nonsense culture, great colleagues and short communication lines make it a great working environment. In the area of production planning Nutricia stands for a challenge in which I have enjoyed thinking along.

I thank dr. ir. S.D.P. Flapper and dr. ir. H.P.G. Van Ooijen for their practical help and their encouragement. Our discussions and their extensive experience in anticipating problems and avoiding pitfalls, and analysis, modelling, and reporting, are truly inspirational and helped enormously in making this project an exceptionally rewarding experience for me.

I would also like to extend my special thanks to Hugo van Daal, Sijmon Hagen, and Heike Zappeij. They provided the opportunity to see all useful angles in the production and planning of operations and offered the base for a project I worked on with great pleasure. Moreover, them sharing their insights, visions, and experiences, and the helpful suggestions, provided me with many new insights, which were, for me, the icing on the cake during the project.

I would like to acknowledge the contributions to this thesis of my colleagues during this semester. I thank the schedulers, Bram and Ronald, who endlessly provided me their data and explanation. I thank the engineering department, and especially Rinse and Jessica, for their input during the process and for their generosity in sharing their findings. Similarly, I want to acknowledge the MPS-planners, the department heads and team leads for their support throughout this study and especially in participating in mapping the processes and problems in the factory.

I would like to thank the consultants at Aimms for their help on compact modelling and the design of the interactive software, and Fons Hofstra for spending a lot of time in providing me with extra computational powertools.

I deeply acknowledge my dearest family (in-law) and friends for all mental support and Rian de Putter for her superb editing. Finally, I want to thank the one person who was most encouraging and patient during this process, providing me with both great mind and stomach support, Maarten.

Jacqueline de Putter

Eindhoven, July 2011

Abstract

This report adds insights to research on batch scheduling models for comprehensive production environments. Previous work on batch scheduling models primarily concerns Mixed Integer Linear Programs (MILPs), for more elaborate models often NP-hard, and models to solve the Economic Lot-Scheduling Problem (ELSP), mostly dedicated to the single line, one-bottleneck situation, largely neglecting coordination between lines. Moreover, both approaches hardly ever consider perishability of intermediates and load balancing between lines and multiple stages. The presented method combines the benefits of ELSP and MILP models to address a large-scale practical problem.

The problem concerns a production scheduling model for a multi-product multi-stage batch processing plant, with heterogeneous parallel lines with and without sequence-dependent cleaning times, intermediate storage space and time restrictions, a sequential process structure with entwined routes and a high utilization level in all stages, and a divergent product structure. Demand is stable and production decisions are made periodically. The proposed model considers the costs resulting from production cycle stock as in most Economic Lot-Scheduling Models and cleanings comparable to the setups in most Economic Lot-Scheduling Models, but also includes, unlike most Economic Lot-Scheduling Models, the relevant costs of labour, costs of cooling intermediate storage tanks, perishability of intermediates and finished goods, coordination, and utilities.

The problem is decomposed into two steps. The first step considers cost-efficient processing lines and batch sizes in the production stage with the highest cleaning time between two subsequent batches, accounting for shelf life, technologically allowed batch sizes, and coordination between lines in terms of utilization and batch splitting. The second step consists of an MILP, scheduling the batches determined in the first step, with the aim to minimize the identified relevant costs. In addition, to reduce problem size further, the problem is solved in relative instead of absolute time.

Keywords

scheduling, hierarchical batch-sizing and production line-assignment, MILP, multi-product, multi-stage, batch plant, heterogeneous parallel lines, intermediate storage time restrictions

Summary

The goal to continue achieving a [redacted] to [redacted]% annual output growth, as they did during the past decade, is for Nutricia the initial motivation to set a research project in motion. As demand forecasts for the coming years have been sharply cut back, the pressure on production capacity expansion has decreased. The pressure on production cost reduction, though, has amplified, in order to continue to increase the market share. Therefore, the question has changed from how to produce the forecasted volumes, into how forecasted volumes can be produced against the lowest cost.

Nutricia's problem is that by reason of its complex production system, the planning department is forced to consider filling lines in isolation. This approach leads to peak loads on the resources employed in the preparation department. The objective desired by Nutricia is to produce forecasted demand at minimal cost of [redacted].

This report adds new insights to research on batch scheduling models for comprehensive production environments. Batch scheduling models hardly ever consider perishability of intermediates and load balancing between lines and multiple stages. The contribution of this research to the contemporary stream of operations research is in the development of a scheduling model for multiproduct multistage batch plants with heterogeneous parallel lines in each stage such that each final product has a partially predefined routing, limited intermediate storage capacity, cleaning times, a high product variety in all stages, and perishable intermediate products, with the objective of producing predefined demand against minimal total costs. The presented method combines the benefits of ELSP and MILP models to address a large-scale practical problem. The problem concerns a production scheduling model for a multi-product multi-stage batch processing plant, with heterogeneous parallel lines with and without sequence-dependent cleaning times, intermediate storage space and time restrictions, a sequential process structure with mixed routes and a high utilization level in all stages, and a divergent product structure. Demand is stable and ordering decisions are made periodically. The proposed model considers the costs resulting from inventories and cleanings, as in most Economic Lot-Scheduling Models, but also includes the relevant costs of labour, intermediate storage, perishability, coordination, and utilities.

As the basis of such an analytical tool, a mathematical model of the system has been constructed. The objective of the model is to find the least costly production schedule, considering the holding, coordination, cleaning and perished product costs while constrained by technical capabilities, requirements, and available capacities of production lines, packaging lines, and storage locations. The scheduling model is modelled in AIMMS and solved with the Cplex to research different scenarios for the next two quarters. The output of the model provides schedules for the first [redacted] months on a weekly basis. The input data is taken from an Excel spread sheet so that it can easily be modified by the users for each period or during scenario analysis, whereas the output is written to an Excel sheet to provide schedules that are easier to use, check and modify.

Testing of the model showed that the model contained too many integer variables to solve on a common pc. Nevertheless, several interesting conclusions can be drawn. The batch size and production line assignment procedure show cost efficiency differences of preparation lines. The decision must be made whether it is preferable to produce on the faster lines with higher setup costs but lower operating costs, creating flexibility through buffer time, or produce cheaper on the slower lines, with the inconvenience of low scheduling flexibility and the risk of service level loss.

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Chapter 1: Introduction

1.1 Problem indication

Because of stringent and detailed characteristics, scheduling in batch processing industries is a challenging task. A predominant characteristic of batch processing industries is that raw materials are blended or reacted in tanks with long setup and cleaning times between subsequent intermediate products that are subsequently stored in intermediate storage tanks with their own specific restrictive characteristics. Generally, later stages in the production system concern the conversion of the smaller range of intermediate products into a wide range of final products, again with distinctive characteristics such as product-dependent processing rates and sequence-dependent cleaning times.

Nutricia Supply Point Zoetermeer is a comprehensive and rather complex example of a batch processing plant. The production process entails multiple production stages, in each stage various production lines with each different capabilities and constraints, sequence-dependent cleaning-times and a divergent product structure, starting with few main ingredients, diverging into [redacted] intermediates, and ending with a final product range of [redacted] unique Stock Keeping Units [redacted]. The complexity stems from a multitude of product-, process-, and production-sequence-specific constraints and interactions' [redacted].

Nutricia would like to discover how newly forecasted volumes can be produced against the lowest costs. Because sequence-dependent cleanings are a major determinant in production cost optimization, a detailed solution approach is required. [redacted]').

In this master thesis project, the problem has been decomposed into a cost-based batch-sizing and production line-assignment method and a Mixed Integer Program (MIP) for start-time decisions. The model (1) provides insight in the current capacity use by taking into account the costs of cleanings, production, holding cycle stock, and perished products, (2) offers the possibility to assess current manual scheduling methods, and (3) facilitates scenario analyses to investigate the consequences of changes in the production system.

1.2 Report Structure

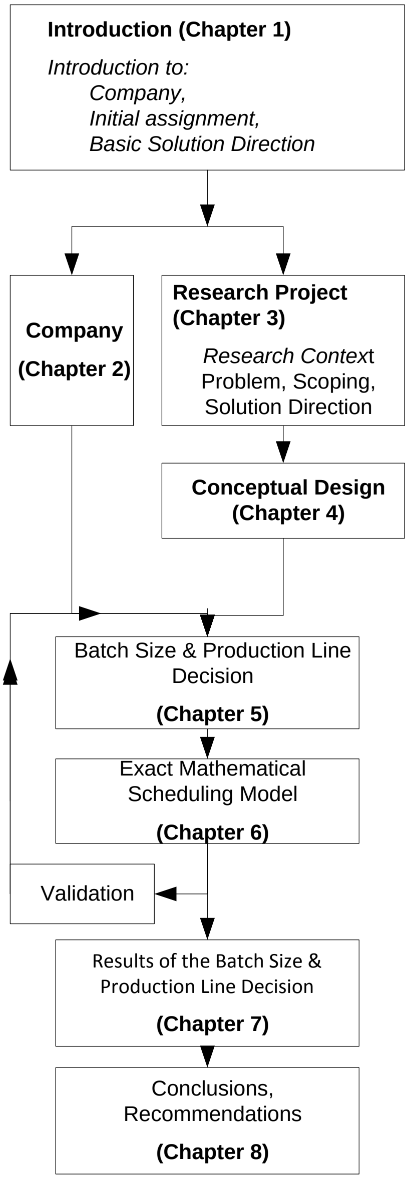


Figure 1: Report outline

Figure 1 illustrates the structure of the report.

Chapter 1 provides an introduction. Since the project takes place in Nutricia N.V., Chapter 2 describes the company and delineates the units of analysis, which are the manufacturing department, detail planning department, and master production schedule department. Chapter 3 describes the research context, the problem and the analysis, which was derived by completing the first steps of a problem-solving project in line with the regulative cycle (Van Aken et al., 2007, see Figure 21). Chapter 4 describes the expected situation (Conceptual design). Chapter 5 provides the proposed approach to solve the batch sizing and line assignment problem based on costs. Chapter 6 presents the mathematical model to solve the scheduling problem. Chapter 7 provides the results of the batch sizing and production line assignment. Chapter 8 provides the major conclusions and the accompanying recommendations.

Chapter 2:

Nutricia

The research has been conducted in Nutricia. This chapter provides the basic information required to comprehend the business problem. Background information concerning the company profile and the market in which Nutricia operates can be found in Appendix B – General Company Information. Section 2.1 describes the general background of Nutricia and Section 2.2 Supply Point Zoetermeer. Section 2.3 describes the products produced and Section 2.4 the production system. Section 2.5 describes the production decisions and by whom these are made.

2.1 Nutricia General

Nutricia was the name of the in 1896 by Martin van der Hagen founded steam dairy company “Wilhelmina”. The medical branch started in 1905 with low-sugar milk for diabetics and iodine-enriched milk for thyroid patients. In 2007, Nutricia became a subsidiary of Danone. The name Nutricia was held as the brand name for medical and baby nutrition.

At present, Nutricia N.V. is market leader and one of the fastest growing international organizations in the rapidly evolving market for Advanced Medical Nutrition, with in 2009 a market share of [redacted]% and sales of [redacted]'. During the past decade, Nutricia was able to achieve annual growths of [redacted] to [redacted]% in terms of both production volumes and margin. This enabled them to keep up with the rapid market growth and increase market share year after year.

Nutricia N.V. consists of the R&D department in Wageningen, the powders department at Supply Point Cuijk, and the ECN (Enteral Clinical Nutrition) Liquids Group at Supply Point Zoetermeer. This project focuses on Supply Point Zoetermeer.

2.2 Nutricia Supply Point Zoetermeer

The ECN Liquids Group, located in Zoetermeer, is the largest Supply Point. Supply Point Zoetermeer produces approximately [redacted]% of the division’s annual turnover of [redacted] and accommodates [redacted] employees of which [redacted]' in production. At Supply Point Zoetermeer, liquid medical nutrition as well as liquid baby nutrition is being developed, produced, and distributed to sales units in [redacted] countries, which in turn record, sell, and supply the products. Since the target groups of Nutricia are babies, the sick, and the elderly, food safety is a main concern.

The products are principally prescribed by medical professionals. The main function areas of the advanced medical nutrition products are among others the application for more rapid recovery, for fewer complications, and against disease-related malnutrition as with cancer, allergies, and metabolic diseases. Product innovation, technology, and strict quality assurance are the core competences of the organization.

2.3 Products

Supply Point Zoetermeer annually produces approximately [redacted]' units final product, categorized in [redacted] recipes (specific combinations of liquid raw materials and powdered ingredients, see Figure 2), and [redacted] SKUs (Stock Keeping Units, i.e. unique combinations of recipe, packaging technology, and packaging size, box type, and label), of which respectively [redacted]' [redacted]' [redacted]' are made at least once per quarter (13 weeks).

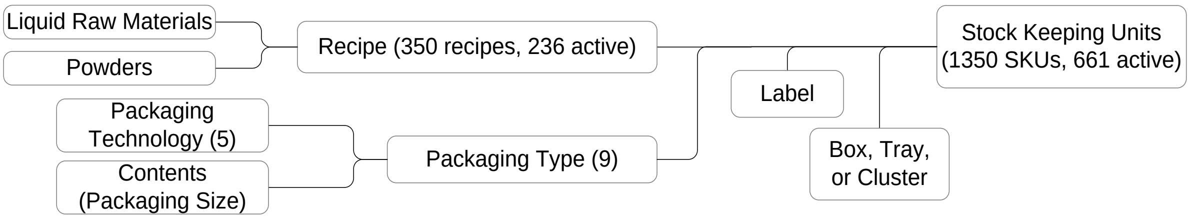


Figure 2: Product Complexity

Each final product requires specific technologies in different stadia in the production process. This makes Supply Point Zoetermeer a complex environment to comprehend. The product range exists of oral supplements in the following packaging technologies:

- Small glass bottles “Ready-to-Feed” (hereafter called “RTF”, [redacted]' [redacted]' [redacted]),
- Tetra (known for its use for milk cartons, here in [redacted]' [redacted])
- Glass bottles (in [redacted]' [redacted]' [redacted]' [redacted]'),
- Plastic bottles (hereafter called “PBF”, in [redacted]'),
- Pouches for intravenous nutrition (tube feeds, hereafter called “Packs”, in [redacted]' [redacted]).

Figure 3: Example Product Types: RTF_[redacted]' [redacted]' [redacted]'

Figure 3 shows an example for RTF, Pack and PBF.

2.4 Production System

Figure 4 presents an overview of the production system of Nutricia Zoetermeer to become acquainted with its processes. A more detailed representation with explanation of individual production lines and storage or buffer units can be found in Appendix C. Below Figure 4, an explanation is provided.

The production plant of Supply Point Zoetermeer consists of three departments (The dark grey blocks in Figure 4): Weighing and Mixing (upper left), Preparation (centre) and Filling (on the right). External suppliers supply powders and liquid raw materials. All finished products are stored in the central DC (Distribution Centre), from which the [redacted] Sales Units (SUs) are supplied.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

2.5 Production Decisions

All production activities are based on [redacted]-week forecasts per SKU by the SUs and planned by two departments: the Master Production Schedule (MPS) department and the Detail Planning (DP) Department. The [redacted]. The production decisions to be made are:

1) Product Families: how to aggregate different SKUs into a “Family” for production purposes
2) Batch Sizes: in which size (the amount of eaches or liters) to aggregate SKU demand of one family into a group of products that can be seen as one in the production processes
3) Production Line Assignments: on which production line should the batch be produced
4) Start Times: at what time should a certain batch start processing in a certain production line

Batch Sizes are determined by the MPS Department, described in Section 2.5.1. Production line Assignment and Start Times are determined by the DP Department, described in Section 2.5.2.

2.5.1 Master Production Schedule

The production decisions made by the MPS department are (1) how to group SKUs into families, and (2) the Batch Sizes (production quantities in eaches) per week for each SKU.

The current planning methods and principles are MRP-based. In addition, the MPS department:

1) aggregates for each filling line the total weekly demand of all SUs per SKU and per label with the same packaging technology-recipe combination and box type,
2) aggregates SKU-demand of subsequent weeks into suitable batches for that filling line:
    a) with technologically allowed batch sizes
    b) that are considered economical, based on average holding costs and an estimate of average cleaning costs
    c) that are smaller than the average demand over the SKUs shelf life period
    d) of which required production and cleaning times together do not exceed the filling line's available hours for one week given the number of shifts employed, by estimating potential sequencing benefits in the filling line, and so preventing unnecessary cleaning in that filling line
    e) of which the sum of the total litres planned does not exceed the estimated volume preparable by the Preparation Department in one week. When the sum exceeds expected feasible production volumes, planned batches of subsequent weeks are reallocated until a plan is found that is expected to be feasible

The MPS planning horizon is rolling and considers [redacted] weeks, because the packaging lead-time is [redacted] weeks. The first [redacted] weeks can be altered as long as enough packaging and raw materials are available for the newly planned products. The final two weeks are frozen to give the DP department the opportunity to schedule the planned products. At present, this method leads to plans and schedules in which each SKU is on average produced [redacted] every four weeks.

2.5.2 Detail Planning

The production decisions made by the DP-department are (1) production line assignment, and (2) start times for all production lines and storage units from UF to Filling within the week for which the MPS-department made a weekly master production plan. The Powders, Liquids, and Weighing and Mixing departments are self-regulative and expected to have the ingredients ready before production is scheduled to start. Therefore, these are outside the scope of Detail Planning.

As the MPS, which is the input for the schedule, is made from scratch every week, also the schedule must be made from scratch every week. Because the currently used scheduling tool (Infor) cannot handle the process size and number of detailed constraints, Detail Planners cannot quantitatively optimize the schedule. Instead, they use the Gantt chart scheduling interface in Infor to manually shift blocks of production until a feasible schedule is found, based on (1) experience, (2) a set of ground rules for basic processing line assignment, and (3) a manufacturing handbook containing detailed constraints concerning processes, production lines, and recipes.

2.6 Summary Project Context

The objective of this chapter was to explore the production system, demand, and production decisions made. The information provided in this chapter serves as a basis of the next chapters, in which the business problem, analysis, and proposed solution are described.

Chapter 3:

Research Project

This chapter describes the first two steps in the problem solving cycle: Problem identification and Analysis. The introduction described the problem briefly. This chapter describes the problem in more detail. It provides the background and motivation for this research (Section 3.1), the problem analysis (Section 3.2), an indication of potential improvements (Section 3.3), the scope of the research (Section 3.4), and the research assignment (Section 3.5).

3.1 Background and Initial Problem

[redacted].

In September [redacted], the expectation of a [redacted] to [redacted]% annual demand growth is for Nutricia the initial motivation to set a research project in motion on the choices in how to continue delivering forecasted demand at high service levels. However, in the months that followed September [redacted], forecasted volumes in terms of litres to be produced were sharply cut back due to a sudden forecast of market saturation and changes in the type of forecasted products. The volumes to be produced (in litres) are expected to grow, but at a much slower rate (up to [redacted]%).

Nutricia management believes that the best strategy to continue to increase the market share and achieve the highest profits is to cut costs in production. Hence, the pressure on production capacity expansion has decreased, but the pressure on production cost reduction has amplified. Therefore, the question has changed from how to produce the forecasted volumes, into how newly forecasted volumes can be produced against the lowest production cost.

[redacted]

Nutricia aspires to produce all forecasted demand at minimum cost, but does not know where improvement potential exists. Different departments have different ideas of what the overall best approach is:

- Production aims to level workloads of departments over time, reduce cleaning times, and reduce the involvement of operators in the process by reducing changeovers, hence reducing cost of labour in production which is at present [redacted].

- Finance has the aim to postpone new asset investments, of which asset depreciation is at present [redacted], and reduce cost of gas, water, and electricity, which is in total at present [redacted].
- Supply Chain desires low stocks to reduce the storage cost of [redacted], and increase production elasticity to reduce the cost of money in cycle stock of [redacted] and serve customers flexibly while maintaining high service levels.

These objectives regularly conflict:

- the way to reduce changeovers is to produce larger batches, which means that cycle and safety stock should increase to obtain the same service levels.
- asset investments can lower the amount of coordination and changeovers required in the factory, facilitate balancing the workload, and/or shorten the time required to produce forecasted demand, hence can be the key to labour cost reduction. E.g. adding capabilities of emulsification lines such that all lines can process all products could prevent frequent changes in destination filling lines (as currently the case).

To uphold the [redacted]% service level (the fraction of the total number of final products forecasted demand that is timely delivered to the Sales Units) and prevent avoidable costs, it is fundamental for Nutricia to have insight in the:

- capacity and level of utilization of Supply Point Zoetermeer
- potential improvements for production decisions (for current methods, see Section 2.5)
- effects of production system improvement endeavours on system behaviour and profitability

Insight in capacity, utilization, and potential production decision improvements is required to assess whether current capacity is enough to fulfil future demand, whether action should be taken, or where action should be directed. Effects of production system improvement endeavours should be assessed to prevent avoidable cost and disappointing results.

[redacted] To solve the deadlock, in the analysis, the capacity and behaviour of the production system have been examined into further detail by means of documentation, archival records, and additional interviews for further explanation.

3.2 Problem Analysis

[redacted]

3.2.1 Capacity-related Key Performance Indicators

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

3.2.2 Discrepancy System Behaviour and Expectations

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

3.2.3 Present Optimization Approaches

At present, Nutricia has no means to quantitatively optimize the system as a whole. Currently used tools cannot deal with the computational complexity that stems from:

- the size of the system.
- the wide product range ([redacted] SKUs, [redacted] recipes).
- the detailed (product-, line-, batch-, and sequence-dependent) constraints that cannot be ignored due to the high utilization levels in filling:
  - maximum run lengths and sequence-dependent changeovers.
  - maximum intermediate storage time that deters decoupling of the system.

[redacted]

To deal with the computational complexity, and quantitatively optimize the production system, Nutricia members considered:

1) optimization on an aggregate level (using averages and estimated production and cleaning times)
2) local optimization of a production stage or line

[redacted] Also future demand scenarios and production system alterations, are manually checked through scheduling, here with some multitude of historical demand as the input to account for the product mix. The major benefit of this approach is that sequencing and runs length constraints can be taken into account. Some drawbacks of the current methods are:

- the possibility exists that outcomes of manual scheduling are only moderately optimal because the results depend on the scheduler's personal insight, experience, and preferences in scheduling
- different scenarios cannot be quantitatively compared:
  - Chances are that outcomes of current scheduling are inconsistent, as schedules are handmade
  - cost tradeoffs can only be roughly estimated, and
  - feasibility can be tested, but differences in the influences of different decisions on the system as a whole are unclear.

3.3 Indication of Potential Improvements

Previous sections described the project context. The analysis showed [redacted] One could think of many options to improve the current situation. General option could be decoupling, capacity and capability adaptations, or different planning, control, or scheduling methods. As decoupling is no option, due to limited intermediate storage time, this section describes some solutions in the areas of capacity and capability, and planning, control, or scheduling methods in which Nutricia management has a special interest:

- Capacity and capability
- Planning, Scheduling, and Coordination Methods

3.3.1 Capacity and Capability

3.3.1.1 Adapting emulsification lines

Nutricia Management would like to reduce the coordination effort required, such that Nutricia will be better able to make better use of the available capacity, and have better insight in where the improvement opportunities are. [redacted]

Since filling lines are restricted to a certain packaging technology, but emulsification lines can be adopted to be able to produce all products in the portfolio, they could be key in reducing the coordination effort required. When the emulsification lines could be adjusted such, that they would be able to process all products, two approaches would be especially interesting to research in order to reduce process complexity:

- Identical emulsification lines and full connectivity
- Dedicating preparation lines to specific filling lines

Identical emulsification lines and full connectivity would limit the restrictions, create flexibility, and increase the potential to increase productivity, because the filling lines could be optimized and pull the products from the first available emulsification line.

Dedicating each preparation line to specific filling lines would eliminate the interactions between parallel Filling lines, requiring the same resources at the same time. Hence, it could reduce time lost in coordination. Moreover, it would increase insight in the production system, because it would consist of multiple smaller lines instead of one big ravel. Dedicating preparation lines to filling lines would provide a better opportunity for local optimization, enabling better directed and continuous improvement.

