DEGREE PROJECT, IN APPLIED MATHEMATICS AND INDUSTRIAL ECONOMICS , FIRST LEVEL
STOCKHOLM, SWEDEN 2015

Optimization of Production Scheduling in the Dairy Industry

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O S K A R A L V F O R S
F R E D R I K B J Ö R E L I N D

Degree Project in Applied Mathematics and Industrial Economics (15 credits)
Degree Progr. in Industrial Engineering and Management (300 credits)
Royal Institute of Technology year 2015
Supervisors at KTH: Johan Karlsson and Anna Jerbrant
Examiner: Boualem Djehiche

TRITA-MAT-K 2015:25
ISRN-KTH/MAT/K--15/25--SE

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Abstract

This thesis presents a case study of mathematical production scheduling optimization applied on Arla Foods AB's production of dairy products. The scheduling was performed as a possible remedy for problems caused by overcrowded finished goods warehouse. Based on the scheduling, conclusions were made on whether the existing two-shift production is sufficient or if an additional night shift should be introduced. In parallel, an empirical and theoretical analysis on the perceived effects of night shift work on employees was conducted.

For the optimization, mixed integer programming was used to model the production context through a discrete time scheduling lot-sizing model developed in this thesis. The model developed and implemented on Arla Foods AB contributes to the research field through its feature of relatively low complexity enabling scheduling of extensive production systems when applied in industrial contexts where products may be categorized.

The thesis concludes that mathematical production scheduling can solve Arla Foods AB's production problematics and suggests reallocation of the existing shifts for the purpose of reduced costs and acceptable warehouse levels. This reallocation would incur production during inconvenient hours whereas management remedies reducing negative effects of night shift work are identified.

Keywords: Mathematical optimization, Mixed integer programming, Production scheduling, Lot-sizing, Shift work.

Optimering av produktionsscheman i mejeriindustrin

Sammanfattning

Denna avhandling innefattar en studie av matematisk optimering av produktionsscheman applicerad på Arla Foods ABs produktion av mejeriprodukter. Schemaläggningen utfördes som en möjlig lösning på produktionsproblematik orsakad av överfyllda färdigvarulager. Utifrån de optimerade produktionsschemana drogs slutsater kring om dagens produktionsstruktur på två skift är tillräcklig eller om introduktion av ett andra nattskift skulle vara fördelaktig. Parallellt med detta presenteras en empirisk och teoretisk studie kring de produktionsanställdas uppfattning kring effekter av att arbeta nattskift.

För optimeringen har heltalsoptimering (*eng: mixed integer programming*) använts för modellering av produktionen genom en produktionsplaneringsmodell med diskret tidsrepresentation (*eng: discrete time scheduling lot-sizing model*) som utvecklas i denna avhandling. Denna model, som även appliceras på Arla Foods ABs produktion, presenteras i detalj och karaktäriseras av låg komplexitet vilket möjliggör schemaoptimering av omfattande produktionssystem givet att produktportföljen kan kategoriseras i produktgrupper med liknande egenskaper ur ett produktionsperspektiv.

Avhandlingen fastslår att matematisk optimering av produktionsscheman har potential att lösa produktionsproblematiken på Arla Foods AB och föreslår en reallokering av den nuvarande produktionen för minskade kostnader och utjämnade nivåer i färdigvarulager. Produktionsomläggningen skulle innebära produktion under obekväm arbetstid vilket föranleder en analys av initiativ som har potential att minska de negativa effekterna av nattskiftarbete för de produktionsanställda.

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Chapter 1

Introduction

1.1 Background

Arla Foods AB's, from now on referred to as "Arla", production site in Kallhäll, Stockholm, produces dairy products supplying an area consisting of approximately three million consumers. The factory produces roughly one million liters a day spread across some 100 articles on 14 parallel single stage production lines with similar capacities and capabilities. The articles are variations of milk, sour milk, cream and sour cream differentiated on fat content, brand and packaging. The products are made on a daily basis and delivered from the factory by truck at certain times in order to reach the stores day fresh. Today the production is operating on two shifts, producing from midnight until 6:00 p.m.

1.2 Identified Problem

In order to supply their customers with products on the same day as produced and at customer specified delivery times, Arla has most trucks leaving the production site between 10:00 a.m. and 5:00 p.m. The narrow delivery time span in relation to the production period often forces Arla to produce to stock and large volumes have to be stored before they can be delivered. Consequently, the storage occasionally gets full resulting in production stops until some finished goods have been delivered. This problem implies rescheduling issues causing disturbance in the production unit and more importantly causes delays that result in Arla failing deliver on time. Overall, these issues increase costs and waste and threaten Arla's customer relationships.