[redacted]

[redacted]

[redacted]

3.3.2 Planning, Scheduling, and Coordination Methods

[redacted]

The general production decisions are (1) SKU-aggregation into families, (2) batch sizing, (3) production line assignment, and (4) start times. These decisions influence the system behaviour, in that they influence the utilization level.

3.3.2.1 Product Families

Batches consist of groups of products, and the way in which these groups are composed can have a major influence on the results in the system. A key decision in the design on batch sizing, further discussed in Section 4.2.3.2, is the choice of the product aggregation level, which almost directly determines the level of coordination required between stages. Hence, reconsidering this choice could provide opportunity for improvement.

3.3.2.2 Batch Sizing

[redacted] The batch size decision is made by the MPS department' [redacted]. The MPS department aggregates SKU-demand of subsequent weeks into suitable batches for that filling line, [redacted].

Preparation utilization consists of the fraction production and CIP of calendar time. The aim is to produce all forecasted demand. [redacted].

3.3.2.3 Production line assignment

At present, line assignment is done by the DP department, who do not have insight in costs, hence costs are not considered in line assignment. As preparation lines can only process a small set of by technology defined batch sizes, the choice in preparation line assignment is implicitly made in the batch size decision, which is at present made by MPS. As line assignment cannot be optimized without considering the technologically allowed batch sizes, the scope of improvement incorporates different batch sizing and line assignment procedures.

3.3.2.4 Start time decision

Section [redacted] explained that no tools are available to quantitatively optimize the production system at a detail level and Section [redacted] concluded with the consequences of the present peak loads as a result of isolated filling line optimization.

Given the amount of interactions between subsequent or parallel processes, the limited amount of detail available for creating the MPS, the short time horizon in scheduling, and the reliance on potentially predispositioned manual scheduling, an integral quantitative scheduling model can provide a more valid base for production decisions in daily practice and in assessing structural system improvements.

3.4 Scope

Section [redacted] described why gaining insight in capacity and utilization, production decision improvements, and the effects of modifying the system on its behaviour and profitability, are a necessity. Section [redacted] and [redacted] describe the shortcoming of the current methods and tools in facilitating insight and efficient use of resources in production. This section explains the scope, before the research assignment is provided. The scope has multiple dimensions: the cost scope, the horizontal span of the production system ("System Boundaries"), and the depth, i.e. the level of detail in the problem. As Nutricia aspires to produce all forecasted demand at minimum cost, this section first provides the cost scope.

3.4.1 Cost Scope

Because the main costs of Nutricia are (1) [redacted]), (2) [redacted]), (3) [redacted]), and (4) [redacted]). In addition, the total annual cost [redacted], of which [redacted]. In view of the increased focus on cost reduction, efficient use of resources are the primary concern of Nutricia management.

For example, [redacted]. This quick estimation indicates that [redacted] has the highest impact of the costs within scope.

3.4.2 System Boundaries

Figure 8 illustrates the choice of system boundaries: before preparation and after final stock. The analysis showed that Emulsification and Filling cannot be decoupled due to maximum intermediate storage time. Between UF and Dissolving are no storage points and their individual capacities are limited, hence, these lines cannot be decoupled and must be taken into account as well. Schedule Adherence figures indicate that [redacted]. Since the focus of this project is on internal operations, availability of raw materials is assumed. The [redacted] sales units (on the right hand side in Figure 8) are decoupled from the production processes [redacted]. Therefore, all processes behind Final Stock are out of scope and Final Stock is within system boundaries.

[redacted]

Figure 8: System Boundaries

3.4.3 Level of Depth

The level of depth required to model the situation at Nutricia is high. The reasoning behind this is as follows.

Many interactions in the system have a major influence on its behaviour. [redacted]

Because of the heavy dependence of the system's behaviour on the moment-to-moment product mix for sequencing benefits and optimal run length use and the similar processing times in all stages, Nutricia requires a detailed approach.

When developing a quantitative model for Nutricia Supply Point Zoetermeer, all heterogeneous parallel lines in the stages UF, Dissolving, Emulsification, the intermediate tank park, and Filling must be taken into account, to prevent infeasibility of the proposed solution:

[redacted]

3.5 Research Assignment

Due to the [redacted], Nutricia requires a detailed integral approach to provide a common base for discussion on what the best solution direction is for cost reduction in production.

Hence, the research assignment is:

Develop a quantitative model for the multiproduct multistage batch plant Nutricia Supply Point Zoetermeer, taking into account its heterogeneous parallel lines in each stage, sequence dependent changeovers, maximum run lengths in the final stage, and perishable intermediate products, with the aim to produce forecasted demand at minimal costs.

3.6 Summary Research Project

This chapter described the motivating problem for the project, provided the results of the problem analysis and presented the research assignment: the development of a scheduling model for the multiproduct multistage batch plant Nutricia Supply Point Zoetermeer, taking into account its heterogeneous parallel lines in each stage, sequence dependent changeovers, maximum run lengths in the final stage, and perishable intermediate products, with the aim to produce forecasted demand at minimal costs.

Chapter 4:

Conceptual Design

The Conceptual design provides the problem characterization, explains what should be taken into account in the in design, the choices in modelling, and how during the course of the project has been dealt with the choices.

4.1 Problem Characterization

The problem can be typified as a cost-optimization problem concerning a sequential multistage multiproduct batch process (flow-shop).

Parallel lines are heterogeneous, in that they have different processing rates, capacities, capabilities, and restrictions. Batch processing times depend on the specific line (also within one department), the batch size, the recipe, and, in filling, the packaging size. Changeovers can be unit-, sequence-, and product-dependent. Equipment assignment is partially variable: potential assignment depends on the capabilities and capacities of a line and vary per recipe, batch size, and/or packaging type. Equipment Connectivity is partial: some lines can serve all lines in the subsequent stage, but others have restricted connectivity. Material transfer is time-consuming. A stage can suffer from run length constraints. After a sequence of batches has been processed with short sequence-dependent cleaning times between batches, a long thorough cleaning is required. The time between the start of the first and the end of the last batch is restricted by a maximum run length (See Section 2.4).

Operators work in shifts. The available time is restricted by the number of shifts. The availability of operators (shift hours) is provided in Section 2.4.

4.2 Design Requirements

The objective of the quantitative model for Nutricia is to provide insight in the production system's capacity and utilization level, and so to facilitate establishing a general vision on the best approach to cut costs in production and produce forecasted demand against lowest production cost (See Section 3.1). The design requirements are the conditions the design must meet concerning the products, the production, and the production decisions.

4.2.1 Products

As explained in Section 3.2.2, very specific product characteristics can have a major influence on the system and are one of the major causes that gaining insight in the system's behaviour is difficult. As insight is the motivation behind this research, the design should account for these product characteristics.

As some products are barely made, taking into account the full product mix is not necessary. Of the [redacted]. Other products have long shelf lives and low demand. Some are produced only once every [redacted] months. To gain insight in the structural capacity and utilization, we choose to take into account the [redacted] structurally produced SKUs, from now on called, the active SKUs.

New product introductions are frequent ([redacted]), but can in generally be ignored, as most of them are updates of existing products with improved functionality but equal production characteristics. [redacted] As such events do not occur structurally, we choose not to take these into account in the design.

4.2.2 Production

Section 3.4.2 and 3.4.3 described the system boundaries and level of depth to take into account in a design. In addition, Section 3.4.3 described why lines do or do not have to be accounted for. As the combination of specific characteristics of single lines and interactions between parallel lines and lines in subsequent stages determine the capacity of the system, the individual capabilities, capacities, restrictions, and characteristics of each line must be taken into account.

Section 3.3.1 described some potential improvements to the system's layout. However, these endeavours can be costly and the effects are uncertain. Again, in order to make a well-substantiated decision to make new investments, more insight is required. Hence, to account for the desire to gain insight in the effects of system modifications on the system's behaviour, the design should be made easily adjustable for these modifications.

4.2.3 Production Decisions

The weekly Sales Unit forecast is the demand that must be scheduled and fulfilled before the end of the forecasted week. The production decisions (Family grouping, batch sizing, production line assignment, and start time decision), have shown to be of major importance on the system's behaviour as well (See Section 3.2.2). Section 3.3.2 describes how potential gains can be realized through the production decisions. This section explains the choices in design and which choices have been made in the design.

4.2.3.1 Family grouping

Section 2.2 described how end products are distinguished: by recipe, packaging type, packaging size, label, and box type. In order to simplify coordination in the factory or obtain economies of scale, products can be grouped into families of products with similar characteristics, that in the factory can be treated as a single products type. With respect to family grouping, Nutricia has three central choices: (1) to aggregate demand purely per recipe, (2) to aggregate Sales Units' demand purely per SKU, or (3) to develop a hybrid approach.

Nutricia can base the batch size purely on recipe. However, recipes are filled in multiple packaging types. When the demand is aggregated to recipe level, a batch must be split just before Filling into the batch sizes required by the different filling lines. Because in Filling, cleaning times are sequence dependent, and each line has its individual sequence, processing time, and run length, the different lines might need the split batch at different points in time. Consequently, one of the split batches might have to wait in intermediate storage for a long time and the batch might perish. Moreover, as the number of intermediate storage tanks is limited ([redacted]) and the number of intermediates large ([redacted]), the occupied tanks might jam the system, such that much coordination between lines is required.

Alternatively, Nutricia can base the ELSP purely on SKUs. This will cause problems with utilization in earlier stages, since for each SKU ([redacted]) a separate batch will be planned. Given that cleaning times in the first and second stage are on average as long as the processing times, starting a new batch for each SKU would increase the total time required.

One approach of a hybrid solution is aggregating the product portfolio per emulsification-filling line combination. The coordination problem of filling recipes is then decreased, but because, some lines fill multiple packaging volumes, not eliminated. Cleaning times between recipes, sleeves and different cluster/box types are in Filling always shorter than the recipe cleaning times in Emulsification, but converting the line to other packaging volumes takes as much time.

A second hybrid approach is to aggregate demand per emulsification and packaging type (combination of packaging technology and packaging size), such that line conversions are taken into account (See Figure 9). Label changeovers take between [redacted] minutes (compared to production times of [redacted] up to [redacted] hours) and box changeovers [redacted] Based on the experience of employees in scheduling and production, label and box changeovers can be neglected, because the time required for these handlings is small compared to processing and cleaning times.

This approach prevents coordination problems between parallel lines, but allow for economies of scale in earlier stages. Hence, in the design, this approach will be adopted.

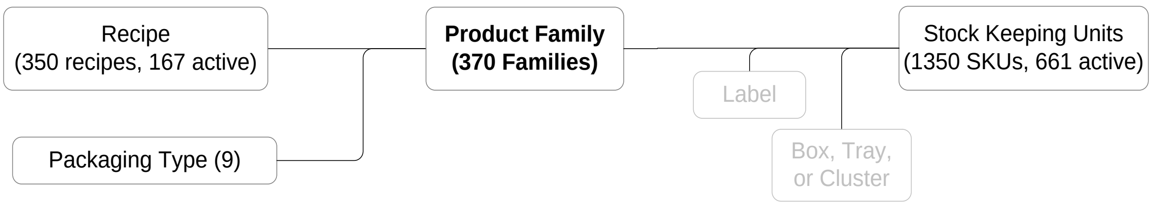


Figure 9: Product Complexity reduced by concept of Family batching

4.2.3.2 Batch Sizing

In the batch sizing decision, the design should allow for a small set of by technology defined allowed batch sizes ([redacted] In addition, in the batch size decision, the model should account for preparation line capabilities and costs [redacted].

4.2.3.3 Production line assignment

From a cost-based perspective, the costs of processing a batch depend not only on cleaning costs and holding cost, but on costs of operating a line as well. Because the cleaning costs of the faster lines are, within Nutricia, higher than those of slower lines, but the processing rates are higher as well, the lower processing costs might outweigh the higher cleaning costs in the assignment decision. In addition, the operator handlings required for a large batch are the same as for a small batch, such that, when the batch size is increased, less handling is required to do the same amount of work. Hence line assignment can:

- reduce the total cost of operations,
- reduce the average utilization level per line (because more batches are processed on faster lines, such that total processing time reduces),
- reduce operator workloads in preparation,
- create flexibility in the system, hence creates productivity potential.

Hence, the design should not consider line assignment in isolation from batch sizing.

4.2.3.4 Start time decision

Two major design requirements are imposed by management. Firstly, (sequence-dependent) cleaning times in filling should be minimized: OE in Filling may not be lower than at present. Secondly, peak loads, especially in UF, Emulsification, and Filling, should be avoided.

The first crucial requirement, minimizing (sequence-dependent) cleaning times in Filling, [redacted]

The second crucial element is to balance workloads between lines and over time [redacted]

The analysis (Section 3.2) described [redacted] Nutricia management searches opportunities to reduce the required coordination effort in production. Implementing procedures concerning the sequences and start times of batches could facilitate a reduction of the required coordination effort. Several options are:

- fixed sequences, to facilitate learning effects and continuous improvement, as small adjustments can be made every cycle
- cluster production of products on an emulsification line that require filling on the same filling line. Although the handlings required to change destination filling lines do not require additional time in the process, (they occur in parallel to production and CIP), they do require operator time, hence increase work pressure and chances of dissatisfaction, mistakes, costs from rework, and scrapped product.
- Periodic repetition of batches (or clusters of batches), to facilitate learning effects, insight in the system, and continuous improvement, as incremental adjustments can be made until satisfaction.

Fixed sequences with an extensive portfolio and by technology defined batch sizes are impracticable, as all products have different and wide-ranging demand rates. The second option could reduce the coordination effort required, as long as the emulsification line can keep up with the filling line. The design will have to allow some flexibility in this approach in order not to jam the system or avoid a decrease of OE in filling. As with fixed sequences, periodic repetition and comparable start times of batches within the subsequent weeks in which they are produced facilitate learning effects, hence reduce the coordination effort required. For example, when every Monday morning 8 a.m. a batch [redacted] is scheduled followed by a batch of [redacted], operators can anticipate the sequences and setups. Unlike fixed sequences, when interarrival times are relaxed, periodic repetition and start time repetition allows for different demand rates (e.g. start every second Monday morning at 8 a.m.) and can be practicable. Hence, to reduce required coordination efforts, the model should take into account the possibility to cluster sets of batches that require the same emulsification line and filling department, and start batches repetitively at comparable times.

4.3 Modelling Requirements

The modelling requirements provide an explanation of the aptness of different modelling approaches to model the characteristics of Nutricia, and which method could best be chosen to gain the best functional representation. The major choices are (1) the type of model to employ, and (2) how to deal with uncertainties.

4.3.1 Simulation or Mathematical Scheduling Model

Nutricia requires a detailed optimization approach to model its process, because of the detailed constraints that cannot be neglected (primarily run lengths and sequence-dependent changeovers). Common detailed modelling methods are (1) simulation-based or (2) MI(NL)P-solver-based. The MI(NL)P-solver-based models are in the literature frequently addressed as "Mathematical Scheduling Model" (See e.g. Kallrath, 2002; Neumann et al., 2005; Pinto & Grossmann, 1994).

Simulation-based modelling has the advantage that modelling, even for complex problems, is relatively simple (Brodsky & Nash, 2006). Simulation-based models have the disadvantage of slow convergence, and the solution is not necessarily optimal. Moreover, according to Klemmt et al. (2009) implementation of time-constraints is difficult: as simulation systems are time directed and generate nondelay schedules, time constraints that often require delays are hard to implement (e.g. due dates, time coupling constraints).

A Mathematical Scheduling Model in contrast, better facilitates modelling time constraints, provides consistency in the proposed solution, allows for quantitative reasoning-based decision-making and an exact solution, including proof, offers the possibility of straight-forward "What if" analyses, the development of new ideas through a deeper understanding of the problem, and better interpretation of the problem and the results. (Kallrath, 2002). A major drawback is that MILP endeavours for multistage environments with a very high product variety can take a long time to solve and often result in NP-hard models. On the other hand, as simulation models are not well suited for optimization yet, simulations are typically optimized by choosing parameters manually, which can take much time as well (Brodsky & Nash, 2006).

When compared, Simulation-based modelling is more suitable for constraint modelling, while solver based optimization can be considered more suitable to model time constraints, such as delays and due dates (Klemmt et al., 2009). As time-constraints play a major role in the Nutricia production system (e.g. delays and maximum intermediate stand time), in this project, a Mathematical Scheduling Model is proposed that integrally considers the overall problem.

4.3.2 Level of Certainty (stochastic-deterministic)

In day-to-day operations, each line has a certain line loss due to changeovers and cleaning (steady [redacted] Based on current practices and historic data, this can be accounted for [redacted] Processing times can be assumed deterministic as well. [redacted].

The nature of advanced medical nutrition implies a stable demand pattern: the number of patients for which advanced medical nutrition is developed is not subject to fluctuations, the products are under prescription, and many products require life-long treatment (as with allergies or metabolic diseases). The Sales Units are, together with the Danone marketing and sales departments, responsible for making all demand forecasts (long- and short-term). The demand forecast for the next years is stable. In addition, safety stocks in the sales units buffer for demand variations and uncertainty. [redacted]

[redacted]

4.4 Design Approach

Based on the modelling requirements explained in Section 4.3, a deterministic mathematical scheduling model will be developed. In line with the regulative cycle, (Van Aken et al., 2007, see Appendix E), a literature review has been performed to develop an understanding of the existing scholarly knowledge concerning scheduling models that address the requirements delineated in the design requirements. As batch sizing is the prime determinant of the behaviour of preparation, the start time decision the prime determinant of the behaviour of filling, and the two departments cannot be decoupled due to intermediate storage time restrictions, an integrated planning and scheduling approach is required.

Based on the design and model requirements, different academic scheduling models have been evaluated on applicable features and a theoretical framework was build for the development of the scheduling model. Appendix J presents a summary of the rival theories that provided the framework for the solution and provides a more detailed evaluation of alternative solution approaches on improvement potential, feasibility of implementation, feasibility of design within the project lead-time, practical model applicability (user friendliness), computational complexity (time), and risks involved (e.g. NP-hardness).

The main conclusions of this review are that:

- cyclic scheduling can facilitate coordination, workload stability, and minimization of (sequence-dependent) cleaning times (Winands, 2007; Vaughan, 2007; Levner et al., 2010)),
- Mathematical Scheduling facilitates consistency in the solution, understanding, and straightforward what-if analyses (See Section 4.3.1 for more benefits of Mathematical Scheduling)
- when batch sizing relies on cyclic scheduling and the start time decision relies on Mathematical Scheduling, the benefits of both approaches can be combined (Broecke et al., 2005, 2008)

As the analysis of the literature indicated that the combination of cyclic and mathematical scheduling provided the best prospects (See Appendix J for the overview), we choose to adopt this approach in the design.

An additional literature review has been performed to investigate how to address the individual cyclic and mathematical scheduling problems. No approaches were found in the literature that addressed the limited number of batch sizes in the batch size decision. Appendix J also presents the three Mathematical Scheduling approaches found that are closest to the design requirements of Nutricia.

4.4.1 Model Structure

As no approaches were found that were straightforwardly applicable for the situation of Nutricia, the decision has been made to create a new scheduling model. Figure 11 provides a graphical representation of the proposed model. The model will consist of two parts. As batch sizing and line assignment are interrelated (see Section 4.2.3.3), the first part mutually considers batch sizes and production line assignment. In line with the design requirements, batch sizes will consider dissimilar lines and be based on the costs as delineated in Section 0. The second part considers start times in all lines in all stages defined in the system boundaries (See Section 3.4.2) and is modelled by means of a MILP.

To prevent ambiguity in the designation, from now on, the batch sizing and line assignment model will be addressed as the *BSPLA model*, the start time decision model will be addressed as the *ST model*, and the total will be addressed as the *scheduling model*. Figure 11 illustrates the proposed model structure.

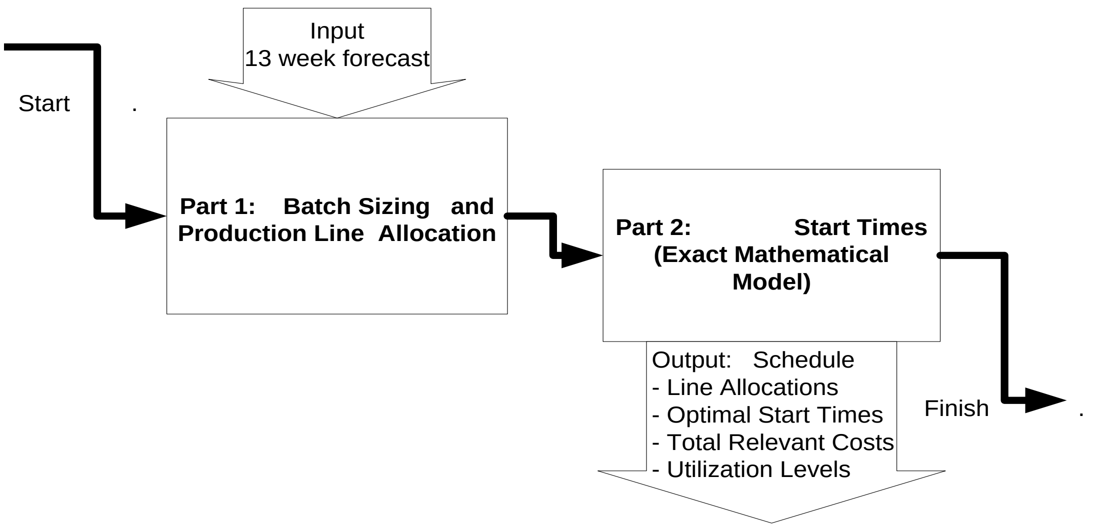


Figure 11: Model Structure with relationship Part 1 and Part 2

Broecke et al. (2007) propose to base the stage choice on the stage with the highest setup cost per setup, or in the case of Nutricia, cleaning cost. The costs of cleaning are proportional to time (See Section 4.4.2). Because in the Nutricia process time is better measurable than costs, here we use the time for comparison. The stage choice is within Nutricia not straightforward, [redacted]

[redacted]

[redacted]

[redacted] As explained in Chapter 2, the batch sizes of each family depend on the production line in Emulsification and are distinct amounts. In the literature, no approaches have been found that consider this or a similar situation. Given that the number of recipes, lines and allowed batch sizes is not too large, the uncapacitated optimum can be found by enumeration.

4.4.2 Objective and Relevant Costs

The objective of the scheduling model is to provide insight in the production system's capacity, utilization level, and utilization-related behaviour. As Nutricia's objective is to reduce costs in production, the objective function is cost-based. Table 1 illustrates how we plan to address the relevant costs defined in the cost scope. The first row provides the costs in the cost scope. The first column provides the two parts of the model. The costs that will be addressed in the BSPLA model relate to the major costs that can be influenced by batch sizing and line assignment. The running related costs are the costs of operating a line. Line assignment can influence these costs as lines have different processing rates. For example, when a batch is assigned to a fast line, costs of running related maintenance, reduce. As reduction of the coordination effort in production is a precondition of management that cannot be addressed in the BSPLA model, this is taken into account in the ST model. Cost of cleaning must be taken into consideration in both models. In the batch size decision, the costs of setup (cleaning in this case), must be weighed against, amongst others, holding cost. In the start time decision, sequence-dependent cleaning times must be minimized. The shelf life constraint is primarily related to the batch size decision and will only be addressed in the batch size decision (BSPLA). Intermediate storage cost are proportional to the residence time in intermediate storage, hence directly relate to the start times of batches in Emulsification and Filling. Inventory holding cost are primarily determined by the batch size. However, the start time determines the holding costs in that early starts of batches cause additional holding costs, such that start times of multiple batches of the same family should be spread equally over time.

Table 1: Relevant Costs

	Human Labour In Production	Asset Depreciation	Utilities	Scrap	Holding Cost
BSPLA Model	Cost of operating a line Cost of running-hours-related maintenance	Cost of running-hours-related depreciation	Cost of Cleanings	Cost of perished goods – Destruction Cost + Cost of goods sold (Raw material, packaging materials and conversion cost)	Inventory holding cost (cost of money) and storage cost
ST Model	Cost of workload Fluctuation per line Cost of Start Time Fluctuation		Cost of Cleanings Cost of intermediate storage		Inventory holding cost (cost of money) and storage cost

4.4.3 Input, output and time horizon

The input for this model is the [redacted] week forecast from the SUs ([redacted]). The expected output of the BSPLA and input for the ST model is the number of forecasted batches, processing times per stage, and a binary that states the capability of a production line or storage facility to process or store a batch, as these parameters depend on the combination of batch size and production line.

The output of the model to be designed should provide quantitative insight in the production system's capacity and behaviour, given the product mix. As the product portfolio is large, the horizon cannot be too short, because than the design would not allow for optimal sequencing as not all products will be made during the short horizon. [redacted]. Hence, when an eight week horizon is chosen, the design allows for minimal cleaning time through optimizing run lengths and sequence-dependent cleaning.

The design and model requirements explained why an [redacted] week scheduling horizon can be adopted: the product mix remains equal and sales are stable over this period. To cover for changes in forecasts, after [redacted] weeks, the production decisions can be reviewed and an adapted schedule can be constructed for the next cycle, which by the end of the [redacted] can be implemented. We choose to implement a review period to account for more permanent changes in demand than the short term fluctuations caused by e.g. the bullwhip effect.

4.5 Summary Conceptual Design

Previous chapters had the aim to structure the problem. The requirements for the design and the model have been established. Based on these and a general and detailed literature review, a conceptual design has been developed. This chapter described the major choices in that development. The model structure provide the a general insight in how the design has been constructed. The objective and relevant cost section relates the costs from the cost scope to the objective function in the two sub models.

Additional steps are the translation of the problem into mathematical language, implementation in software, validation, and interpretation of the results.

Chapter 5:

Batch Sizing and Production Line Assignment

Chapter 4 explained why the scheduling model is addressed in two parts: the BSPLA and the ST model. This chapter describes the BSPLA model. As the BSPLA and ST model rely on the same base assumptions (see Section 4.2), only some specific assumptions are described in this chapter. The translation of the problem into mathematical language is presented in Appendix F.

As the scheduling model is split in two, this chapter and Chapter 6, which describes the ST Model, provide first a detailed scope, as some topics from the design requirements are addressed on both models and others are covered in one of the two models.

5.1 BSPLA Problem Characterization

The objective of the BSPLA model is to determine the batch sizes and the Production Line Assignment of the product families resulting in the minimum relevant costs. The total relevant costs consider only part the costs in scope (Section 3.4.1), as not all costs are considered in both the BSPLA and the ST model. The solution area is restricted by predefined by technology allowed batch sizes, allowed emulsification lines, and shelf life. The costs and constraints are in line with the design requirements.

The total relevant costs in the economic batch size problem are determined by the following parameters:

- Annual demand rate per product family
- Annual production rate per product family
- Annual stock keeping unit holding costs per product family in the final stock
- Predefined permitted batch sizes per recipe per emulsification line (1-5 different sizes per recipe per line)
- Cleaning costs, which are slightly higher when a product is filled in a different factory than the one in which the batch has been prepared through extra cleaning of the piping
- Cost of operating an Emulsification Line, because each line has its own processing speed and processing a batch on a faster line with longer cleaning time required might be preferable over processing the same batch on a slower line with a less long (expensive) cleaning.
- Shelf life, i.e. cost of perished product, the first being a given determined by quality control and customer contracts, and the second derived from conversion cost per SKU plus a cost for waste-removal

Intermediate storage costs are not relevant here, because intermediate storage is not a controlled stock point, but merely a buffer between Emulsification and Filling. Hence in this phase of the optimization, these costs cannot be influenced yet.

Many of the parameters taken into account in the list above are considered in the standard ELSP approach. For Nutricia, the predetermined batch sizes per recipe-line combination must be taken into account as well. We choose to add the hourly costs of operating a line. The major advantage of this approach is that the processing rates of parallel lines are very different, by taking the hourly cost rates into account, human labour in production and asset depreciation, which are the major costs in Nutricia, can be taken into account in the batch size and production line assignment decision already. Similarly, we chose to differentiate between the cost of cleaning piping, to make the model more realistic. In addition, as holding costs are relatively low compared to the costs related to production and cleaning, it can be expected that batch sizes become large. Hence, shelf life should be taken into account, to prevent perished products in stock. We choose not to model a hard bound, but take into account the expected costs of destructed product at the end of shelf life.

5.2 Model Structure

This section describes the steps to be taken in the BSPLA model and how these steps interrelate. Figure 12 illustrates the procedure developed for the BSPLA model. The separate steps are explained in the sections below.

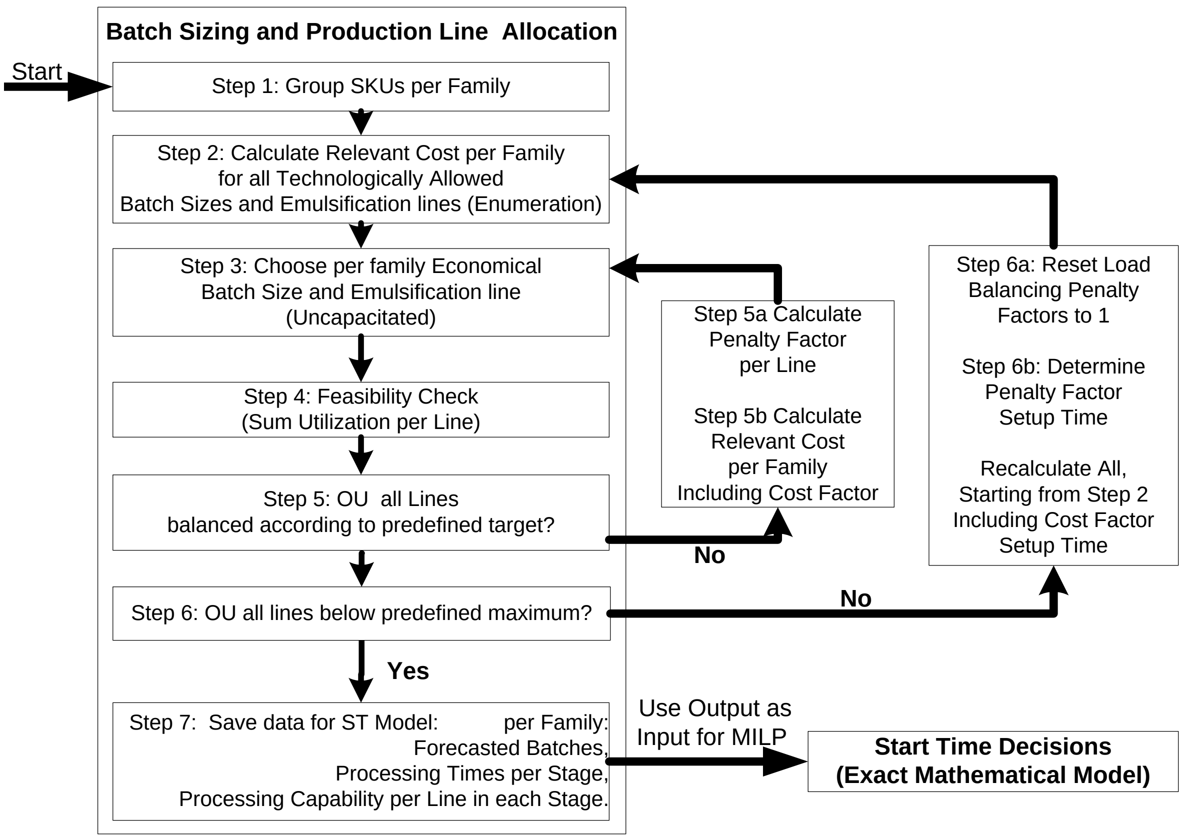


Figure 12: The Economic Batch Sizes and Production Line Assignment model

The input of the model is the [redacted] week forecast delivered by the sales units. The advantage of taking into account the entire period is that, when demand increases over time, this could be anticipated by starting to build-up stock earlier. The output consists per family of the forecasted batches, processing times per stage, and the Preparation line allocation.

Step 1: Group SKUs per Family

First, the total demand for each product family can be determined by computing the sum of SKU demand in the category of products that have the same recipe, packaging technology, and packaging. The choices in family grouping and the line of reasoning have been explained in Section 3.3.2.1.

Step 2: Relevant cost calculation for batch sizing and production line assignment

Given limited shelf life, the batch size must be chosen such, that the cost of production and holding inventories is weighed against cleaning and perished product cost. In this approach we assume stable demand (see 4.3.2). In the second step, for each product family, the relevant cost per unit time is calculated per Family for all technologically allowed batch sizes and emulsification lines (complete enumeration). The relevant costs consist of:

- average cleaning cost per unit time (lye, acid, water, steam)
- average holding cost per unit time (cost of money and stock location)
- average production cost per unit running time (production related utilities and maintenance, plus a cost for human labour, since cleaning is labour intensive)
- average cost of perished product when a batch size is larger than the demand over the shelf life period (Cost of destruction and cost of goods sold minus conversion cost, as this has been accounted for during production, i.e. raw materials, packaging materials)

When a batch is produced that exceeds the demand over shelf life, the excess is not destructed immediately, but only as shelf life has run out. Within Nutricia, the goods must be shipped at one-third of retail shelf life. In practice, some sales units agree with receiving shipments with less than 2/3 shelf life remaining. The gains from these outlets outweigh the extra cost of storage. Especially since holding costs are relatively low.

Step 3: Batch size and Emulsification line choice

After in step two all allowed possibilities have been calculated, the batch size – emulsification line combination with the lowest cost can be chosen for each family. In an uncapacitated environment, this would be the best solution within the range of allowed batch sizes and emulsification lines. However, given that all lines have unique combinations of emulsification and cleaning rates, not all lines will be equally economical. Hence, it can be expected that the workloads are not evenly spread.

Step 4: Feasibility check

The fourth step considers the calculation of the line utilization level, in order to examine the feasibility of the in step 3 derived solution. Remember that the line utilization is defined as the ratio of production and cleaning hours to calendar time. When the solution is considered feasible, one could accept the current solution. The decision criterion used is a management decision. With higher utilization levels, chances of problems in realizing demand are higher. Within Nutricia, this level has been set at [redacted]% for the filling lines. Other lines do not have a specific target. At present, preparation capacity is conceived problematic, while the average utilization per line is between [redacted] and [redacted]%. Therefore, it is advisable to seek improvement when the utilization of a emulsification line is above [redacted]%. Step 5 provides an enhancement approach. When the levels are considered feasible, one could accept the current solution and stop the procedure here.

Step 5: Levelling workloads in parallel lines

In the preparation department, human resources are a major cost. All parallel lines are served by the same human resources and the number of shifts and working hours is equal for all lines. When the workloads could be balanced between lines (see Figure 13) potential cost savings are earlier discovered, and the disadvantages of peak loads (as described in section 3.2.2) are easier to prevent.

Therefore, it is beneficial to level the workload between the lines until all lines require an equal amount of time for their tasks, such that in total, the least amount of time is required. Hence, the fifth step considers an iterative procedure to balance the utilization of the lines.

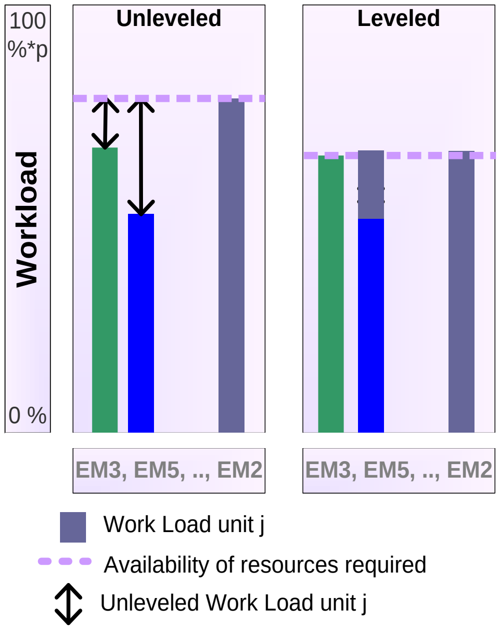


Figure 13: Example Workload Fluctuation

Figure 13 shows an example of unbalanced workloads on the left and levelled workload on the right. However, in the situation of Nutricia, it will not be possible to fully level the workloads, as we determine a line for each family and the choice is integer. Moreover, unique line capabilities limit the approach. Hence, lines can be levelled to some extent, but not entirely.

Step 5a: Calculate penalty factor

In order to balance the workloads, the costs of using higher utilized lines could be increased artificially. One approach could be to increase the setup cost, as when batch sizes increase, less cleaning is required, and the utilization would decrease. The disadvantage of such an approach is that lower utilized lines still have more idle hours, and batch sizes should increase a lot to level the workloads in the entire factory. Therefore, in this approach, we chose to use a penalty factor to increase the total cost of operating a line, such that families, for which the allocation to different lines has the smallest effects on the cost, receive different allocation decisions first.

The penalty factor is calculated for each line individually. In the base situation, the factor is one. When a line has a higher utilization level than other lines, the factor is gradually increased. This can be done by hand, but in order to come to faster convergence of the utilization levels, this approach proposes a stepwise procedure to calculate each line’s penalty factor. The procedure is based on each line’s relative absolute deviation from the mean utilization. How much the factor increases every step, depends on the difference between the line’s utilization and the utilization of the least utilized line. Hence, when a line is highly utilized, the penalty factor increases faster than when a line is moderately high utilized. The penalty factor of the lowest utilized line is not increased, such that production on that line becomes more attractive.

Step 5b: Determine total relevant cost times penalty factor

In order to spread the workload, the penalty factor can be multiplied with the total relevant cost, as determined in Step 2, such that the entire cost of operating that line increases proportionally with the factor. After the utilizations of all lines have been calculated once more (Step 3). The procedure can be repeated starting from step 3, until in step 4 an acceptable solution is found. When utilization levels cannot be levelled further, but the utilization of lines is too high to be acceptable, one can proceed with step 6.

Step 6: When lines are levelled and OU is high

When lines are levelled but OU is too high to be acceptable, one could restart the procedure with an artificially increased setup cost and the penalty costs reset to 1.

Step 5 and 6 have different effects on the system behaviour. In step 5, the entire cost of operating a single line is increased, which means that the product family of which the total relevant cost differs the least with the costs on an alternative line, change to the alternative line. In step 6, only the setup cost is increased, but for all lines, such that batch sizes on all lines increase proportionally.

All adaptations to the cost function lead to less cost efficient batch sizes (e.g. larger batches at the expense of higher holding cost). However, as some emulsification lines have comparable costs and capabilities, a small artificial increase of the total cost of a line could imply the choice of a different line with limited negative effects on the total costs.

Step 7: Save the output for the ST Model

When a solution has been obtained, the data can be prepared that serves as an input for the ST model. The information required by the mathematical scheduling model is :

- The forecasted batches per product family
- The processing times per product family per stage, as these are line dependent and batch size dependent
- The line capability to process the batch

Because the aim of this procedure is to derive appropriate batch sizes and preparation lines for the mathematical scheduling model, disaggregation of demand into SKUs is not required (See Chapter 6).

5.3 Summery BSPLA

This chapter described the Batch Sizing and Production Line Assignment model. Models to solve the Economic Lot-Scheduling Problem (ELSP), are mostly dedicated to the single line, one-bottleneck situation, largely neglecting coordination between lines and hardly ever considering perishability of intermediates and workload balancing between lines. This first part of the scheduling model considered cost-efficient processing lines and batch sizes in the production stage with the highest cleaning time between two subsequent batches, accounting for shelf life, technologically allowed batch sizes, and coordination between lines in terms of utilization and run lengths. The output of this model serves as the input for the Start Time model

Chapter 6:
Start Time Model

This chapter describes the second part of the scheduling model: the Start Time model. First, the environment to be modelled will be shortly described. Subsequently, the objectives will be described, followed by the restrictions.

6.1 The ST Model

The objective of the ST model is to determine the start times of the family batches, within the scheduling horizon, resulting in the minimum relevant costs. The model should be able to take into account all characteristics described in the Problem Characterization in Section 3.2. The detailed requirements and restrictions that the model should be able to capture, have been delineated in detail in Section 4.2. A wide range of specific production related constraints (See Appendix C) restricts the solution area. This chapter explains how the design requirements of Chapter 4 have been incorporated in the model and how these requirements have been translated into mathematical language, which difficulties have been encountered and how has been dealt with these difficulties.

As this part of the model requires more detail than previous parts, the first section will provide a deeper scope and a more specific objective.

6.2 Detailed Scope

[redacted]

Figure 14: System Boundaries

Table 2: The number of production lines per stage

[redacted]

Figure 14 illustrates the detailed production process. Table 2 provides an overview of the stages and their units as used in the mathematical formulation. The detailed scope considers nine stages in the factory. Five of these stages are actually production stages: UF, Dissolving, Emulsification, UHT, and Filling. The other stages are storage stages. A list of production unit specific constraints can be found in Appendix C. The model will follow the design requirements strictly, but first Section 6.2 will explain the objective function, how it has been derived, what the difficulties were in modelling and how these have been solved.

6.2.1 The items to be scheduled

The aim of the exact mathematical scheduling model is to determine a start time for each batch in one production line of each stage. The batch sizes and cost-efficient production lines in Emulsification have been determined in the ELSP (See Chapter 5.2). Batches will not be mixed or split throughout the process (See Chapter 6). Therefore, all stages draw on the cost-efficient batch size determined in the ELSP. The cost-efficient interarrival time follows from the batch size divided by the average demand rate. Consequently, within a certain period, multiple batches of the same product can be produced. In order to be able to model the relation between batches of the same family, two indices are introduced: a product family index f, and a batch designation i.

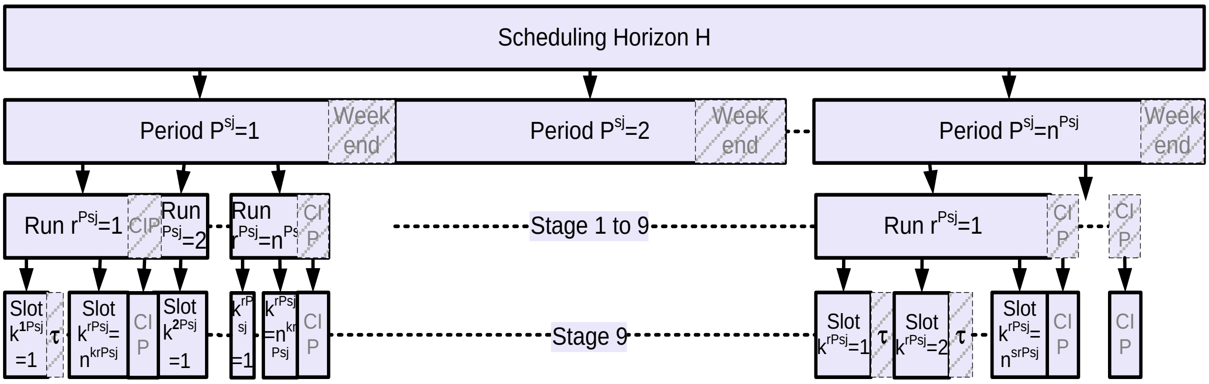
6.2.2 Time Representation

As, given the product portfolio and the production environment, the number of items to be scheduled is quite large, we choose to adopt a relative-time-based view, based on the processing times and sequencing constraints in the process, as opposed to absolute (clock time). Most MILP models in the literature determine for each point in time whether and with what a machine is busy. In this approach a decision variable for each unit at point in time is required, which can make the model large when the unit time is chosen small. Another approach is to record each point in time a batch starts and finishes processing, and make sure that each subsequent batch starts later than the time the previous batch finished. The clear disadvantage of this method is that every start time in each line becomes relative to its history. This can complicate the linkage with other lines, as each unit has its own time line. The absolute advantage of the method is that the number of decisions to be made drops, from every absolute point in time, to each starting (or finishing) point in time of a batch in each unit. As the process is quite large and complex, with many flows and many products to be scheduled accurately, due to the high utilization levels, a relative-time perspective has been chosen to model Supply Point Zoetermeer. Instead of a fixed unit time (e.g. Minute, Hour, Week), the unit time is the length of the processing time of a batch in a line. To be able to model this., each processing line has a number of slots that can be used for production. A slot can, but does not have to be used. An empty slot has a duration 0. Subsequent slots are intermitted by the time required by the line to prepare (through CIP, setup, or sequence-dependent cleaning), or wait for the next batch that will be processed. As this approach limits the number of decision variables required in the final mathematical model, it is expected that it will save computational effort required in solving the model.

This section describes the different time-related concepts used in the model: Periods and Runs. A period is measured in absolute time, e.g. a week. A run is measured in relative time, i.e. the duration of a run is the time from the start of the first batch in the run, until the en of the final batch in the run, regardless what happens in between. The length is determined by technological restrictions. An overview of terms used is provided in the Glossary in Appendix A.

6.2.2.1 *Periods*

The model will schedule forecasted demand for a scheduling horizon H. The scheduling horizon H can be subdivided into periods P^{sj}. Period lengths are production line specific. Each subsequent period starts as soon as the previous period ended, at the so-called Period Release Time, and ends with a cluster of unused available time (no production planned). [redacted] Figure 15 illustrates this categorization of the horizon into equal periods ending with a cluster of unused available time.



White space := No production planned (e.g. “Weekend”), differs per department, might deviate per period (depending workload)
CIP := Cleaning in Place after each Run, differs per unit, same for each run within one unit
τ := Sequence Dependent Changeover between 2 Batches (1 batch per time slot), differs for each product combination Only in final stage, earlier stages 1 product per run

Figure 15: Time categorization

6.2.2.2 *Runs and batches*

[redacted] However, due to clogging of the line, at a predefined time after starting the first batch in a run, a CIP is required as well. The run duration starts at the start of production of the first batch after the previous CIP. In the final stage, CIPs are required in two cases: (1) when the maximum run length is almost reached and no other full batch can be processed within the remaining time, regardless the waiting time in between processing of batches, the number of batches processed, or the individual processing times since the start of the first batch, or (2) when no other products are allowed to be processed after the previous batch in the run, regardless the start time of the run under consideration.

Each production line processes during a certain run r before it stops, is cleaned, and starts a new run (r+1), such that a period generally consists of a sequence of runs. Within each run, multiple batches can successively be processed with only a smaller sequence-dependent cleaning time tau. Each batch requires a timeslot k for production and, when sequenced beneficially, small cleanings between subsequent batches suffice within the run. However, due to clogging in the line, after a predefined maximum run length, the line requires a lengthy cleaning, the CIP. CIPs are also required before stopping production and therefore planned at the end of the final batch before white space. Note that no sequence dependent cleanings are required before CIPs take place.

6.3 Objective Function and Relevant Costs

During the analysis, interviews yielded a list of objectives to incorporate in the objective function of the ST model. Although most were cost –based, coordination should be addressed as well.

provides an overview of the objectives related to costs in the scope (See Section [redacted]), including the approach to address the sub objective in the final model. Each term will be explained below the table.

One of the challenges in modelling is to address all different sub objectives while preventing contradictions. E.g., while the people from supply chain have the aim to reduce inventories and flexibly respond to demand, the production department desires levelled workloads and repetition of schedules to build routine, prevent mistakes, and lower the cost of coordination. Note that, although most objectives require trade-offs, minimizing intermediate storage time saves both utility cost and minimizes the risk of perished product, while balancing workloads saves both cost of labour and assets. Clustering unused available time per period (e.g. week) can interfere with levelling the workload. To facilitate both ends, unused available time can be clustered for a period that facilitates shift reduction (e.g. weekly) and the remainder is spread over time.

As all models are just representations of the real world, and it would be unfeasible to incorporate all specific characteristics, it has been decided to limit the objectives to the ones with the largest estimated effect. As Labour and Utilities (in Write-offs) have the largest cost-based potential (See *section 3.4.1),* the model will focus on the major costs within these categories. The objective function, which has been determined in consultation with Nutricia Management, is based on the following costs:

- Intermediate storage (IS), — the cost of cooling tanks is proportional to storage time
- Workload fluctuation (WLF) — workload stabilization, potential shift reduction and asset depreciation (postponement of investments, insight)
- Cleaning Time (CO) — cost of cleaning (human labour, utilities)
- Start time fluctuation (STF) — relates to the cost of coordination (human labour, scrap)
- Levelling inventories (IH) — relates to the inventory holding cost

The objective of this model is to find start times during the scheduling horizon for each forecasted batch that minimizes the total cost required for Intermediate storage (IS), Workload fluctuation (WLF), asset depreciation, Cleaning Time (CO), Start time fluctuation (STF), and Levelling inventories (IH).

Table 3: Scheduling Objectives with proposed scheduling objective

Scheduling Objective

Meet service levels at minimal cost of:

- Labour
  - Minimize number of shifts required
    - Balance workload* over time in each stage
    - Cluster (weekly) White Space**
- Assets
  - Minimize discounted investment cost***
    - Balance workload over time in each stage
- Write-offs
  - Minimize start-up cost
    - Cluster production
  - Minimize costs of Coordination
    - Cluster weekly routings****
    - Repeat routing cluster start times on a regular basis
    - Repeat batch production start times on a regular basis
    - Repeat maintenance on a regular basis
  - Minimize changeover cost
    - Minimize total sequence-dependent changeover time
    - Minimize number of production runs required (CIP)
  - Minimize utility cost
    - Minimize intermediate storage time (cooling)
    - Minimize transportation between intermediate tanks (water)
    - Minimize number of UHTs working simultaneously (water & heat)
  - Minimize waste (perished product in intermediate storage)
    - Minimize intermediate storage time
  - Minimize inventory holding cost
    - Equally spread production runs of the same product over horizon

) Workload is defined as the total machine time required for production and cleaning per planning time frame.*

*)** In this context, white space is the time during which empty time slots are scheduled, i.e. the available machine time during which no production is planned. When a white space cluster is large enough, the number of shifts can be reduced.*

*)*** Discounted investment cost is the asset depreciation over volume produced per planning time frame.*

*)**** Routing clusters are sets of products with the same preparation as well as filling line and final format content size, e.g. "emulsifier 1 to PB_200", "emulsifier 1 to PB_500", "emulsifier 1 to Tetra_200", "emulsifier 4 to PB_200" or "emulsifier 4 to Pack_500"*

6.3.1 Intermediate storage (IS)

As intermediate storage tanks require cooling, the cost of the energy required to cool the tanks should be accounted for.

Intermediate storage cost consists primarily of the cost of cooling the intermediate product to prevent decay. Cooling of intermediates starts at the start of emulsification (stage [redacted]), and finishes only at the completion of filling (stage [redacted]).

$$IS = \sum_{f \in F} \sum_{i \in I^f} CT_{fi9} - ST_{fi3} \tag{1}$$

6.3.2 Workload fluctuation (WLF)

Workload fluctuation is the absolute deviation from the production line-specific expected workload per period p (see Figure 16). Workload is defined as the total amount of time required for production and cleaning. To level the workloads per planning period over the horizon, in the objective function, the deviation from the expected value is charged with a cost, accounting for additional human resources and assets required during peak loads.

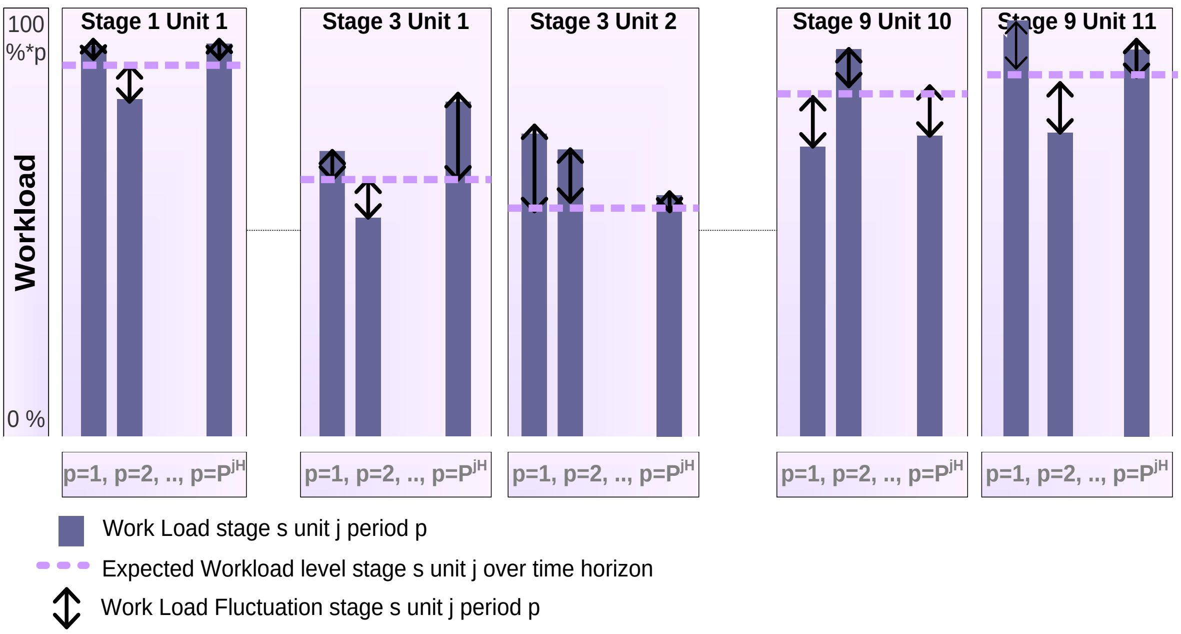


Figure 16: Example Workload Fluctuation

$$\mathrm{WLF}_s = \sum_{j \in U_s} \sum_{p \in P^H} WLF_{sj.p} \tag{2}$$

$$WLF_{sj.p} \geq 0 \tag{3}$$

$$WLF_{sj.p} \geq \sum_{r \in R^{pj}} \sum_{k \in K} \sum_{f \in F} \sum_{i \in I^f} PT_{fi.sj} y_{fi.sj.p-rk} + \tau_{sj.fif'i'} \; y_{fi.sj.p-rk} + y_{f'i'.sj.p-r(k-1)} - 1 + \sum_{r \in R^{pj}} y_{fi.sj.pr1} \sigma_{sj} - \overline{WL}_{sj} \tag{4}$$

$$WLF_{sj.p} \geq \overline{WL}_{sj} - \sum_{r\in R^{pj}}\sum_{k\in K}\sum_{f\in F}\sum_{i\in I^{f}} PT_{fi.sj}\, y_{fi.sj.prk} + \tau_{sj.fif'i'}\;\; y_{fi.sj.prk} + y_{f'i'.sj.pr(k-1)} - 1 - \sum_{r\in R^{pj}} y_{fif'i'.sj.pr1}\sigma_{sj} \qquad (5)$$

6.3.3 Coordination

Two mechanisms facilitate coordination: minimization of changeovers between runs, routes, families, and batches, and similar start times of the same product family every period. However, in spreading the production of batches within one family over the horizon, still the inventory holding costs must be taken into account.

6.3.4 Cleaning Time (CO)

Cleaning in place (CIP) is required at the end of each run (see Figure 15, page 37 for the time categorization). In the stages 1 to 8, runs consist of one batch, and the number of batches is predefined by the ELSP. Therefore, the costs of CIP of the stages 1 to 8 are not included in the optimization function. In stage 9, a run can consist of any number of time slots (i.e. batches), and optimization occurs through maximizing the run length up to the maximum allowed run length. Therefore, CIP cost for stage 9 is included in the optimization function, using the CIP time sigma (σ), which is, to facilitate modelling, charged for each new run.

The time cost of changeovers between families and batches in the final stage can be included in one sequence-dependent cleaning time tau (τ).

Remember that the route is defined as the combination of production lines in the stages three and nine (emulsification and filling) and time and coordination in preparation (stage 1 to 6) can be avoided by diminishing route conversions. Because this cost is caused by sequencing in stage 9, but accumulates in earlier stages, it is accounted for in the total cost of changeovers with sequence-dependent time factor phi (φ), but not in the timing restrictions.

The parameter omega (ω) indicates the transportation time between tanks in intermediate storage, which can be avoided by skipping intermediate storage stages. For this purpose, ghost tanks have been modelled with a residence ("processing"), cleaning, and zero transportation time.

$$\begin{aligned} SC = & \sum_{j\in U_9}\sum_{p\in P^{9jH}}\sum_{r\in R^{p9j}}\sum_{f\in F_{9j}}\sum_{i\in I_{9j}} \sigma_{9j}\, y_{fi.9j.pr1} + \\ & \sum_{j\in U_9}\sum_{p\in P^{sjH}}\sum_{r\in R^{pj}}\sum_{k\in K^{rpj}}\sum_{f\in F_j}\sum_{i\in I_j} \tau_{9j.fif'i'} + \varphi_{9j.fif'i'}\;\; y_{fi.9j.prk} + y_{f'i'.9j.pr(k-1)} - 1 \; + \\ & \sum_{j\in U_4\cup U_5\cup U_6}\sum_{p\in P^{sjH}}\sum_{r\in R^{pj}}\sum_{k\in K^{rpj}}\sum_{f\in F_j}\sum_{i\in I_j} \omega_{sj}\, y_{fi.sj.prk} \end{aligned} \qquad (6)$$

6.3.5 Start time fluctuation (STF)

To facilitate comparable start times of batches within the subsequent weeks in which they are produced, a whole-week interarrival time is modelled. Not fixing the interarrival time, but including a cost for deviation, facilitates sequencing of batches with different interarrival times. Because the actual optimal interarrival time is not in integer weeks, a decision variable is included that facilitates production of the batch earlier or later weeks.

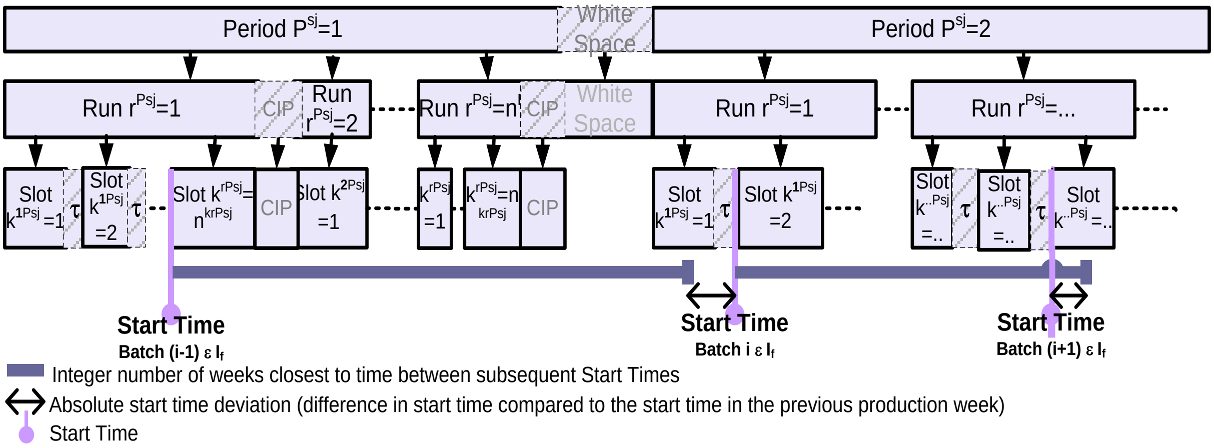


Figure 17: Example Start Time Deviation

$$STF = \sum_{s}\sum_{f\in F}\sum_{i\in I} STF_{fi.s} \qquad (7)$$

$$STF_{fi.s+} \geq 0 \qquad \forall \mathrm{i} \in \mathrm{I}, \mathrm{f} \in F, s \in S \qquad (8)$$

$$STF_{fi.s+} \geq b_{fi} - ST_{fi.s} + ST_{f(i-1).s} \qquad \forall \mathrm{i} \in \mathrm{I}, \mathrm{f} \in F, s \in S \qquad (9)$$

$$STF_{fi.s+} \geq ST_{fi.s} - ST_{f(i-1).s} - b_{fi} \qquad \forall \mathrm{i} \in \mathrm{I}, \mathrm{f} \in F, s \in S \qquad (10)$$

$$ST_{fis} - ST_{f(i-1)s} \geq 0$$

$$ST_{f0s} = ST_{fn^f H-1}$$

6.3.6 Holding inventories (IH)

To ascertain that the required number of batches to be produced is equally spread over the horizon, a holding cost factor is included in the cost optimization function for the difference between early and late production. To prevent biases in the cycle when each subsequent batch due time would be based on the previous batch completion time, the due times are based on the completion time of the last batch of the previous period plus an integer multitude of the cost-efficient interarrival time derived from the ELSP. To ascertain correctness of the multitude, the batch designation i is used as the multiplication factor and a restriction is included that a batch with a higher batch number is completed later then a batch with a lower designation.

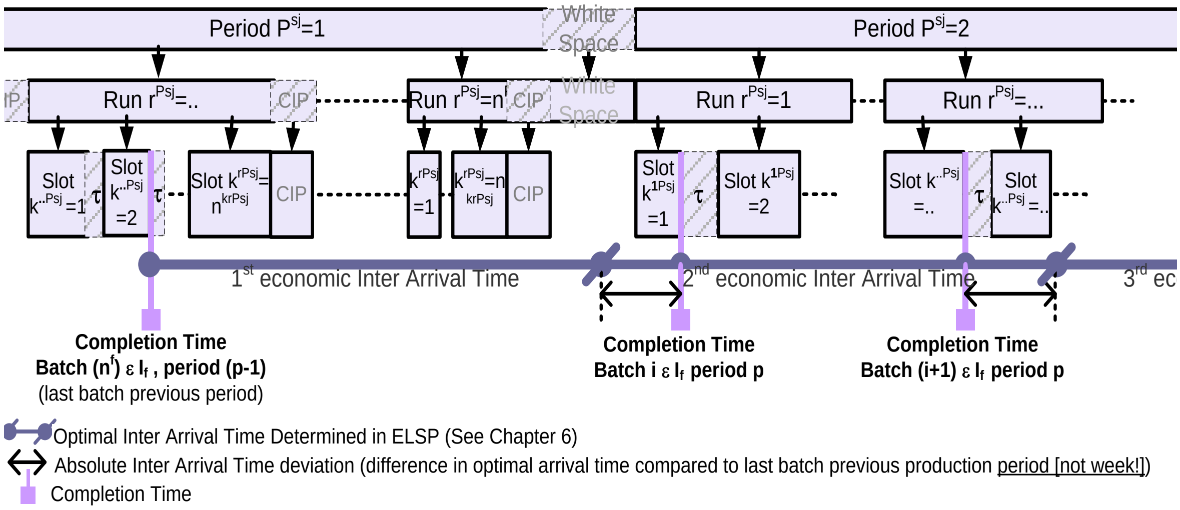


Figure 18: Example extra inventory holding time due to deviation from economic Inter Arrival Time

$$\mathrm{HI} = \sum_{f \in F} \sum_{i \in I^f} \mathrm{HI}_{fi} \tag{11}$$

$$\mathrm{HI}_{fi} \geq 0 \tag{12}$$

$$\mathrm{HI}_{fi} \geq CT_{fi.9} - CT_{f(0).9} + \mathrm{IAT}_{fi} \tag{13}$$

$$\mathrm{HI}_{fi} \geq CT_{f(0).9} + \mathrm{IAT}_{fi} - CT_{fi.9} \tag{14}$$

$$CT_{fi.9} \geq CT_{f(i-1).9}$$

$$CT_{f(0).9} = CT_{fn^f.9.H-1}$$

$CT_{fn^f.9.H-1}$:= completion time of final batch of family f in previous scheduling cycle

$\mathrm{IAT}_{\mathrm{fi}}$:= cost efficient completion time batch i of family f, derived from ELSP

6.3.7 Decision variables

The decisions to be made are:

- The start times of batches on each production line j in the stages one, three, five, six, seven, and nine.
- The storage or production lines in the stages 2, 4, 5, 6, 7, and 9, but nine onl**y** when the allowed production lines are 4-6 and 9-11.

Other production line assignments are predefined and other start, end, processing, and storage times follow from the decisions above.

Based on the time slot structure proposed b**y** Lui and Karimi (2007; 2008), and within the horizon accounting for period and maximum production runs, this can be modelled with three decision variables:

$$y_{fi.sj.prk} = \begin{cases} 1, \text{ if unit j of stage s processes batch i of product family f in its unit-slot k, } j \in U_s, \; i \in I \\ 0, \text{ otherwise} \end{cases}$$

$t_{sj.pr0}$ $\qquad$ $t_{sj.pr0}$ >=0

$CT_{fi.s}$ $\qquad$ $CT_{fi.s}$ >=0

6.3.8 Constraints

The proposed scheduling model consists of the following t**y**pes of restrictions:

- Process Constraints
- Production Time constraints
- Timing between batches in the same production line
- Linking production in successive stages

Process constraints

Because each production line can at maximum process one batch at a time:

$$u_{sj.prk} = \begin{cases} 1, \text{ if unit j of stage s processes a batch in its slot k of run r in period p, } \quad j \in U_s \\ 0, \text{ otherwise } \qquad \text{(indicates empty slot)} \end{cases}$$

$$u_{sj.prk} = \sum_{f \in F} \sum_{i \in I^f} y_{fi.sj.prk}, \qquad \forall j \in U_s, k \in K^{sj.pr}, r \in R^{sj.p}, p \in P^{sjH} \qquad (15)$$

Moreover, in each stage, a batch must be processed exactl**y** once (equation (65)), on a processing production line that can process that batch (equation (66)). Because within each famil**y**, all batches are equal and as determined b**y** the ELSP, one capabilit**y** constraint per product famil**y** suffices for each processing production line.

$$\sum_{p \in P^{sj}} \sum_{r \in R^{sj.p}} \sum_{k \in K^{sj.pr}} \sum_{j \in U_s} y_{fi.sj.prk} = 1 \qquad \forall i \in I^f, f \in F, s \in S \qquad (16)$$

$$y_{fi.sj.prk} \le L_{f.sj} \qquad \forall j \in U_s, k \in K^{sj.pr}, r \in R^{sj.p}, p \in P^{sj} \qquad (17)$$

The equations (64), (65), and (66) hold in general. However, given that onl**y** in stage nine sequence-dependent changeovers are allowed, in all other stages, each batch occupies a separate run. Therefore, in these stages, each run can at most contain one occupied production line-slot (equation(67)).

$$\sum_{k \in K^{pr}} u_{sj.prk} = 1 \qquad \forall j \in U_s, s = 1,2,\ldots,8, \; r \in R^{sj.p}, p \in P^{sj} \qquad (18)$$

Production line specific Production Time constraints

Since we decided to accumulate white space at the end of each period, empty slots must be pushed to the end of these periods. The workload balancing objectives spread the workload over the available time. Pushing the empty slots to the end of the scheduling horizon would make the inclusion of periods in the model redundant.

Empty slots are pushed to the end of a run by:

$$u_{sj.prk} \geq u_{sj.pr(k+1)}, \qquad \mathrm{j} \in \mathrm{U_s} \tag{19}$$

Empty slots are pushed to the end of the time period p by:

$$u_{sj.prK^{pr}} \geq u_{sj.p(r+1)1}, \qquad \mathrm{j} \in \mathrm{U_s} \tag{20}$$

Timing between batches in the same production line

The end time of a time slot depends on the start time, processing time of the batch processed in this time slot, the (sequence-dependent) cleaning time, and transportation time. Each run is concluded with a cleaning in place (CIP). A period length is predefined, production line-specific, and processing the first batch in the new period starts either at the period's production line release time $URT_{sj.p}$, or after preceding stages have finished processing new batches.

The equations (70), (71), (72) hold in general. Given that only in stage 9 the cleaning and cleaning time is sequence dependent, the value for tau is in all other stages equal for all products (zero). Given that only in stage 9 a run can consist of multiple batches, the value sigma is in all other stages added for each batch. Finally, given that only stage 4, 5, and 6 suffer from transportation time, the value for omega is zero in all other stages.

Slot transition

$$t_{sj.prk} \geq t_{sj.pr(k-1)} + \sum_{k \in K} \sum_{f \in F} \sum_{i \in I^f} \begin{pmatrix} PT_{fi.sj} y_{fi.sj.prk} + \omega_{sj} y_{fi.sj.prk} \\ \tau_{sj.fif'i'} \ y_{fi.sj.prk} + y_{f'i'.sj.pr(k-1)} - 1 \end{pmatrix} \tag{21}$$

$$r \in R^{sj.p}, p \in P^{sj}, \mathrm{j} \in \mathrm{U_s}, i' \in I^f, i \neq i', k \geq 1$$

Run transition

$$t_{sj.pr0} \geq t_{sj.p(r-1)n^{p\ r-1}} + \sigma_{sj} \tag{22}$$

Period transition

$$t_{sj.p00} \geq \max\left[URT_{sj.p}, \min_i \sum_{s'<s} \min_{j' \in U_{s'}, j' \in J_i} PT_{fi.s'j'} \right] \qquad \forall \mathrm{j} \in \mathrm{U_s}, p \in P^{sj} \tag{23}$$

Period and Run length constraints

The run length can be restricted for technological reasons and differs per production line. Therefore, the difference between the completion time of the final and the start time of the first batch of the run must be smaller than the maximum run length RT^{sj}. When no specific maximum run length exists, RT^{sj} can be replaced by period length P^{sjH}. When a hard constraint on white space exists (e.g. weekends), this can be modelled using the time from release time up to the time the last batch of that period should be finished.

$$t_{sj.prn^{pr}} - t_{sj.pr0} \leq RT^{sj}, \quad \forall j \in U_s,\ r \in R^{sjp}, p \in P^{sjH} \tag{24}$$

RT^{sj} ≔ maximum run time unit j of stage s

$$NA_{sj} + t_{sj.pn^p n^{pr}} - URT_{sj.p} \leq p^{sjH}, \qquad \forall j \in U_s,\ p \in P^{sjH} \tag{25}$$

p^{sjH} ≔ unit specific predefined period length

NA_{sj} ≔ unit specific time Not Available for production at the end of each period (e.g. weekend)

Linking production in successive stages

The completion time per stage can be determined using the knowledge of which batches are processed in which time slot at which production line, and linearization using a Big-M formulation. The general zero wait formulation for production lines with no intermediate storage and start of processing in the next stage as soon as the previous stage finished is as follows (Reference numbers refer to original reference numbers by Lui & Karimi, 2008, pp. 685):

$$CT_{fi0} + \sum_{j' \in U_1 \cap J_i} \sum_{k'} PT_{fi.sj'} y_{fi.1j'.prk} \geq t_{1j.prk} \text{-M}(1\text{-} y_{fi.1j'.prk}) \qquad j \in U_1, i \in I_j \qquad \text{(LK26d)}$$

$$CT_{fi0} + \sum_{s' \leq s} \sum_{j' \in U_{s'} \cap J_i} \sum_{k'} PT_{fi.sj'} y_{fisj's'prk} \leq t_{sjprk} + \text{M}(1\text{-} y_{fi.sj.prk}) \qquad j \in U_1, i \in I_j \qquad \text{(LK26e)}$$

$$CT_{fi0} + \sum_{s \leq s'} \sum_{j' \in U_{s'} \cap J_i} \sum_{k'} PT_{fisj'} y_{fis'j'prk} \geq t_{sjpr(k-1)} + \text{M}(1\text{-} y_{fi.sj.prk}) \qquad j \in U_1, i \in I_j, s > 1 \qquad \text{(LK26f)}$$

Equation (LK26d) fixates the release time of the batch to the time the processing of that batch starts in the first stage by searching the end time of the slot in which the batch is processed in the first stage. The equations (LK26d) and (LK26e) describe that the completion time of a batch is its release time plus the sum of its processing times in all previous stages and vice versa, which ascertains immediate precedence. Equation (LK26f) ensures availability of the stage's production line when the previous stage finishes processing.

In the proposed model, in some stages (2, 4, 7, 8, 9), batches must start processing in later stages before earlier stages have been completed (see Figure 20). However, later stages cannot finish before earlier stages have finished.

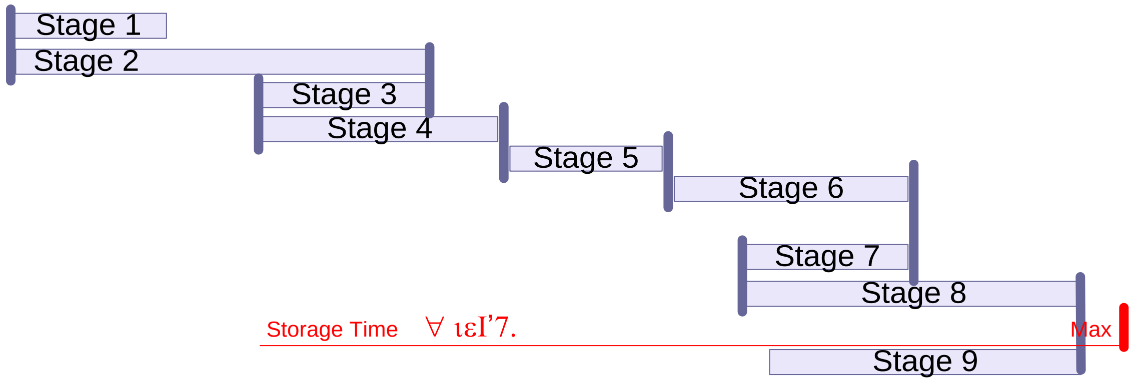


Figure 19: Gantt chart Process Transitions: Parallel, Simultaneous Starts, and Immediate Precedence

Given the processing structure, both NIS/UW and NIS/ZW formulations are required. In addition, given that (1) subsequent processes sometimes have the same start or ending times, (2) some batches have the opportunity to skip stages, and (3) connectivity between stages is limited, the general formulations in the literature do not hold and new formulations are required.

The first step is to link the production line specific time slot end times to specific batches. CT_{fis} is the completion time of a batch in a stage. $t_{sj.prk}$ is the end time of a production line-specific time slot.

$$CT_{fi.\ s-1} = \sum_{j\in U_s} \sum_{p\in P^H} \sum_{r\in R^p} \sum_{k\in K^{pr}} y_{fi.sj.prk} t_{sj.prk} \qquad \forall s \in S \qquad (26)$$

This equation requires linearization for the MILP. Based on the findings of Lui and Karimi (2007) that Big-M formulations provide faster computable results than convex-hull linearizations, a Big-M formulation is applied:

$$CT_{fi.s} \geq t_{sj.prk} + M(1 - y_{fi.sj.prk}) \qquad i \in I \qquad (27)$$

$$CT_{fi.s} \leq t_{sj.prk} + M(1 - y_{fi.sj.prk}) \qquad i \in I \qquad (28)$$

The lower bound for the completion time in the first stage is established follows:

$$CT_{fi.1} \geq t_{11.000} + \sum_{k} PT_{fi.11} y_{fi.11.prk} \qquad i \in I_1 \qquad (29)$$

To prevent an early start in subsequent stages in general completion times of earlier stages max never exceed those of succeeding stages:

$$CT_{fi.s} \geq CT_{fi.(s-1)} \qquad i \in I_s \ s>1 \qquad (30)$$

The linkage of stages depends on the process. E.g.: stages 5 and 6 start the moment the preceding stage finishes (Equation(80), (81)). Equation (82) describes that the previous stage max only end after the tank in the present stage is emptied and cleaned when a new batch arrives. The stages 2, 4, and 8 start at the same time their preceding stage starts processing (Equation (83)), and for these preceding stages, availability must be ensured as well (Equation (84)). When the final stage can start processing depends on whether treatment is required in stage 7 (Equation (85)-(91)).

To ensure production line availability of production line j in stage s after production line j' in stage (s-1) has finished processing when production is strictly sequential (immediate precedence, or

NIS/ZW), and account for transport times between intermediate storage facilities. Note that this formulation does not include a path dependent transportation time, but only the production line specific transportation time ω_{sj} . Doing so, the formulation can remain fairly simple, while ghost production lines in stages that can be skipped do not account for additional transportation time, such that the model will not generate unnecessary transportation between tanks. The difference with cleaning time is that transportation time is the time overlap between the previous stage and the next, and part is of the processing time.

$$CT_{fi(s-1)} + \sum_{j'\in U_s}\sum_k PT_{fi.sj'} y_{fi.sj'.prk} - \omega_{sj} \geq t_{sj.prk} - M(1-y_{fi.sj'.prk}) \quad i\in I_j, s=5,6 \tag{31}$$

$$CT_{fi(s-1)} + \sum_{j'\in U_s}\sum_k PT_{fi.sj'} y_{fi.sj'.prk} - \omega_{sj} \leq t_{sj.prk} - M(1-y_{fi.sj'.prk}) \quad i\in I_j, s=5,6 \tag{32}$$

$$CT_{fi.\ s-1} \geq t_{sj.pr\ k-1} + \omega_{sj} y_{fi.sj.prk} - M(1-y_{fi.sj.prk}) \qquad \text{i} \in I_{sj}\ \text{s=5,6} \tag{33}$$

To ensure availability of production line j in stage s for parallel production when it should be available as soon as production in previous stage (s-1) starts:

$$CT_{fi.\ s-1} \geq t_{sj.pr(k-1)} + \sum_{j\in J_i}\sum_k PT_{fi.(s-1)j} y_{fi.(s-1)j.prk} - M(1-y_{fi.sj.prk}) \qquad \text{i} \in I_{sj}\ \text{s=2,4,8} \tag{34}$$

To ensure availability of production line j for parallel production when it has its own independent processing time, but should be finished at the same time as the previous system:

$$CT_{fi.\ s-1} \geq t_{sj.pr(k-1)} + \sum_{j\in J_i}\sum_k PT_{fi.(s)j} y_{fi.(s)j.prk} - M(1-y_{fi.sj.prk}) \quad \text{i} \in I_s\ \text{s=3,7,9} \tag{35}$$

To ensure subsequent production line availability when stages 7 and 8 are skipped by a set of products:

$$CT_{fi.6} \geq t_{9j.pr\ k-1} - \sum_{j\in J_i}\sum_k PT_{fi.sj} y_{fi.sj.p-rk} - M(1-y_{fi.9j.prk}) \quad \text{i} \in I'_s\ \text{s=7,8} \tag{36}$$

$$CT_{fi.9} = CT_{fi.8} \geq t_{9j.prk} - M(1-y_{fi.9j.prk}) \qquad \text{i} \in I_7 \tag{37}$$

$$CT_{fi.7} = CT_{fi.6} \geq t_{7j.prk} - M(1-y_{fi.7j.prk}) \qquad \text{i} \in I_7 \tag{38}$$

$$CT_{fi.9} = CT_{fi.6} \geq t_{9j.prk} - M(1-y_{fi.9j.prk}) \qquad \text{i} \in I'_7 \tag{39}$$

$$CT_{fi.9} = CT_{fi.8} \geq t_{9j.prk} + M(1-y_{fi.9j.prk}) \qquad \text{i} \in I_7 \tag{40}$$

$$CT_{fi.7} = CT_{fi.6} \geq t_{7j.prk} + M(1-y_{fi.7j.prk}) \qquad \text{i} \in I_7 \tag{41}$$

$$CT_{fi.9} = CT_{fi.6} \geq t_{9j.prk} + M(1-y_{fi.9j.prk}) \qquad \text{i} \in I'_7 \tag{42}$$

For start times in general holds, as with completion times:

$$ST_{fis} \geq t_{fi.sj.prk} - \sum_{j\in J_i}\sum_k PT_{fi.sj} y_{fi.sj.prk} + M(1-y_{fi.sj.prk}) \quad \forall\ i\in I_s \tag{43}$$

$$ST_{fis} \leq t_{fi.sj.prk} - \sum_{j \in J} \sum_{k} PT_{fi.sj} y_{fi.sj.prk} + M(1 - y_{fi.sj.prk}) \ \ \forall\ i \in I_s \tag{44}$$

Such that:

$$ST_{fi.9} \leq t_{8j.prk} - \sum_{j \in J_i} \sum_{k} PT_{fi.9j} y_{fi.9j.prk} + M(1 - y_{fi.9j.prk}) \ \ \text{i} \in I_9 \tag{45}$$

$$ST_{fi.9} \geq t_{8j.prk} - \sum_{j \in J} \sum_{k} PT_{fi.9j} y_{fi.9j.prk} + M(1 - y_{fi.9j.prk}) \ \ \text{i} \in I_9 \tag{46}$$

Consequently, the intermediate storage time restrictions can be taken into account (see formulae(96),(97),(98))

$$ST_{fi9} \leq ST_{fi3} + \text{w}_{\text{i\_max}} \tag{47}$$

$$ST_{fi3} \geq t_{2j.prk} - \sum_{j \in J} \sum_{k} PT_{fi.2j} y_{fi.2j.prk} + \text{p}_{\text{ijf2\_min}} \tag{48}$$

$$ST_{fi3} \leq t_{2j.prk} - \sum_{j \in J} \sum_{k} PT_{fi.2j} y_{fi.2j.prk} + \text{p}_{\text{ijf2\_max}} \tag{49}$$

$$ST_{fi2} \geq t_{1j.prk} - \sum_{j \in J} \sum_{k} PT_{fi.1j} y_{fi.1j.prk} + M(1 - y_{fi.2j.prk}) \tag{50}$$

$$ST_{fi1} \geq t_{01.000} \tag{51}$$

6.4 Software Implementation

In order to implement the scheduling model in software, different tools have been used. The BSPLA model was entirely modelled in MS Excel. The ST Model has been modelled in AIMMS and solved in CPLEX 12.2. The reason for this is as follows.

Excel is a very commonly used program within Nutricia. Hence it is easy to communicate and exchange the model. Current capacity assessment approaches in Nutricia are performed in Excell and current planning and scheduling software is compatible with Excel (Infor, APO).

Aimms has been chosen to model the ST model. Aims is a comprehensible tool that requires relatively little programming knowledge to model complex mathematical programs. The tool is very well applicable for large industrial purposes. The academic license facilitates modelling without limitations on the number of restrictions, variables, and constraints. Aimms allows for straightforward adaptation of existing models and allows for parallel sessions. In addition, the Aimms license includes free licenses of some powerful solvers. Finally, Aimms is compatible with excel and can bot read from and write to Excel without much loss of time. As the data required to run the model is very data intensive, an efficient read and write function to Excel is indispensible.

The appropriateness of a solver, depends on the programming model. The scheduling problem of Nutricia Zoetermeer has been modelled as a Mixed Integer Linear Program (MILP). This type of model is supported by many solvers (e.g. CPLEX 12.2, Gurobi 4.0, Mosek 6.0, XA15). As the problem size is considerable, the main requirement for the solver is that it is capable of solving large models (with over 10000 variables, of which at least 6000 integer). Hence most XA15 and Mosek are less suitable than CPLEX12.2 and Gurobi 4.0. As based on the information provided by AIMMS, CPLEX 12.2 has the best applicability and most extensive functionality for large MILP models, CPLEX 12.2 is used to solve the model.

The model runs have been executed on 2 personal computers: one PC with an Intel Duo Core processor with 2,40 GHz and 4 GB ram, and one PC with an Intel Quad Core 2,00 GHz and 4 GB ram.

6.5 ST Model Results in short

The full model turns out to be NP-hard. Small instances (Less than 15 batches) can be solved within minutes or even seconds. However, when half of the PBF-demand per week is given as input (22 families, between 1 and 3 batches per family), to be scheduled in three parallel filling lines and prepared in 5 preparation lines, a feasible solution could not be found, even after 192 hours. This means that in the current form, the model is not practicable for Nutricia.

The specific case requires inclusion of maximum run lengths, i.e. a production sequence may never take longer than a predefined time, after which a special cleaning treatment is required. This practical limitation requires more timeslots than a situation without this restriction and slows down computation until NP-hardness. Preliminary studies without the inclusion of runs show fast calculations, even for the system with 9 stages and 73 production lines divided over these stages (within five minutes for instances with over 25 batches per week and a utilization per stage of [redacted]%). Unfortunately, this was outside of the scope of the project because considering a system without runs is unrealistic under the circumstances.

Chapter 7:

Results BSPLA

Although originally the BSPLA was meant to be the input of the ST model, some conclusions can be derived from the model itself as well. We investigated several scenarios for two load-levelling cut-off criteria in the fourth step of the procedure: (1) level until no further convergence is gained, and (2) level until all lines have utilization levels below [redacted]% (current average of the highest utilized emulsification line). Table 4 presents the four scenarios. The parameter values are based on accounting, production, and engineering data. [redacted].

Table 4: BSPLA Scenarios

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

The procedure described in Section 8.4 results after [redacted] iterations in an average utilization of [redacted]% in stage [redacted], with per line a minimum of [redacted]% and a maximum of [redacted]%. The exact line, recipe, batch size combinations are listed in Table [redacted] in Appendix [redacted].

Table 5 provides a summary of the results Line [redacted] stays behind in utilization, because its specific capabilities and high minimum batch size exclude production of other products on this line. Line [redacted] has the highest weighing factor, due to its wide-ranging capabilities and, despite its high cleaning cost, comparatively low cost of operating the line due to its higher processing speed.

For Nutricia, in weighing the costs of cleanings, production, cycle stock, and perishability, the results are most sensitive for [redacted], since for a major part of the product portfolio, [redacted] outweigh [redacted] considerably. As one can expect, the inclusion of production costs has a higher impact on the distribution between lines than on the overall utilization.

Table 5: Results of batch sizing for scenarios stage [redacted]

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

	Scenario 1	Scenario 2	Scenario 3'
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Chapter 8: Conclusions and Recommendations

The analysis and (re)design of operational business processes and the supporting information systems is strongly determined by the technologies used, and state-of-the-art technological knowledge. Since at present, products, markets, technologies, and knowledge are subject to fast, large changes, especially in the field of medical nutrition, efficient adaptation to these changing circumstances is a key success factor. This is the starting point for Nutricia to implement new strategies that serve to build and sustain the competitive lead in its markets. This closing chapter provides the key conclusions of the project and presents a choice of recommendations for Nutricia Supply Point Zoetermeer.

8.1 Conclusions

As the production environment turned out to be much more computational complex than anticipated, an integral scheduling model could not be developed and implemented during the project lead-time. Hence, quantitative insight in different scenarios with all benefits of mathematical scheduling could not be accomplished within a reasonable time (24 hrs). The cost-based batch-sizing and production line-assignment did however lead to some interesting conclusions. Hence, the project results are:

1. Filling and Preparation have different characteristics. Isolated optimization of Filling lines leads to volatile use of Preparation.

2. The number of batches in the system per week drops from [redacted] at present, to approximately [redacted] when line assignment and batch sizing are cost-based and operating hours are taken into account. When filling a batch takes on average [redacted] hours, this would accumulate to ca. [redacted]' hrs per week in the entire filling department, such that not only costs drop, but easier coordination of production is facilitated as well.

3. When batch sizes and run lengths would be better compatible, filling could be used more efficiently (like lego blocks)

4. Profit and OU suffer when preparation would be controlled on OE, e.g. line [redacted] is more cost efficient than [redacted] and [redacted] due to the hourly production rates.

5. Emulsification line [redacted] is relatively large and has few capabilities. Hence, utilization is relatively low.

8.2 Recommendations

1. As long as Filling and Emulsification cannot be decoupled by reason of maximum intermediate storage times, an integral approach of control of the production system would facilitate efficient use of the system. Hence, Nutricia should keep investigating potential resolutions

2. Nutricia should adopt cost-based batch sizing and line assignment decisions for more cost-efficient production.

3. Batch size determined processing times take at present major or minor parts of the maximum run length. In order to fill efficiently, the batch size choice should be in consideration of run length constraints.

4. With respect to Profit and OE.

   4.1. Nutricia should take into account costs in scheduling. When possible, a batch scheduled on Em [redacted] instead of Em [redacted] and [redacted] deteriorates the department's OE, but results in lower overall costs and time required for production.

   4.2. Preliminary investigations with the partially implemented optimization model show that a purely cost-based solution and fixed line assignment per product family would not improve the situation in terms of OU and OE through flexibility reduction.

5. Preparation utilization would drop if Em[redacted] had more capabilities, given its fast production rate and current low utilization through few capabilities

8.3 Interesting future research directions Nutricia

[redacted]

[redacted]

[redacted]

[redacted]

8.4 Contribution to scientific literature

Conventional (capacitated) economic batch sizing approaches consider setup and holding cost in a one line per stage one bottleneck situation, do not consider the choices of production lines in parallel line situations, and generally neglect perishability or shelf life issues. This approach considers capacitated batch-sizing for a situation with a small amount of predefined integer batch sizes of a wide product range, that must be processed on multiple parallel lines. The primary choice of lines and batch sizes is exactly determined (by enumeration). Although one might believe this method is infeasible for larger instances, the case considered a wide product range (1350 products), 12 parallel lines, 25 allowed batch sizes, and close-together parameter values of different products and lines. Given its quick and easy applicability in this instance, we deem this method as practicable for a wide range of applications where the number of predefined batch sizes is predefined and limited.

A second feature is the inclusion of utilization levels of parallel lines. To take into account limited capacity of lines, a heuristic has been developed that levels workloads between parallel lines based on occupation of the line. The choice whether workload levels of parallel lines are ultimately balanced or balanced until all occupation levels are deemed feasible is a strategic choice and left to management. The heuristic allows for both options.

A third new feature of the proposed method is inclusion of the cost factors for operating a line and shelf life, compared to restriction to holding and setup costs in conventional methods. The current case shows that differences in parallel line setups and processing rates actually make that the conventional method leads to subobtimality, since it automatically assigns products to lines with the lowest setup time, while the case shows that differences in line-speed and perishability of products differentiate beneficiality of lines. Although each product has its own preferred batch size and processing line, calculations show that, even when batch sizes are not extremely large, a faster line with a longer required setup time is the most economically attractive option for the majority of products.

Although the methods of decomposition and batch-sizing are new as well, the, in our view, major contribution of this report to the literature is the relative-time-based solution for multistage, heterogeneous parallel line scheduling problems, since it provides a solution for large scheduling problems. The difference compared to earlier sequence-based methods is the linkage of different production line-specific relative times in two dimensions (within line and between lines and stages) which allows for larger scheduled instances or faster computation. The major benefit of the current solution compared to conventional absolute time (time-slot) methods is that, instead of a decision node for each absolute time timeslot, in this case, only a single slot for each batch suffices. This allows for tighter formulation, tighter scheduling in multiple stages and parallel lines, a higher utilization, since immediate precedence is more easily facilitated, and much faster computation.

Unfortunately, the specific case under consideration requires inclusion of maximum run lengths, i.e. a production sequence may never take longer than a predefined time, after which a special cleaning treatment is required. This practical limitation requires more timeslots than a situation without this restriction and slows down computation until NP-hardness. Preliminary studies without the inclusion of runs show extremely fast calculations, even for the system with 9 stages and 73 production lines divided over these stages (within five minutes for instances with over 25 batches per week and a utilization per stage of 75%). Unfortunately, this was outside of the scope of the project because considering a system without runs is unrealistic under the circumstances. We leave it to future studies to more rigorously prove the differences in computational power between the current method and previous methods.

Finally, more contributions to the literature can be found in the inclusion of limited maximum storage time in intermediate storage, maximum run lengths, different production line-specific capabilities and specific connectivity restrictions between lines, which all are rare subjects in planning and scheduling literature, while the combination of these restrictions lacks entirely. This is a major gap in the literature, because the combination and interaction of settings make the scheduling problem in practice most complex.

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Appendices

Appendix A – Glossary

BSPLA	:=	Batch Sizing Planning Line Assignment
DC	:=	Distribution Centre, in case of Nutricia, the central distribution centre near the production plant
Discounted investment cost		asset depreciation over volume produced per planning time frame
ECN	:=	Enteral Clinical Nutrition
KPI		key performance indicator
MPS	:=	Master Production Schedule, weekly aggregate plan based on sales units' forecasts, prepared in the MPS department
MRP	:=	Materials Requirements Planning; Scheduling, production planning and inventory control approach using demand and due dates as a starting point to calculate which materials are required when, where and in which amount in the process. In the case of Nutricia, the MPS department applies this approach in the filling lines, taking into account shelf life and technologically allowed batch sizes per product, and aiming to cluster products that can be produced in sequence without CIP.
OE		Operational Efficiency' [redacted]
OU		Operational Utilization; [redacted]
Packs	:=	Packaging technology involving pouches for intravenous nutrition
PBF	:=	Packaging technology involving plastic bottles
Product family	:=	a set of final products consisting of the same recipe, packaging technology, and packaging content-size
Production Line	:=	A set of sequential production units in which processing can be seen as one handling, i.e. as a black box with one entrance and exit, in which (raw) materials are transformed to suit onward use or into a final product ready to sell
Production Process	:=	the steps required to complete a product, from the raw materials to the final product

Production Stage	:=	A phase in the production process consisting of one or multiple parallel lines aimed to complete a specific task in the process (e.g. dissolving or filling). A product can skip a stage or be processed in a stage multiple times. Within Nutricia, a batch visits each stage once.
Recipe	:=	(in this case) a specific combination of ingredients
Route	:=	the selected path through subsequent stages in the production process along which to send batches for processing.
Route clusters		sets of products with the same preparation as well as filling line and final format packaging volume, e.g. [redacted]
Routing	:=	the process of selecting the paths through subsequent stages in the production process along which to send batches for processing
RTF	:=	Packaging technology small glass bottles "Ready-to-Feed"
Run	:=	a series of production of batches uninterrupted by a major cleaning, which is required either after a technologically required time after the start of the first batch, or when batches cannot be sequenced with a small cleaning in between due to differences in taste or product recipe
Scheduling	:=	the process of selecting the batch sizes, production line assignment, and start times for batches in each production line
Sequencing	:=	the process of selecting the batches to process subsequently in a certain line, usually with the aim to minimize sequence-dependent cleaning times
Sequential	:=	serial (as opposed to parallel)
SKU	:=	See Stock Keeping Unit
Stage	:=	a phase in the production process, e.g. dissolving or filling, in which one or more production lines process
Stock Keeping Unit	:=	a unique number associated with a specific product to identify a product, e.g. for inventory purposes. Within Nutricia, specific features of each SKU are: recipe (consisting of liquid and powdered ingredients), packaging size and packaging technology, label, and type of box, tray or cluster. Within Nutricia, SKUs are measured in eaches.
SU	:=	Sales Unit, the organisational units responsible for sales and customer relations. In case of Nutricia, SUs are autonomous national organizations spread over 45 countries worldwide
Timeslot	:=	The production line-specific time required to process one batch, hence each timeslot can have a different duration
UF	:=	Ultra Filtration, the process during which a fluid is filtered through a membrane under high pressure

UHT	:=	Ultra High Temperature (UHT) Pasteurization process, in which the temperature of the intermediate product is raised to approximately 141 degrees Celsius for one or two seconds, which sterilizes the product.
Utilization	:=	Fraction of calendar time used for production and cleaning (CIP as well as sequence-dependent cleanings required)
white space		the time during which empty time slots are scheduled, i.e. the available machine time during which no production is planned. When a white space cluster is large enough, the number of shifts can be reduced
Workload		the total machine time required for production and cleaning per planning time frame

Appendix B – General Company Information

This Master Thesis project took place at Nutricia N.V. and is being conducted in the Nutricia Supply Chain Management department, of which planning of operations is a responsibility. This chapter gives a short overview of the company, department involved and the market in which Nutricia operates.

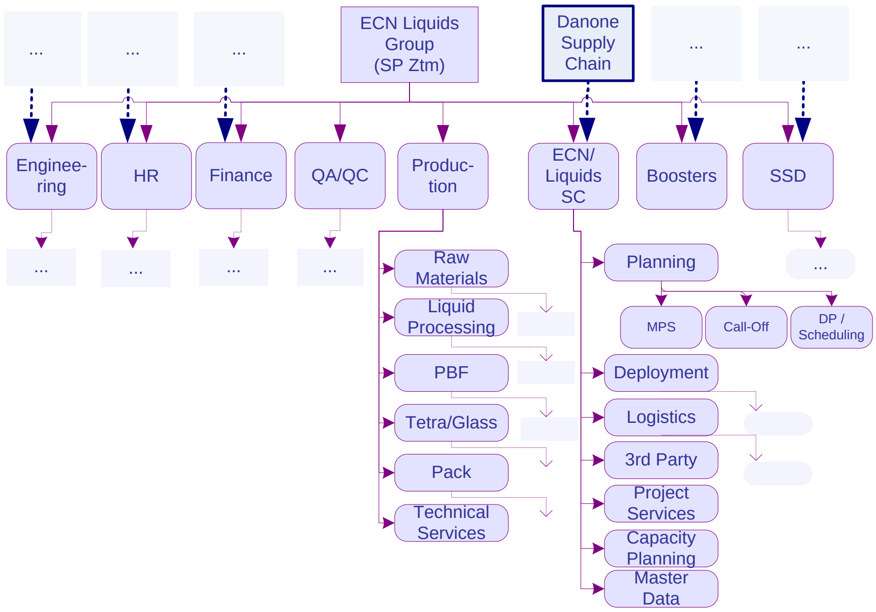
Nutricia N.V.

Nutricia was the name of the in 1896 by Martin van der Hagen founded steam dairy company "Wilhelmina". Although soon it started producing mother milk substitutes, initially the firm produced margarine. The medical branch started in 1905 with low-sugar milk for diabetics and iodine-enriched milk for thyroid patients. In 2001, the Nutricia dairy and drinks division was sold to Friesland Coberco, and in 2007, Nutricia became a subsidiary of Danone. The name Nutricia was held as the brand name for medical and baby nutrition. At present, Nutricia N.V. consists of the powders department located in Cuijk, R&D in Wageningen, and the ECN (Enteral Clinical Nutrition) Liquids Group Danone in Zoetermeer. This project focuses on the ECN Liquids Group Danone in Zoetermeer, also known as Supply Point Zoetermeer.

Supply Point Zoetermeer

At Supply Point Zoetermeer, liquid medical nutrition as well as liquid baby nutrition is being developed, produced, and distributed to sales units in 45 countries, which in turn record, sell, and supply the products. The product range exists of oral supplements in plastic flasks, glass bottles and tetra packs, as well as in plastic pouches for tube feeds. Supply Point Zoetermeer produces [redacted] [redacted]' recipes, [redacted] SKUs, and [redacted] entities final product per year. The products are principally prescribed by medical professionals. The main function areas of the advanced medical nutrition products are the application for more rapid recovery, for fewer complications, and against disease-related malnutrition as with cancer, allergies, and metabolic diseases. Since the target groups of Nutricia are babies, the sick, and the elderly, food safety is a main concern. Product innovation, technology, and strict quality assurance are the core competences of the organization.

The organizational structure of Nutricia Supply Point Zoetermeer is reflected in the figure below: The ECN/Liquids group organization.



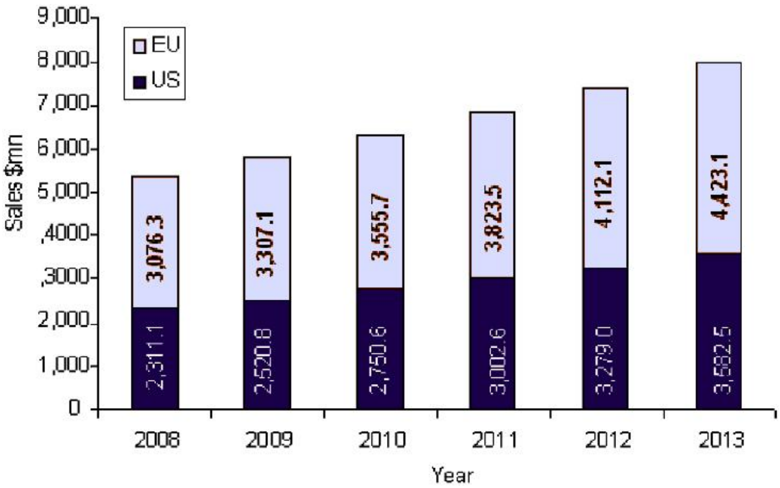
The ECN/Liquids group organization

The Market

During the last five years, the enteral and baby nutrition markets demonstrated a strong annual growth, partially due to the continuous trends towards disease-specific nutrigenic products, the aging population, rising rates of illness, rising rates of premature births in Europe, Canada, and the U.S., the intensifying recognition and attractiveness of home care products, insurance reimbursements, and emerging markets.

The clinical nutrition industry is becoming more concentrated since major actors divest and acquire operations. The consolidating market results in strong competition between key players, who vie for the leadership position. The most important competitors are respectively Abbott, B. Braun, Baxter, Fresenius Kabi, Hospira, Mead, Wyeth, and Nestlé Healthcare. Since few have expertise in both the European and U.S., all current market shares remain below 20 per cent of the total market (See Figure Market volume and development).

In the growing enteral and baby nutrition market, Danone is one of the fastest growing international organizations, with a third and fourth position in the world and a leading position in Europe. Sales of baby and medical nutrition were in 2009 respectively [redacted] and [redacted] [redacted]' and volume growths respectively [redacted] [redacted] [redacted] per cent.



Market volume and development (Source: www.globalbusinessinsights.com/content/ rbcn0001m.pdf)

During the last five years, Supply Point Zoetermeer realized a 10-15% annual growth. To be able to realize this growth, the focus of Nutricia N.V. has long been on capacity expansion. However, currently, baby product manufacturing is being transferred to other Danone plants and demand for advanced medical nutrition seems to be stabilizing. Moreover, product innovations led to new products, the so-called "Compact" products, which require half the volume for the same nutritional effects. The result of these developments is that the overall demand volume in litres will approximately remain at the current level, but the product range and the volume in numbers of end items (the number of bottles or packs) will keep expanding. In order to gain and maintain competitive advantage, Nutricia management pursues a focal shift from output volume growth towards cost efficiency.

Planning Departments

MPS Planning

The task of the MPS department is to keep the stock levels of each of the 45 SUs between an upper and lower limit. Each MPS planner is responsible for one packaging technology and constructs, based on the SUs' forecasts, a one-week production proposal for all lines filling concerning that packaging technology.

Because especially in filling, the equipment is expensive and the number of human resources required is high, the MPS department focuses on the planning of the filling lines. The preparation department is supposed to follow the production rate of filling. Its available capacity level is generally ignored in the construction of the MPS.

The target utilization level (fraction of calendar time required for production and cleaning) [redacted]

[redacted].

Finally, generally, to avoid reaching the best before-date before sales, [redacted].

The figure below shows the planning horizon for the MPS and Detail Planning departments. The MPS plan offers a [redacted] forecast on SKU level with an [redacted]-frozen window. The [redacted] Up to week [redacted], the MPS department is allowed to change the plan when enough packaging and raw materials are available for the new products in the plan. Before week [redacted], MPS must establish a final MPS, based on which DP-planners can construct a detailed production schedule.

Planning horizon MPS and Detail Planning

Detail Planning

One week before production, a detail planner constructs a schedule with the SKUs planned in the MPS. Per SKU, the DP-planner must determine a routing and start time for each production stage, taking into account the different processing times for each recipe-production line -batch size combination. Per SKU, the filling line is a given, but the emulsification line choice depends on (a) the recipe, (b) the batch size and (c) line availability. The schedule is constructed based on experience and a set of ground rules that propose an emulsification line for each filling line - batch size combination. Intermediate product batches can be split to serve multiple filling lines, but this hardly ever happens since coordination between lines is perceived difficult. Therefore, usually, a batch from preparation is completely filled in one filling department. Intermediate tanks are chosen based on connectivity and availability.

[redacted].

Appendix C – Production Unit Structure

Simplified Manufacturing Process

Appendix D- Available Production System Performance Benchmarks

Although costs are the main objective and the major benchmark for improvement, four other performance indicators provide additional measures for the aptness of the proposed scheduling approach. These are the performance indicators that at present play the major roles in planning and scheduling of operations within Nutricia:

- Schedule adherence
- MPS adherence
- Operational Utilization (OU)
- Operational Efficiency (OE)

Schedule adherence is [redacted]

MPS adherence [redacted]

[redacted].

[redacted]

Operational Utilization (OU) [redacted]

Operational Efficiency (OE) [redacted]

[redacted]

[redacted]

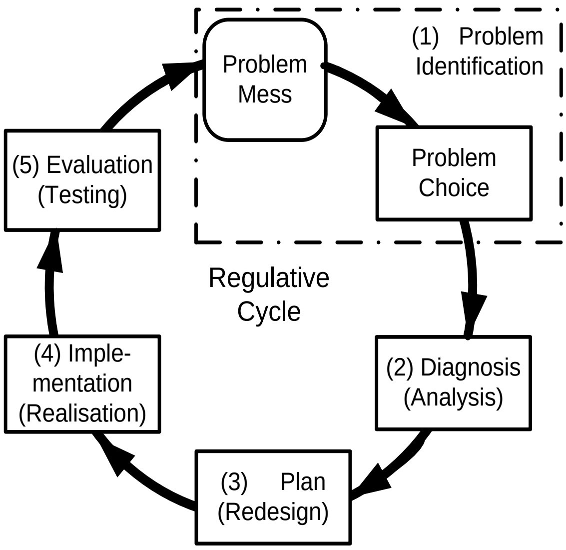
Categorization of time for utilization and assessment purposes

Appendix E- Research methodology

The project concerns a design-oriented and performance-focussed business problem-solving project and focuses on the analysis and (re)design of operational planning and control at Nutricia. The research project has been conducted as a structured project according to field-tested and academically accepted research methods. This chapter describes the research methodologies employed.

Research Approach

The research is conducted by going through the five steps in the regulative cycle by Van Aken et al. (2007, see the figure below: Regulative and Reflective Cycle): (1) Problem identification, (2) Analysis, (3) Plan, (4) Implementation, and (5) Testing. Because the iterative process of interventions required for implementation and evaluation will take several months, the project duration of 5 months does not allow for both design and implementation. Hence, the project focus is on the redesign steps ((1) Problem identification, (2) Analysis, (3) Plan).



Regulative and Reflective Cycle (Van Aken, Berends & Van der Bij, 2007)

Problem Identification (Step 1)

In determining the current situation (problem), desired situation (requirements), and expected situation (impact of design) which happened in consultation with the company supervisors, the design propositions by Simon (1996) are used. As by Van Aken et al. (2007), a *problem mess* is presumed, i.e. a mix of existing problems. From this mess, one particular problem is selected, which acts as the basis of further analyses. The problems defined are translated into a comprehensible problem characterization with a feasible project scope.

Analysis (Step 2)

Analysis and diagnosis are meant to generate a more specific definition and cause of the existing problems. The situation has been analyzed by means of the sources of evidence as described in Yin (2009, p.102):

- Interviews: dialogues and discussions with 12 key actors in different functional areas of the Supply chain and Production departments
- Documentation: descriptions of processes, lines, technologies, and information flows
- Archival records: schedules, master production plans, and production output
- Participant observation: detail schedulers reported causes of misfits between Master Production Plan and Schedules, and of deviations between production and schedules

Information of different sources was checked against information of other sources, departments, and stakeholders (triangulation). Since data and interviews were in times ambiguous, the problem identification and analysis have been performed in an iterative process. Chapter 4 presents the results of both.

The logic linking the data to propositions has been build using four strategies: (1) Developing a case description, (2) Using qualitative and quantitative data, (3) Relying on theoretical propositions, and (4) Examining rival explanations. The case description, including the units of analysis (Chapter 2), and analysis (Chapter 3) are based on both qualitative and quantitative data. Within the company, different departments share different information and explanations for the outcomes of processes. Examination of these rival explanations provided additional insights, but the theoretical propositions (Chapter 4) on which the solution builds (Chapters 5-6) include rival hypotheses as well.

Plan (Step 3)

Based on the problem and analysis in previous steps and on literature, a redesign has been developed to solve the practical business problem of Nutricia N.V. The methods used to reach to the newly developed solution are based on rigorous field-tested research from the research field of operations planning and scheduling in batch processing industries.

Model

Based on the analysis, a Mixed Integer Program has been developed for the Nutricia production system, with definitions, constraint formulations, and the objective function (See Chapter 7). The constraints are imposed by the technology employed in the Nutricia production system. The objective function is established in consultation with the Nutricia Supply Chain Director, Production Manager, Planning Manager, and staff members of the Engineering department. The actual parameter and variable values in the Nutricia supply chain have been used to solve the model. The parameter values are fixed and given. The variable values can be changed during the planning horizon and are determined by the proposed model.

Optimization

At present, no quantitative optimization tools are available within Nutricia. Therefore, new software has been selected to model the proposed mathematical model: AIMMS. AIMMS can be applied to model large and complex problems. It uses one of the most powerful solvers in the market (CPLEX 12.2) which provides many specific options to solve large and complex models. Moreover, AIMMS has a straightforward interface with Microsoft Excel, which is used most in current forecasting and estimation efforts in Nutricia.

After the design of an adequate model, sensitivity and scenario analyses help providing insight in the answers to the research question and underlying structures (Chapter 9-11). Doing so facilitates the conception a deeper understanding of the problems and builds a genuine significance of the results for the future of Nutricia.

Methods used for validation and testing

The resulting solution is tested as proposed by Van Aken, Berends, and Van der Bij (2007) in order to determine whether the proposed model results in the desired outcome (Chapter 8-11). Cost-accounting data, utilities, operator tasks, and production data are confirmed once more to ascertain validity of the input data. The reliability of the model is confirmed by a range of data tests. These concerned extreme value analysis, e.g. zero demand and zero costs, or extremely high demand or costs, and intentionally omitting required constraints, data, cells, columns, or rows.

The validity of the model is checked by asking the key actors whether all relevant constraints have been taken into account, no surprises occur after running the model, the model has enough depth, and how the model could be improved until satisfaction.

Summary Research Methodology

This chapter described the research methodologies employed. The project focus is on the redesign steps of a business problem solving project as defined by Van Aken et al (2007): (1) Problem identification, (2) Analysis, (3) Plan. The research project has been conducted as a structured project according to field-tested and academically accepted research methods.

operators (See Appendix H for the list of interviewees and Appendix B for the organizational chart).

- In this section, a more detailed focus on the production system is been adopted. Hence, where we in earlier chapters spoke mainly about the stages UF, Emulsification, and Filling, in this chapter the page 34

Appendix F- Formal Mathematical Batch Sizing and Production Line Assignment Model

Nomenclature

Indices :

g : = SKU

f : = product family

j, j' : = Emulsification line , j= 1,..,5

m_{fj} : = allowed batch size of family f on unit j

v : = iteration

Sets :

G : = set of SKUs

G^f : = subset of SKUs of family f

F : = set of product families

J : = set of production units

M^{fj}: = set of allowed batch sizes of product family f on unit j

Parameters :

$b_{fjm_{fj}}$: = allowed batch size m of family f on production unit j (in liters)

d_j := hourly processing cost of unit j

e_f := cost of discarding perished product (per liter)

h_f := family-dependent unit inventory holding cost of product family f per unit calendar time

p_j := family-independent processing rate of line j per unit time

r_g : = demand per unit time of SKU g

r_f : = demand per unit time of product family f

s_j : = cost of cleaning in unit j

t_j : = time required per cleaning in production unit j

T_f : = maximum DC shelf life of family f

TA : = time available for production related activities per unit calendar time

Variables :

b_g^* := cost efficient batch size of SKU g

b_f^* := cost efficient batch size of product family f

C_f := total average relevant cost per unit time

C_f' := weighed average relevant cost per unit time

$x_{b_{fjm_{fj}}}$:= Binary variable equal to 1 if $b_{fjm_{fj}} \le r_i * T_i$, and 0 otherwise

α_{jv} := weighing factor

ρ_j := utilization level of production line j as the ratio of the sum of hours required for setup and cleaning over the total time available for production related activities

$\overline{\rho_{j' \in J}}$:= average utilization level of all production units $j' \in J$

$\overline{\left| \rho_j - \overline{\rho_{j' \in J}} \right|}$:= average deviation from average utilization level of units $j' \in J$

Procedure

The batch sizing and line assignment problem can be solved using a six-step approach, firstly determining the economic batch size and production line by enumeration, and secondly levelling the workloads over different lines.

Step 1: Demand aggregation

The first step is to determine demand rate per product family:

$$r_f = \sum_{g \in G^f} r_g \qquad \forall f \in F \qquad (1)$$

Step 2: Relevant cost calculation batch and production lines

The second step is meant to determine for each allowed batch size per product family the relevant cost per unit time. In case the batch size is larger than the demand over the shelf life period, the remainder is destructed at the end of the shelf life period. When the batch size is limited by shelf life, on average, holding cost are higher, because the products that are destructed by the end of the shelf life incur holding costs. Cleanings happen at least once every shelf life period instead of economic period, production cost is on average higher because no less than the entire batch can be made, and destruction of perished product is costly as well. Nevertheless, it can be beneficial to make one large batch instead of two small ones if the amount of perished products remains equal or cleaning costs way up against perished product cost. The average cost per unit time in step 2 consist of four the factors:

- Average cleaning cost per unit time (equation (2))
- Average cost of processing a batch of family f on production line j per unit time (equation (3))
- Average holding cost per unit time (equation (4))
- Average cost of perished product per unit time (equation (5))

To conclude step 2, equation (6) provides the total relevant cost per unit time.

$$x_{b_{ijm}} \frac{s_j r_i}{b_{ijm}} \quad + \quad 1 - x_{b_{ijm}} \; \frac{s_j}{T_i} \tag{1}$$

$$x_{b_{ijm}} \frac{r_i d_j}{p_j} \quad + \quad 1 - x_{b_{ijm}} \; \frac{b_{ijm}}{T_i} \frac{d_j}{p_j} \tag{2}$$

$$x_{b_{ijm}} \, 0{,}5 h_i \left(1 - \frac{r_i}{p_j}\right) b_{ijm} \quad + \quad 1 - x_{b_{ijm}} \quad h_i \left(b_{ijm_{ij}} - 0{,}5 r_i T_i \left(1 - \frac{r_i}{p_j}\right)\right) \tag{3}$$

$$1 - x_{b_{ijm}} \quad e_i \left(\frac{b_{ijm}}{T_i} - r_i \right) \tag{4}$$

$$\begin{aligned} C_i(b_{ijm_{ij}}) = {} & x_{b_{ijm_{ij}}} \left[r_i \left(\frac{s_{ij}}{b_{ijm_{ij}}} + \frac{d_j}{p_j} \right) + 0{,}5 h_i \left(1 - \frac{r_i}{p_j}\right) b_{ijm_{ij}} \right] \\ & + \quad 1 - x_{b_{iijm_{ij}}} \left[\frac{s_{ij}}{T_i} + \frac{d_j b_{ijm_{ij}}}{p_j T_i} \quad + h_i \left(b_{ijm_{ij}} - 0{,}5 r_i T_i \left(1 - \frac{r_i}{p_j}\right)\right) + e_i \left(\frac{b_{ijm_{ij}}}{T_i} - r_i \right) \right] \end{aligned} \tag{5}$$

$$x_{b_{ijm}} = \begin{cases} 1, & \text{if } b_{ijm} \le r_i T_i \\ 0, & \text{otherwise} \end{cases} \qquad \forall i \in I, \forall j \in J, \forall m_{ij} \in M^{ij}$$

Step 3: Optimal batch size

Step three aims to determine the cost efficient batch size b_f^* for product family i:

$$C_i(b_i^*) = \underset{j \in J, m_{ij} \in M^{ij}}{Min} \left[C_i \;\; b_{ijm_{ij}} \;\; \right] \qquad \forall i \in I \tag{6}$$

Step 4: Feasibility check

To estimate the feasibility of the solution, in step 4 per line the utilization resulting from the cost optimal solution is computed:

$$\rho_j(b_i^*) = \sum_i \left[\frac{r_i}{p_j} + \frac{r_i t_j}{B_i TA} \right] \qquad \forall i \in I, j \in J, \text{given TA} \tag{7}$$

When the solution of step 4 yield a satisfactory solution, i.e. the levels of utilization are considered feasible (below a maximum) and no additional load levelling is required or considered desirable (when a certain level of balance has been reached), the solution resulting from step 4 can be used for the sequel. When the solution results in infeasibility or an undesirable unbalance in workload, the costs of producing a product in a certain line can be weighed against production of the same product in another line, or increasing the batch size.

Step 5: Levelling workloads in parallel lines

Given that the unbalanced workload is one of the major problems in the factory, this approach provides balancing the load between lines. Step 5 considers determining an artificially increased relevant cost per unit time for each production line j using a penalty factor σ , v indicating the vth iteration, starting with 1. This step consists of a sub steps (equation(9),(10)) that can be iterated until feasibility or an acceptable solution is reached. In order to recalculate the utilization levels, equation (8) can be reapplied using the newly determined optimal batch sizes and product-processing line combinations.

11.1.1.1 Step 5a: Calculate penalty factor

$$\alpha_{jv} = \left(\left| \rho_j - \overline{\rho_{j' \in J}} \right| \Big/ \overline{\left| \rho_j - \overline{\rho_{j' \in J}} \right|} \right) \left(\frac{\rho_j}{\underset{j' \in J}{Min}\left[\rho_{j'} \right]} - 1 \right) + \alpha_{j\ v-1} \qquad \forall\, j \in J, \alpha_{j0} = 1 \qquad (8)$$

11.1.1.2 Step 5b: Determine total relevant cost times penalty factor

$$C_i'(b_i^*) = \underset{j \in J, m_{ij} \in M^{ij}}{Min} \left[\alpha_{jv} C_i \ \ b_{ijm_{ij}} \right] \qquad \forall i \in I \qquad (9)$$

Step 6: When lines are levelled and OU is high

When lines are levelled and OU is high, the most straightforward approach to lower the utilization is to increase batch sizes. Hence, either holding cost should be lowered or setup cost increased. Because the reaction of the system on such an approach is highly reliant on the nature of the production environment, we propose a cautious proportional increase of the setup cost per unit time. Batch sizes on all lines increase proportionally.

Step 7: Input for the mathematical scheduling model

As the figures derived from the previous steps are input parameters in for the mathematical scheduling model, a simple spreadsheet containing the following suffices:

- The number of forecasted Batches per product family
- The Processing Times per product family per Stage, as these are line dependent and batch size dependent
- The Line and Storage Capability to process or store the batch

Disaggregation of demand

As explained in Section 5.2, disaggregation is not required as input for the mathematical scheduling model. When one would like to distribute batches over SKUs in proportion to their relative demand rate, equation (11) can be applied.

$$b_g^* = \frac{r_g}{r_i} b_i^* \qquad \forall\ g \in G \qquad (10)$$

Concluding these six steps solves the complete batch sizing and production line assignment part of the scheduling problem. The results can be used as inputs for the remaining scheduling problem: determining start times per product batch on each production line.

Appendix G-Formal Mathematical Scheduling Model

Nomenclature

Indices:

f, f' := product families

i, i' := batches

j, j' := production units

k, k' := time slots

p, p' := time periods

r, r' := production runs

s, s' := production stages

Sets:

I^{f} := Set of batches that belongs to family f

I_{s} := Set of batches that require treatment in stage s

$K^{sj.pr}$:= Set of unit slots of unit j in stage s, that belongs to run r of period p

$R^{sj.p}$:= Set of runs of unit j in stage s, that belongs to period p

$P^{sj.H}$:= Set of periods of unit j in stage s, over planning horizon

U_{s} := Set of units j that belongs to stage s

Parameters :

C_{IS} := Cost factor Intermediate Storage

C_{WLF} := Cost factor Workload Fluct

C_{SC} := Cost factor Setups/Changeovers

C_{STF} := Cost factor Start Time Fluct (Coord, waste , mistakes)

C_{UHTO} := Cost factor UHT Overlap (Costs per hour of each UHT more than one running)

C_{HI} := Holding cost / L / y, per unit, etc)

$CT_{fn^f H-1}$:= start time of final batch of family f in the previous scheduling cycle

H := Planning Horizon

IAT_{fi} := cost efficient completion time for batch i of family f derived from ELSP

$L_{fi.sj}$: = Predefined binary, 1 if unit j in stage s is capable of processing batch i of family f, 0 otherwise

M : = Large constant in $Big - M$ constraints

n^{pr} := number of slots during run r of period p

n^{p} := number of runs during period p

n^{f} := number of batches in family f during scheduling horizon

NA_{sj} := unit specific time the unit is Not Available for production at the end of each period (e.g. weekend)

$PT_{fi.sj}$:= processing time of batch i of family f in unit j of stage s

$p_{fi\_\min}$:= minimum dissolving time in stage 2 (product dependent)

$p_{fi\_\max}$:= maximum dissolving time in stage 2 (product dependent)

$p^{sj.H}$:= unit-specific predefined period length

RT^{sj} := max run length of unit j in stage s

$\text{w}_{i\_\max}$:= maximum intermediate storage time

W_{sj} := time measure indicating the available time per calendar week of unit j in stage s

$\overline{WL}_{sj}$:= Expected WorkLoad unit j in stage s

$ST_{fn^f H-1}$:= start time of final batch of family f in the previous scheduling cycle

$\text{URT}_{js.p}$:= release time of unit j in stage s at start period p

σ_{sj} :=Time required for Cleaning in Place (CIP) after each production run of unit j in stage s

$\tau_{sj.fif'i'}$:= sequence-dependent changeover time required in stage s when batch i is processed immediately after i' on unit j in stage s

$\varphi_{9j.fif'i'}$:= accumulated coordination time required in the stages 1 to 6 when batch i is processed immediately after i' on unit j in stage 9

ω_{sj} := transport time between intermediate tanks

Variables:

HI := Sum of deviation in time that batches are delivered early of late (per week)

IS := Total time required for intermediate storage

SC := Total time required for setups, changeovers, transportation, and cleaning

$ST_{fi.s}$:= Start time batch i from family f in stage s (follows from Completion Time $\text{CT}_{fi.s}$)

STF := Total deviation of all products and all units in start time during the week compared to the previous weeks the products are produced

TC := Total Relevant Cost over scheduling horizon

WLF_s := the sum of hours that the weekly workload deviates from the average within the scheduling horizon (in productive hours, i.e. production and cleaning)

Continuous Decision Variables:

$\text{CT}_{fi.s}$:= Completion Time of batch i of family f in stage s

HI_{fi} := Deviation from predefined cost efficient completion time, derived from ELSP

$STF_{fi.s}$:= Deviation per stage per product in start time during the week compared to the previous week the product was produced

$\text{t}_{js.prk}$:= time at which unit – slot k ends on unit j in stage s

$\text{WLF}_{sj.p}$:= absolute deviation from average workload in period p

Integer Decision Variables:

b_{fi} := number of integer weeks between production of batch i and batch (i-1) within the same family

Binary Decision Variables:

$u_{sj.prk}$:= binary decision variable, 1, if unit j processes a batch in its unit – slot k

$y_{fi.sj.prk}$:= binary decision variable, 1, if unit j of stage s processes batch i of product family f in its unit-slot k

Objective Function

The scheduling objective is to minimize the total relevant cost TC over the time horizon H, i.e. the sum of costs C of:

- Intermediate storage (IS), cost of cooling tanks
- Workload fluctuation (WLF) cost of human labour (shift reduction) and asset depreciation (postponement of investments)
- Coordination:
  - Start-up and Changeovers (SC) cost of changeover (human labour, assets, utilities)
  - Start time fluctuation (STF) cost of coordination (human labour, scrap)
  - Levelling inventories (IH) inventory holding cost
- UHT start overlap (UHTO) cost of utilities (steam and deep cool water)

To deal with the prioritization of stages in workload fluctuation (see Section **Error! Reference source not found.**), this factor incurs a stage-dependent cost. For all other aspects a single cost factor suffices.

I.e.:

$$Minimize: \quad TC \;=\; C_{IS}IS + \sum_{s\in S} C_{WLF_s}WLF_s \;+ C_{SC}SC \;+ C_{STF}STF + C_{HI}HI \tag{11}$$

Intermediate storage (IS)

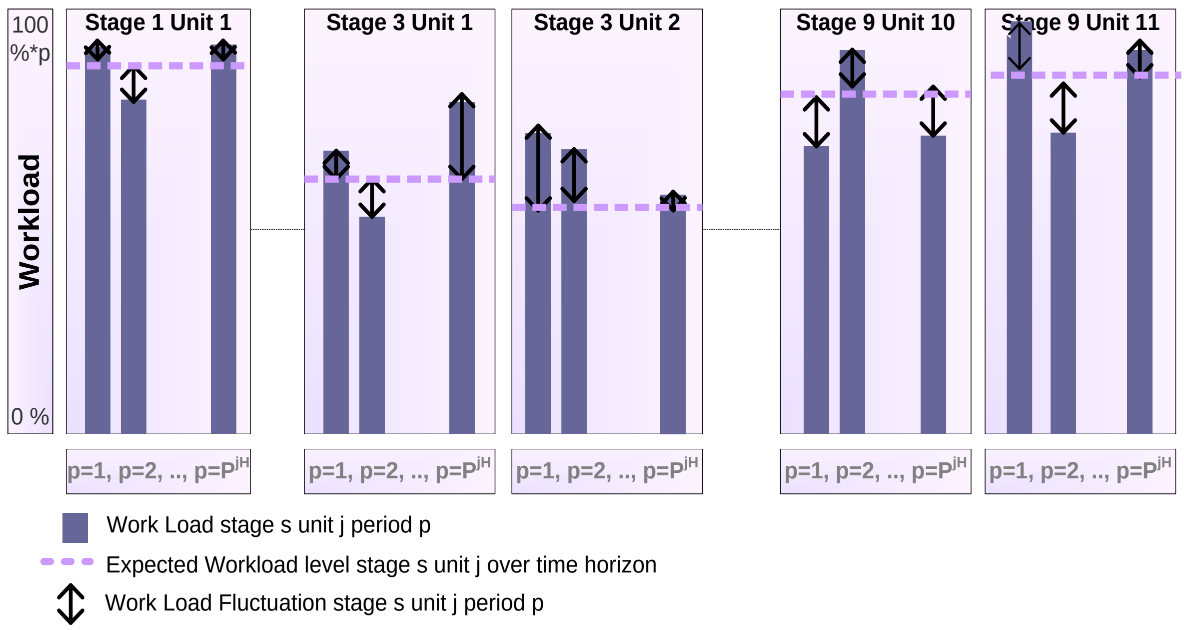
As intermediate storage tanks require cooling, the cost of the energy required to cool the tanks should be accounted for.

Intermediate storage cost consists primarily of the cost of cooling the intermediate product to prevent decay. Cooling of intermediates starts at the start of emulsification (stage 3), and finishes only at the completion of filling (stage 9).

$$IS = \sum_{f\in F}\sum_{i\in I^f} CT_{fi9} - ST_{fi3} \tag{12}$$

Workload fluctuation (WLF)

Workload fluctuation is the absolute deviation from the production line-specific expected workload per period p (see the figure below). Workload is defined as the total amount of time required for production and cleaning. To level the workloads per planning period over the horizon, in the objective function, the deviation from the expected value is charged with a cost, accounting for additional human resources and assets required during peak loads.



Example Workload Fluctuation

$$\mathrm{WLF}_s = \sum_{j \in U_s} \sum_{p \in P^H} WLF_{sj.p} \tag{13}$$

$$WLF_{sj.p} \geq 0 \tag{14}$$

$$WLF_{sj.p} \geq \sum_{r \in R^{pj}} \sum_{k \in K} \sum_{f \in F} \sum_{i \in I^f} PT_{fi.sj} y_{fi.sj.p-rk} + \tau_{sj.fif'i'} \; y_{fi.sj.p-rk} + y_{f'i'.sj.p-r(k-1)} - 1 + \sum_{r \in R^{pj}} y_{fi.sj.pr1} \sigma_{sj} - \overline{WL}_{sj} \tag{15}$$

$$WLF_{sj.p} \geq \overline{WL}_{sj} - \sum_{r \in R^{pj}} \sum_{k \in K} \sum_{f \in F} \sum_{i \in I^f} PT_{fi.sj} \, y_{fi.sj.prk} + \tau_{sj.fif'i'} \; y_{fi.sj.prk} + y_{f'i'.sj.pr(k-1)} - 1 - \sum_{r \in R^{pj}} y_{fif'i'.sj.pr1} \sigma_{sj} \tag{16}$$

Coordination

Two mechanisms facilitate coordination: minimization of changeovers between runs, routes, families, and batches, and similar start times of the same product family every period. However, in spreading the production of batches within one family over the horizon, still the inventory holding costs must be taken into account.

Changeovers (CO)

Cleaning in place (CIP) is required at the end of each run. In the stages 1 to 8, runs consist of one batch, and the number of batches is predefined by the ELSP. Therefore, the costs of CIP of the stages 1 to 8 are not included in the optimization function. In stage 9, a run can consist of any number of time slots (i.e. batches), and optimization occurs through maximizing the run length up to the maximum allowed run length. Therefore, CIP cost for stage 9 is included in the optimization function, using the CIP time sigma (σ), which is, to facilitate modelling, charged for each new run.

The time cost of changeovers between families and batches in the final stage can be included in one sequence-dependent cleaning time tau (τ).

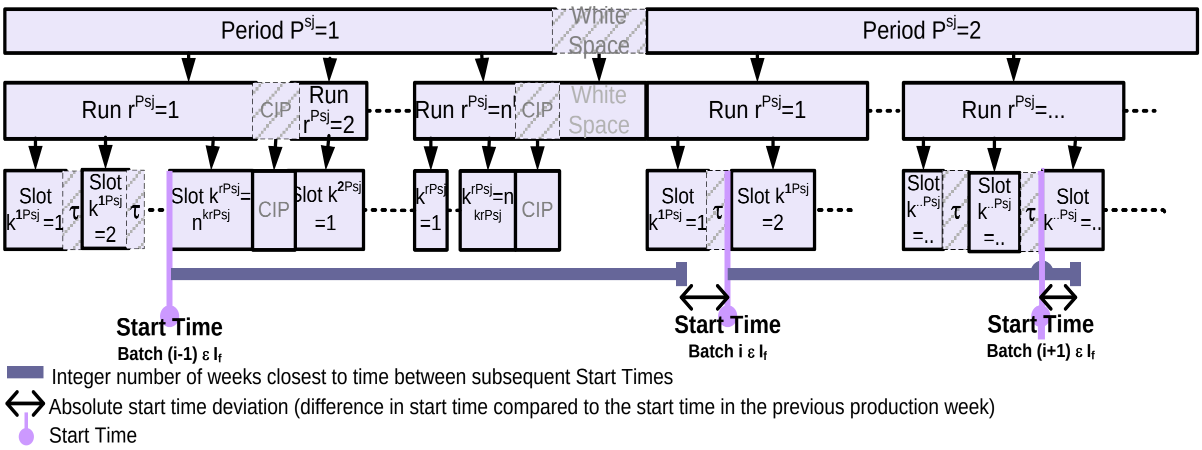
Remember that the route is defined as the combination of production lines in the stages three and nine (emulsification and filling) and time and coordination in preparation (stage 1 to 6) can be avoided by diminishing route conversions. Because this cost is caused by sequencing in stage 9, but accumulates in earlier stages, it is accounted for in the total cost of changeovers with sequence-dependent time factor phi (φ), but not in the timing restrictions.

The parameter omega (ω) indicates the transportation time between tanks in intermediate storage, which can be avoided by skipping intermediate storage stages. For this purpose, ghost tanks have been modelled with a residence ("processing"), cleaning, and zero transportation time.

$$SC = \sum_{j \in U_9} \sum_{p \in P^{9jH}} \sum_{r \in R^{p9j}} \sum_{f \in F_{9j}} \sum_{i \in I_{9j}} \sigma_{9j} y_{fi.9j.pr1} +$$
$$\sum_{j \in U_9} \sum_{p \in P^{sjH}} \sum_{r \in R^{pj}} \sum_{k \in K^{rpj}} \sum_{f \in F_j} \sum_{i \in I_j} \left(\tau_{9j.fif'i'} + \varphi_{9j.fif'i'}\right)\left(y_{fi.9j.prk} + y_{f'i'.9j.pr(k-1)} - 1\right) + \quad (17)$$
$$\sum_{j \in U_4 \cup U_5 \cup U_6} \sum_{p \in P^{sjH}} \sum_{r \in R^{pj}} \sum_{k \in K^{rpj}} \sum_{f \in F_j} \sum_{i \in I_j} \omega_{sj} y_{fi.sj.prk}$$

Start time fluctuation (STF)

To facilitate comparable start times of batches within the subsequent weeks in which they are produced, a whole-week interarrival time is modelled. Not fixing the interarrival time, but including a cost for deviation, facilitates sequencing of batches with different interarrival times. Because the actual optimal interarrival time is not in integer weeks, a decision variable is included that facilitates production of the batch earlier or later weeks.



Example Start Time Deviation

$$STF = \sum_{s} \sum_{f \in F} \sum_{i \in I} STF_{fi.s} \quad (18)$$

$$STF_{fi.s+} \geq 0 \qquad \forall i \in I, f \in F, s \in S \quad (19)$$

$$STF_{fi.s+} \geq b_{fi} - ST_{fi.s} + ST_{f(i-1).s} \qquad \forall i \in I, f \in F, s \in S \qquad (20)$$

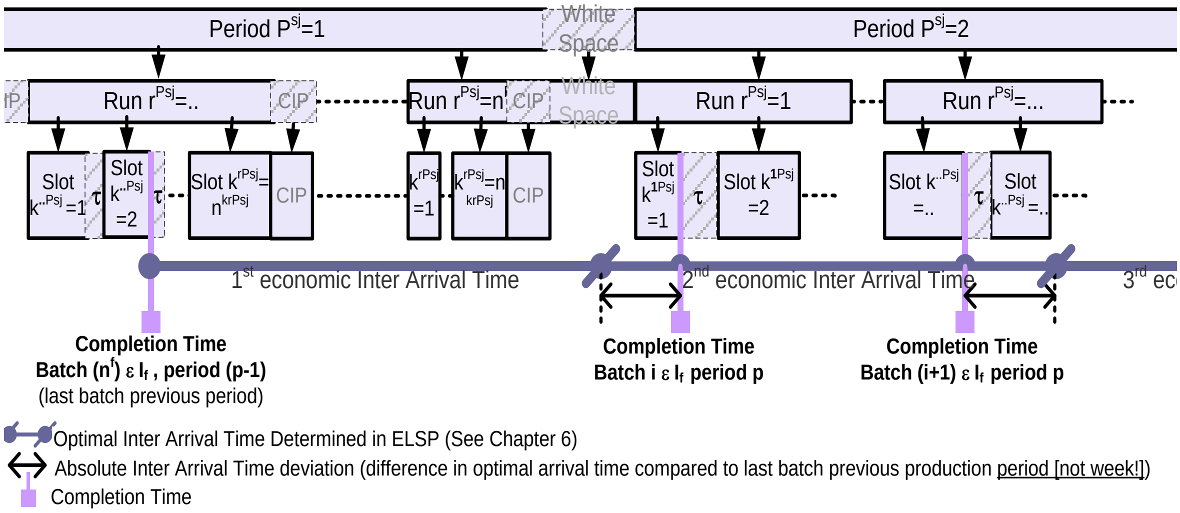
$$STF_{fi.s+} \geq ST_{fi.s} - ST_{f(i-1).s} - b_{fi} \qquad \forall i \in I, f \in F, s \in S \qquad (21)$$

$$ST_{fis} - ST_{f(i-1)s} \geq 0$$

$$ST_{f0s} = ST_{fn^f H-1}$$

Holding inventories (IH)

To ascertain that the required number of batches to be produced is equally spread over the horizon, a holding cost factor is included in the cost optimization function for the difference between early and late production. To prevent biases in the cycle when each subsequent batch due time would be based on the previous batch completion time, the due times are based on the completion time of the last batch of the previous period plus an integer multitude of the cost-efficient interarrival time derived from the ELSP. To ascertain correctness of the multitude, the batch designation i is used as the multiplication factor and a restriction is included that a batch with a higher batch number is completed later then a batch with a lower designation.



Example extra inventory holding time due to deviation from economic Inter Arrival Time

$$\mathrm{HI} = \sum_{f \in F} \sum_{i \in I^f} \mathrm{HI}_{fi} \qquad (22)$$

$$\mathrm{HI}_{fi} \geq 0 \qquad (23)$$

$$\mathrm{HI}_{fi} \geq CT_{fi.9} - CT_{f(0).9} + \mathrm{IAT}_{fi} \qquad (24)$$

$$\mathrm{HI}_{fi} \geq CT_{f(0).9} + \mathrm{IAT}_{fi} - CT_{fi.9} \qquad (25)$$

$$CT_{fi.9} \geq CT_{f(i-1).9}$$

$$CT_{f(0).9} = CT_{fn^f.9.H-1}$$

$CT_{fn^f.9.H-1}$:= completion time of final batch of family f in previous scheduling cycle

IAT_{fi} := cost efficient completion time batch i of family f, derived from ELSP

Decision Variables

The decisions to be made are:

- The start times of batches on each unit j in the stages 1, 3, 5, 6, 7, and 9.
- The storage or processing units in the stages 2, 4, 5, 6, 7, and 9, but 9 only when the allowed units are 4-6 and 9-11.

Other unit assignments are predefined and other start, end, processing, and storage times follow from the decisions above.

Table 1: Batch Starting Time Decision Variables and Derivations

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

Table 2: Number of Run and Slot-related Decision Variables (DVs) and Derivations, DVs in bold

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

Constraints

The proposed scheduling model consists of the following types of restrictions:

- Process Constraints
- Production Time constraints
- Timing between batches in the same production line
- Linking production in successive stages

Process constraints

Because each production line can at maximum process one batch at a time:

$$u_{sj.prk} = \sum_{f \in F} \sum_{i \in I^f} y_{fi.sj.prk}, \qquad \forall j \in U_s, k \in K^{sj.pr}, r \in R^{sj.p}, p \in P^{sjH} \qquad (26)$$

Moreover, in each stage, a batch must be processed exactly once (equation(27)), on a processing unit that can process that batch (equation(28)). Because within each family, all batches are equal and as determined by the ELSP, one capability constraint per product family suffices for each processing unit.

$$\sum_{p\in P^{sj}}\sum_{r\in R^{sj.p}}\sum_{k\in K^{sj.pr}}\sum_{j\in U_s} y_{fi.sj.prk} = 1 \qquad \forall i \in I^f,\ f\in F, s\in S \tag{27}$$

$$y_{fi.sj.prk} \le L_{f.sj} \qquad \forall\ j\in U_s, k\in K^{sj.pr}, r\in R^{sj.p}, p\in P^{sj} \tag{28}$$

The equations (26), (27), and (28) hold in general. However, given that only in stage 9 sequence-dependent changeovers are allowed, in all other stages, each batch occupies a separate run. Therefore, in these stages, each run can at most contain one occupied unit-slot (equation(29)).

$$\sum_{k\in K^{pr}} u_{sj.prk} = 1 \qquad \forall\ j\in U_s, s=1,2,\ldots,8,\ r\in R^{sj.p}, p\in P^{sj} \tag{29}$$

Production line specific Production Time constraints

Since we decided to accumulate white space at the end of each period, empt**y** slots must be pushed to the end of these periods. The workload balancing objectives spread the workload over the available time. Pushing the empt**y** slots to the end of the scheduling horizon would make the inclusion of periods in the model redundant.

Empt**y** slots are pushed to the end of a run b**y**:

$$u_{sj.prk} \ge u_{sj.pr(k+1)}, \qquad j\in U_s \tag{30}$$

Empt**y** slots are pushed to the end of the time period p b**y**:

$$u_{sj.prK^{pr}} \ge u_{sj.p(r+1)1}, \qquad j\in U_s \tag{31}$$

Timing between batches in the same production line

The end time of a time slot depends on the start time, processing time of the batch processed in this time slot, the (sequence-dependent) cleaning time, and transportation time. Each run is concluded with a cleaning in place (CIP). A period length is predefined, production line-specific, and processing the first batch in the new period starts either at the period's production line release time $URT_{sj.p}$, or after preceding stages have finished processing new batches.

The equations (33), (34), (35) hold in general. Given that onl**y** in stage 9 the cleaning and cleaning time is sequence dependent, the value for tau is in all other stages equal for all products (zero). Given that onl**y** in stage 9 a run can consist of multiple batches, the value sigma is in all other stages added for each batch. Finall**y**, given that onl**y** stage 4, 5, and 6 suffer from transportation time, the value for omega is zero in all other stages.

Slot transition

$$t_{sj.prk} \ge t_{sj.pr(k-1)} + \sum_{k\in K}\sum_{f\in F}\sum_{i\in I^f}\begin{pmatrix} PT_{fi.sj}y_{fi.sj.prk} + \omega_{sj}y_{fi.sj.prk} \\ \tau_{sj.fif'i'}\ y_{fi.sj.prk} + y_{f'i'.sj.pr(k-1)} - 1 \end{pmatrix} \tag{32}$$

$$r\in R^{sj.p}, p\in P^{sj}, j\in U_s, i'\in I^f, i\ne i', k\ge 1$$

Run transition

$$t_{sj.pr0} \ge t_{sj.p(r-1)n^{p\,r-1}} + \sigma_{sj} \tag{33}$$

Period transition

$$t_{sj.p00} \geq \max\left[URT_{sj.p}, \min_{i} \sum_{s'<s} \min_{j' \in U_{s'}, j' \in J_i} PT_{fi.s'j'} \right] \qquad \forall \mathrm{j} \in \mathrm{U_s}, p \in P^{sj} \quad (34)$$

Period and Run length constraints

The run length can be restricted for technological reasons and differs per production line. Therefore, the difference between the completion time of the final and the start time of the first batch of the run must be smaller than the maximum run length RT^{sj}. When no specific maximum run length exists, RT^{sj} can be replaced by period length P^{sjH}. When a hard constraint on white space exists (e.g. weekends), this can be modelled using the time from release time up to the time the last batch of that period should be finished.

$$t_{sj.prn^{pr}} - t_{sj.pr0} \leq RT^{sj}, \quad \forall \mathrm{j} \in \mathrm{U_s},\ r \in R^{sjp}, p \in P^{sjH} \qquad (35)$$

RT^{sj} ≔ maximum run time unit j of stage s

$$NA_{sj} + t_{sj.pn^{p}n^{pr}} - URT_{sj.p} \leq p^{sjH}, \qquad \forall \mathrm{j} \in \mathrm{U_s},\ p \in P^{sjH} \qquad (36)$$

p^{sjH} ≔ unit specific predefined period length

$\mathrm{NA_{sj}}$ ≔ unit specific time Not Available for production at the end of each period (e.g. weekend)

Linking production in successive stages

The completion time per stage can be determined using the knowledge of which batches are processed in which time slot at which production line, and linearization using a Big-M formulation. The general zero wait formulation for production lines with no intermediate storage and start of processing in the next stage as soon as the previous stage finished is as follows (Reference numbers refer to original reference numbers by Lui & Karimi, 2008, pp. 685):

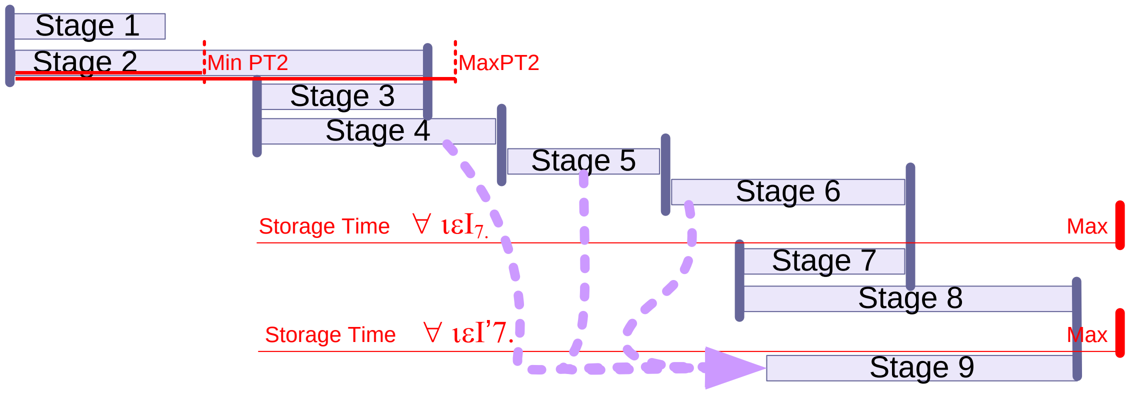
$$CT_{fi0} + \sum_{j' \in U_1 \cap J_i} \sum_{k'} PT_{fi.sj'} y_{fi.1j'.prk} \geq t_{1j.prk} \text{-M(1-} y_{fi.1j'.prk}) \qquad j \in U_1, i \in I_j \qquad \text{(LK26d)}$$

$$CT_{fi0} + \sum_{s' \leq s} \sum_{j' \in U_{s'} \cap J_i} \sum_{k'} PT_{fi.sj'} y_{fisj's'prk} \leq t_{sjprk} + \text{M(1-} y_{fi.sj.prk}) \qquad j \in U_1, i \in I_j \qquad \text{(LK26e)}$$

$$CT_{fi0} + \sum_{s \leq s'} \sum_{j' \in U_{s'} \cap J_i} \sum_{k'} PT_{fisj'} y_{fis'j'prk} \geq t_{sjpr(k-1)} + \text{M(1-} y_{fi.sj.prk}) \qquad j \in U_1, i \in I_j, s > 1 \qquad \text{(LK26f)}$$

Equation (LK26d) fixates the release time of the batch to the time the processing of that batch starts in the first stage by searching the end time of the slot in which the batch is processed in the first stage. The equations (LK26d) and (LK26e) describe that the completion time of a batch is its release time plus the sum of its processing times in all previous stages and vice versa, which ascertains immediate precedence. Equation (LK26f) ensures availability of the stage's production line when the previous stage finishes processing.

In the proposed model, in some stages (2, 4, 7, 8, 9), batches must start processing in later stages before earlier stages have been completed (see the figure below: Gantt Chart Process Transitions: Parallel, Simultanaous Starts, and Immediate Precedence). However, later stages cannot finish before earlier stages have finished.



Gantt Chart Process Transitions: Parallel, Simultaneous Starts, and Immediate Precedence

Given the processing structure, both NIS/UW and NIS/ZW formulations are required. In addition, given that (1) subsequent processes sometimes have the same start or ending times, (2) some batches have the opportunity to skip stages, and (3) connectivity between stages is limited, the general formulations in the literature do not hold and new formulations are required.

The first step is to link the production line specific time slot end times to specific batches. CT_{fis} is the completion time of a batch in a stage. $t_{sj.prk}$ is the end time of a production line-specific time slot.

$$ST_{fis} \le t_{fi.sj.prk} - \sum_{j \in J} \sum_{k} PT_{fi.sj} y_{fi.sj.prk} + M(1 - y_{fi.sj.prk}) \quad \forall\ i \in I_s \qquad (38)$$

$$CT_{fi.\ s-1} = \sum_{j \in U_s} \sum_{p \in P^H} \sum_{r \in R^p} \sum_{k \in K^{pr}} y_{fi.sj.prk} t_{sj.prk} \qquad \forall s \in S \qquad (37)$$

This equation requires linearization for the MILP. Based on the findings of Lui and Karimi (2007) that Big-M formulations provide faster computable results than convex-hull linearizations, a Big-M formulation is applied:

$$CT_{fi.s} \ge t_{sj.prk} + M(1 - y_{fi.sj.prk}) \qquad \mathrm{i} \in I \qquad (38)$$

$$CT_{fi.s} \le t_{sj.prk} + M(1 - y_{fi.sj.prk}) \qquad \mathrm{i} \in I \qquad (39)$$

The lower bound for the completion time in the first stage is established follows:

$$CT_{fi.1} \ge t_{11.000} + \sum_{k} PT_{fi.11} y_{fi.11.prk} \qquad i \in I_1 \qquad (40)$$

To prevent an early start in subsequent stages in general completion times of earlier stages may never exceed those of succeeding stages:

$$CT_{fi.s} \ge CT_{fi.(s-1)} \qquad \mathrm{i} \in I_s \ \ \mathrm{s}>1 \qquad (41)$$

The linkage of stages depends on the process. E.g.: stages 5 and 6 start the moment the preceding stage finishes (Equation(43), (44)). Equation (45) describes that the previous stage max only end after the tank in the present stage is emptied and cleaned when a new batch arrives. The stages 2, 4, and 8 start at the same time their preceding stage starts processing (Equation(46)), and for these preceding stages, availability must be ensured as well (Equation(47)). When the final stage can start processing depends on whether treatment is required in stage 7 (Equation (48)-(54)).

To ensure production line availability of production line j in stage s after production line j' in stage (s-1) has finished processing when production is strictly sequential (immediate precedence, or NIS/ZW), and account for transport times between intermediate storage facilities. Note that this formulation does not include a path dependent transportation time, but only the production line specific transportation time ω_{sj} . Doing so, the formulation can remain fairly simple, while ghost production lines in stages that can be skipped do not account for additional transportation time, such that the model will not generate unnecessary transportation between tanks. The difference with cleaning time is that transportation time is the time overlap between the previous stage and the next, and part is of the processing time.

$$CT_{fi(s-1)} + \sum_{j'\in U_s} \sum_{k} PT_{fi.sj'} y_{fi.sj'.prk} - \omega_{sj} \geq t_{sj.prk} - \mathrm{M}(1- y_{fi.sj'.prk}) \quad i \in I_j, s = 5,6 \tag{42}$$

$$CT_{fi(s-1)} + \sum_{j'\in U_s} \sum_{k} PT_{fi.sj'} y_{fi.sj'.prk} - \omega_{sj} \leq t_{sj.prk} - \mathrm{M}(1- y_{fi.sj'.prk}) \quad i \in I_j, s = 5,6 \tag{43}$$

$$CT_{fi.\ s-1} \geq t_{sj.pr\ k-1} + \omega_{sj} y_{fi.sj.prk} - M(1- y_{fi.sj.prk}) \qquad \mathrm{i} \in I_{sj}\ \ \mathrm{s{=}5,6} \tag{44}$$

To ensure availability of unit j in stage s for parallel production when it should be available as soon as production in previous stage (s-1) starts:

$$CT_{fi.\ s-1} \geq t_{sj.pr(k-1)} + \sum_{j\in J_i} \sum_{k} PT_{fi.(s-1)j} y_{fi.(s-1)j.prk} - M(1- y_{fi.sj.prk}) \qquad \mathrm{i} \in I_{sj}\ \ \mathrm{s{=}2,4,8} \tag{45}$$

To ensure availability of unit j for parallel production when it has its own independent processing time, but should be finished at the same time as the previous process:

$$CT_{fi.\ s-1} \geq t_{sj.pr(k-1)} + \sum_{j\in J_i} \sum_{k} PT_{fi.(s)j} y_{fi.(s)j.prk} - M(1- y_{fi.sj.prk}) \quad \mathrm{i} \in I_s\ \ \mathrm{s{=}3,7,9} \tag{46}$$

To ensure subsequent unit availability when stages 7 and 8 are skipped by a set of products:

$$CT_{fi.6} \geq t_{9j.pr\ k-1} - \sum_{j\in J_i} \sum_{k} PT_{fi.sj} y_{fi.sj.p-rk} - M(1- y_{fi.9j.prk}) \quad \mathrm{i} \in I'_s\ \ \mathrm{s{=}7,8} \tag{47}$$

$$CT_{fi.9} = CT_{fi.8} \geq t_{9j.prk} - M(1- y_{fi.9j.prk}) \qquad \mathrm{i} \in I_7 \tag{48}$$

$$CT_{fi.7} = CT_{fi.6} \geq t_{7j.prk} - M(1- y_{fi.7j.prk}) \qquad \mathrm{i} \in I_7 \tag{49}$$

$$CT_{fi.9} = CT_{fi.6} \geq t_{9j.prk} - M(1- y_{fi.9j.prk}) \qquad \mathrm{i} \in I'_7 \tag{50}$$

$$CT_{fi.9} = CT_{fi.8} \geq t_{9j.prk} + M(1- y_{fi.9j.prk}) \qquad \mathrm{i} \in I_7 \tag{51}$$

$$CT_{fi.7} = CT_{fi.6} \geq t_{7j.prk} + M(1 - y_{fi.7j.prk}) \qquad \mathrm{i} \in I_7 \tag{52}$$

$$CT_{fi.9} = CT_{fi.6} \geq t_{9j.prk} + M(1 - y_{fi.9j.prk}) \qquad \mathrm{i} \in I_7' \tag{53}$$

For start times in general holds, as with completion times:

$$ST_{fis} \geq t_{fi.sj.prk} - \sum_{j \in J_i} \sum_k PT_{fi.sj} y_{fi.sj.prk} + M(1 - y_{fi.sj.prk}) \quad \forall\, i \in I_s \tag{54}$$

$$ST_{fis} \leq t_{fi.sj.prk} - \sum_{j \in J} \sum_k PT_{fi.sj} y_{fi.sj.prk} + M(1 - y_{fi.sj.prk}) \quad \forall\, i \in I_s \tag{55}$$

Such that:

$$ST_{fi.9} \leq t_{8j.prk} - \sum_{j \in J_i} \sum_k PT_{fi.9j} y_{fi.9j.prk} + M(1 - y_{fi.9j.prk}) \quad \mathrm{i} \in I_9 \tag{56}$$

$$ST_{fi.9} \geq t_{8j.prk} - \sum_{j \in J} \sum_k PT_{fi.9j} y_{fi.9j.prk} + M(1 - y_{fi.9j.prk}) \quad \mathrm{i} \in I_9 \tag{57}$$

Consequently, the intermediate storage time restrictions can be taken into account (see formulae(58),(59),(60))

$$ST_{fi9} \leq ST_{fi3} + \mathrm{w_{i\_max}} \tag{58}$$

$$ST_{fi3} \geq t_{2j.prk} - \sum_{j \in J} \sum_k PT_{fi.2j} y_{fi.2j.prk} + \mathrm{p_{ijf2\_min}} \tag{59}$$

$$ST_{fi3} \leq t_{2j.prk} - \sum_{j \in J} \sum_k PT_{fi.2j} y_{fi.2j.prk} + \mathrm{p_{ijf2\_max}} \tag{60}$$

$$ST_{fi2} \geq t_{1j.prk} - \sum_{j \in J} \sum_k PT_{fi.1j} y_{fi.1j.prk} + M(1 - y_{fi.2j.prk}) \tag{61}$$

$$ST_{fi1} \geq t_{01.000} \tag{62}$$

ST_{ijfs} := Start time batch i of family f in unit j of stage s

$TT_{j's'js}$:= time required for transport from tank j′ in stage s′ to tank j in stage s

$\mathrm{w_{i\_max}}$: = maximum residence time in intermediate storage

$\mathrm{p_{ijf2\_min}}$:= minimum dissolving time

$\mathrm{p_{ijf2\_max}}$:= maximum dissolving time

Appendix-H Production System

This Appendix provides detailed constraints and configurations of the production system.

[redacted]

3) [redacted]
4) [redacted]
5) [redacted]

[redacted]

a) [redacted]
b) [redacted]
c) [redacted]
d) [redacted]
e) [redacted]
f) [redacted]
g) [redacted]

h) [redacted]

6) [redacted]

a) [redacted]

i) [redacted]

b) [redacted]

c) [redacted]

[redacted]

Appendix-I

Literature Review

Theoretical Background

According to Neumann et al. (2005, pp. 252): "*Batch scheduling allocates scarce resources like production lines, workers, and intermediate storage facilities to the operations arising from the batching step such that the regular objective function of detailed production scheduling is minimized*."

In the field of batch scheduling problems in processing industries, since the 1990s considerable advances have been made. However, the general batch scheduling models neglect perishability of intermediates (e.g. Kallrath, 2002, Méndez et al., 2006), and the models taking into account perishability of intermediates neglect complexities in process configurations (Trautmann & Schwindt, 2009), or ignore cleaning or setup times (Akkerman, 2007). Akkerman et al. (2007) conclude that the combination of constraints is the cause of complexity in scheduling problems. For Nutricia, the challenge is in how to deal with their wide-ranging combination of constraints.

Based on the findings in the literature (see e.g. Fleishmann & Meyr, 2003), three specific scheduling methods can be considered in a multiproduct multistage batch processing environment: MRP (currently employed), exact mathematical scheduling models, and cyclic scheduling models.

General scheduling models

MRP disregards finite capacity planning and is material instead of process oriented (See e.g. Entrup et al., 2005). Within Nutricia, balancing investments in capacity and productivity is a major issue and explosion of the bill of materials is not relevant. Therefore, MRP is not the most suitable scheduling method for Nutricia.

Cyclic (periodic) scheduling is an effective scheduling method for various manufacturing processes with stable demand, especially those where setup, cleaning and transportation times are significant (see e.g. Winands, 2007; Vaughan, 2007; Levner et al., 2010), due to:

- better production line utilization
- workload stability
- efficient material handling
- easier production floor control
- easy communication to production, and anticipation by production
- coordination throughout the supply chain, since up- and downstream facilities know when to expect demand and supply
- ever cycle an opportunity to improve due to repetition
- amount of required information to monitor the system is minimal

These characteristics make cyclic scheduling an attractive approach for cyclic multi-product multi-stage batch scheduling. Although these scheduling approaches consider work in process and the cost of idle time, the lack applicability for environments with dissimilar parallel lines, a high product variety, and high utilization in all stages, because the remain restricted to sequential serial lines with single or similar machines per stage, a single bottleneck, and a limited number of final products (See e.g. Khouja & Goyal, 2008; El-Najdawi, 1997; Wu & Ierapetritou, 2004).

Given the computational complexity of the capacitated batch-sizing problem, for this case often heuristics are applied (See e.g. Doll & Whybark, 1973). A heuristic is a rule of thumb that ensures fewer required operations to solve a problem. Broecke, et al. (2008) show that application of the simple batch-sizing heuristic by Doll & Whybark (1973) on the stage with the highest setup cost leads to near optimal results and requires substantially less computational time than solving the capacitated batch-sizing problem.

With respect to exact mathematical scheduling, Kallrath (2002) denotes the following benefits:

- Consistency in the proposed solution
- A deeper understanding of the problem:
    - Better interpretation of the problem and the results
    - Satisfying all constraints
    - The development of new ideas
    - Focused "experiments" though the possibility of trying different parameter settings
- Quantitative reasoning-based decision-making
- The possibility of straight-forward "What if" analyses
- Relatively straightforward maintenance of the model

Exact scheduling through mathematical programming can result in optimality. However, a major drawback is that MILP endeavours for multistage environments with a very high product variety often result in NP-hard models (see e.g. Aytug et al., 2005; Begnaud et al., 2008; McKay & Wiers, 2001; Trautmann & Fündeling, 2007). Moreover, Méndez et al. (2006) claim that in practice scheduling to optimality might not be relevant for four reasons:

- The generation of a solution can require substantial computational time, while in practice the time available is limited
- Optimality is easily lost in dynamic environments
- The actual processes might limit schedule implementation
- It might not be able to justly address all scheduling objectives in a model

Nevertheless, advances in modelling techniques make solutions increasingly practicable. For example, restrictions in industrial environments often imply that solvers must find (near) optimal solutions in a vast search space with a small feasible region. Reducing the search space reduces computational time, can produce more robust and implementable results (through more general applicability), and generate more stable and predictable outcomes, which allows for better interpretation of the problem and the results (Méndez et al., 2006).

In conclusion, cyclic scheduling and exact mathematical scheduling have complementary benefits and disadvantages. The combination of both can be advantageous.

Cyclical Batch Sizing and Exact Scheduling

To benefit from the advantageous feature of both ELSP-planning and exact mathematical scheduling-scheduling, Broecke, et al. (2005; 2008) suggest the following two-step procedure:

- Part 1: solve the economic batch sizing problem for the production stage with the highest cost per setup, and for the (based on volume) fastest moving 80% of products, such that the schedule remains intact when demand in the tail of the demand distribution varies:
  - define cycle length and frequencies (See e.g. Doll & Whybark, 1973; Vaughan, 2007)
  - round cycle length towards practical cycle length
  - use intermediate plan as input constraint in determining production frequencies for final products based on cost
- Part 2: sequence operations through exact mathematical optimization (See e.g. Prasad and Maravelias, 2008)
  - use cycle length and production frequencies as input constraint
  - add symmetry constraints
  - minimize load fluctuations
  - respect capacity constraints

Broecke, et al. (2008) compare solving the ELSP with solving the Capacitated Lot-Sizing Problem (CLSP) in the first part, i.e. the mathematical optimum. The results show that the ELSP-based solution is able to achieve a near optimal solution (2,8% deviation from the optimum) due to the load smoothening restrictions in the ELSP-approach. Moreover, for the number of products considered (between one and five), the computational effort required for the CLSP increased exponentially (from 2 to 332 minutes), while the computational effort for solving the ELSP remained equal for these numbers (2 minutes). Field-testing in a two-stage sequential process shows, that robustness of the solution is enforced by a load-smoothening algorithm, limiting the model to the fast-moving items and basing the ELSP on the stage with the highest setup cost.

Solution Direction

Potentially appropriate solution approaches are Exact Mathematical Scheduling, Periodic (Cyclic) Scheduling, i.e. ELSP, CLSP, and ELSP in combination with Exact Mathematical Scheduling. MRP has shown to be inappropriate for Nutricia due to the importance of capacity restrictions and the process focus for Nutricia. Table 4 lists the gains of the potentially appropriate approaches in terms of improvement potential in terms of financial prospects, feasibility of implementation, feasibility of the redesign within project lead-time, user friendliness for practitioners once implemented, time required to generate a solution (computational complexity), and risks involved.

An exact mathematical schedule optimization model (Model 1 [M1], See Table 3) has the highest improvement potential [C1], because it can capture all detailed constraints and solve to optimality. However, the model complexity makes its feasibility of implementation [C2] and user friendliness for practitioners once implemented [C4] low because concise insight in the model is required to adapt it, while, given the vast amount of the lines, constraints, (intermediate) products, and interactions in the Nutricia production system, the computational complexity, the resulting time required to generate a solution, and the risk of NP-hardness are high [C3].

Table 3: Comparison of models found in the literature

Model Criterion	[M1] Exact Mathematical Scheduling	[M2] Periodic [Cyclic] Scheduling, ELSP	[M3] Capacitated Periodic (Cyclic) Scheduling,CLSP	[M4] ELSP + exact mathematical scheduling
[C1] Improvement Potential	High	Low	Moderate	Moderately High
[C2] Feasibility Implementation	Low	Moderately High	Moderately low	Moderately High
[C3] Feasibility design within project Lead-Time	Moderate	High	Moderate	Moderate
[C4] Practical Model Applicability (User friendliness)	Moderately High	High	Moderately low	Moderately High
Risks	NP-hardness (High)	Non-optimality (High)	NP-hardness (High)	NP-hardness exact part (Moderate)
Examples in the literature	Lui & Karimi (2007, 2008), Méndez et al. (2006), Prasad & Maravelias (2008)	Doll & Whybark (1973), Goyal (1973), El-Najdawi (1994), Vaughan (2007)	Broecke, et al. (2008)	Broecke, et al. (2005, 2008)
Applicability of examples in the literature	Multi-Product, Multi Stage Batch Scheduling with Dissimilar Parallel Lines, (Seq.-Dep) Cleaning & Changeovers, Interstage Storage Time Restrictions (Not Storage Capacity, No Runs, Small number of stages, lines, and products)	Multiproduct, but all multistage approaches one-bottleneck situations, no capacity restrictions, no dissimilar parallel lines,	No dissimilar parallel lines, multistage approaches regard only stage with highest setup cost	

Given that demand shows a stable pattern, the batches to be processed, can be assumed to be repeated an infinite amount of times, which facilitates cyclic scheduling [ELSP, M2]. The user friendliness [C4] is high because ELSP is easy to understand, and due to its straightforwardness, design requires relatively little time [C3]. However, the improvement potential in terms of costs [C1] of solving the ELSP is low, primarily because ELSP does not account for capacity restrictions, sequencing, run lengths, and shelf life. These restrictions will also limit the feasibility of the implementation in practice [C2].

The improvement potential [C1] for CLSP [M3] is slightly higher than for ELSP [M2], because it takes capacity into account. However, given the number of intermediates (350) and SKUs (1350), the risk of NP-hardness in solving the CLSP is high as well, which limits feasibility of implementation [C2], design within project lead-time [C3], and practical applicability [C4]. Nevertheless, because Nutricia's costs of production capacity are more influential than the costs of holding inventory (annual asset depreciation: 9M€; annual cost of labour in production: 20M€; annual inventory costs: 4M€), levelled production and stocks buffering variations in the chain, promise to provide better results in terms of costs than levelling the stock, requiring the production to be able to absorb the deviation in workload with extra capacity, as it is currently the case.

The final approach, first solving the ELSP and subsequently scheduling the processes exact by means of a MILP [M4], provides the best prospects, because in this case, the benefits of cyclic scheduling, feasibility of implementation [C2], design within project lead-time [C3], and practical applicability [C4], can be combined with the advantages of mathematical modelling, the improvement potential [C1]. The proven capability of the approach to provide near-optimal solutions (see Broecke et al. 2005; 2008), indicates high improvement potential, while solving the

ELSP before the exact mathematical scheduling model reduces the chances of NP-hardness. Therefore, this approach will be developed into an implementable plan.

Theoretical Basis

A thorough examination of the literature did not yield an existing model that, with small adjustments, could be made applicable for the problem of Nutricia. The processes within Nutricia are more elaborate than the processes described in the literature, in that there are more production stages (9 instead of 2 or 3), more parallel lines (11 instead of 2 to 5), more intermediates (350 instead of 11) and more final products (1350 instead of up to 20). Moreover, the Run-concept as used by Nutricia has not been found in the literature.

The main procedure of the mixed integer optimization for cyclic scheduling of the multiproduct multistage batch plant takes place in two parts: (1) solving the ELSP, and (2) solving an exact mathematical scheduling model for cyclical scheduling with the results from the first part.

The general procedure of the new scheduling model can be based on the procedure as described by Broecke, et al. (2005; 2008, see Section 10.1.2), who used procedure by Doll & Whybark (1973) to solve the ELSP. Broecke, et al. (2005; 2008) do not consider dissimilar parallel lines in subsequent stages or a situation with predefined allowed batch sizes. Nevertheless, the line of reasoning can be used as a basis to solve the current business problem. With adaptations for different costs and capabilities of different parallel lines, run lengths, shelf life, and capacity restrictions, the model can be made applicable for the new scheduling model. The models found for the exact mathematical scheduling-part require more adaptations. Based on the model requirements listed in Chapter 4, Table 3 provides an overview of the three best applicable exact mathematical scheduling models found in the literature that can be used as a base for the new exact mathematical scheduling model.

Lui and Karimi (2007, 2008, see Table 4) describe the scheduling model for a multiproduct multistage batch plant with dissimilar parallel lines and different intermediate storage settings, but no parallel starts in different stages, runs, or cost-based objective. Prasad and Maravelias (2008) describe the scheduling model for a multiproduct multistage batch plant with dissimilar parallel lines with sequence-dependent changeovers, and a wide range of objectives, among which costs, but no intermediate storage time or space restrictions, no parallel starts in different stages, and no runs.

Because the models found are not straightforwardly applicable, a new scheduling model will be created.

Table 4: Applicability of theoretical models exact mathematical scheduling

Required Model Features	Lui & Karimi (2007)	Lui & Karimi (2008)	Prasad & Maravelias (2008)
Batch Sizes	**Yes**, Predefined	**Yes**, Predefined	No, Min, Max requirements
Multi-Product	**Yes**, (43 examples, max 11 products, each 1 batch)	**Yes**, (43 examples, max 11 products, each 1 batch)	**Yes**, (8 products, each 1 batch)
Multi -Stage	**Yes**	**Yes**	**Yes**
Parallel starts, Immediate precedence, Storage with restrictions	No, Unlimited Inter-mediate Storage	**Yes**, Immediate Precedence	No, Unlimited Intermediate Storage
Dissimilar Parallel Lines	**Yes**	**Yes**	**Yes**
Setups & Changeovers	**Yes**, Sequence & production line dependent	No, Included in processing times	**Yes**, path-, production line-, order- dependent
Runs	No	No	No
Cost-based objective	No, only Make span	No, only Make span	**Yes**, minimization of make span, earliness, lateness, and production cost + profit maximization