1.3 Purpose & Research Question

The purpose of this thesis is to investigate the potential of an optimized production schedule in order to remedy Arla's production problems caused by high levels of inventory in the finished goods warehouse. Furthermore, since a possible solution from the scheduling optimization would require a majority of the employees to work night shift and inconvenient hours, the purpose also includes investigating how night shift work affects employees' perceived health in terms of sleep, stress and social life, issues that could damage Arla's reputation as an employer. The research questions hence are as follows:

- Does production schedule optimization have the potential to solve Arla's problems caused by high levels of inventory in the finished goods warehouse and what is the optimal schedule?
- How does night shift production affect employees' perceived health in terms of sleep, stress and social life and what management remedies can minimize the negative effects?

1.4 Restrictions

For the purpose of this thesis, only optimizing the production scheduling and introducing three-shift production are regarded as plausible solutions for the problematics. Other possible solutions such as investing in larger warehouses, increasing production capacities and reducing setup or changeover times are left for evaluation in other contexts since they require to be included in a long term strategy and hence cannot solve the urgent issue.

Chapter 2

Description of the Arla Production

This section describes the Arla production in order to establish an understanding of the general context of this thesis.

Arla's production site in Kallhäll can conceptually be divided into five operational stages that all products have to pass in chronological order. The first stage receives the milk by trucks delivered from the farmers. The second stage processes the milk to dairy products and store them in large silos. In the third stage, the dairy products are packaged and in the fourth stage, the finished goods warehouse, all products are stored until delivery from the loading bay, the fifth stage. This thesis mainly considers the third part, the packaging, and the interaction with the fourth part, the finished goods warehouse. The dairy products that are subject for the packaging in the third part are stored in large silos, serving as buffers, why they can be considered to be available for the packaging at all times. Figure 2.1 conceptualizes the entire production with more detail on the third stage.

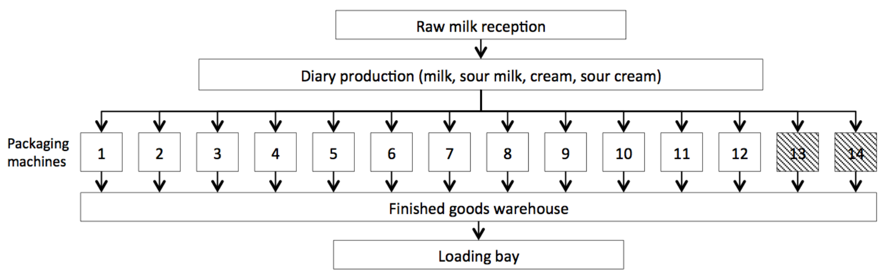

Figure 2.1: Schematics of the Arla Production

The packaging is the stage that is subject for the optimization in this thesis. The packaging machines process the dairy products from the previous production stage and package them into different kind of packages and brands. There are four different product categories; milk, sour milk, cream, and sour cream. Altogether, the different combinations of products, fat contents, packages, and brands compose about a 100 articles. However, all articles are not produced every day and some are packaged into larger packages than one liter on line 13 and 14 why only the 43 most common articles are considered in this thesis, produced on 12 production lines.

The 43 articles are to be produced during the day on 12 parallel single stage production lines with similar capacities and capabilities, in other words, all articles can be produced on any of the production lines. The capacities of the machines vary between 14,000 and 16,000 liters per hour. When the articles are ready from the packaging they are delivered into the fourth part of the production, the finished goods warehouse. Due to customers desiring different delivery times, there are multiple due times for the articles in the production throughout the day. This circumstance is the main cause of Arla's current problems. Most due times are between 10:00 a.m. and 5:00 p.m. and therefore the packaging unit has to pile up the finished goods warehouse in order to meet all the demand. However, the finished goods warehouse is limited, 1290 m^2, and occasionally gets overcrowded forcing the production to pause until some products have been delivered. This naturally causes rescheduling issues that makes Arla fail to deliver on time. An optimized production schedule, i.e. a production schedule defining what articles that should be produced on what production line at what time throughout the day, could possibly make Arla meet the due times for deliveries while reducing costs and maintaining acceptable levels of inventory in the finished goods warehouse.

In order to reduce costs, it is necessary to understand which costs are dependent on the production schedule. At Arla, these costs mainly are the labour costs needed for keeping the production lines running. The costs for running a production line comprise of the salary for the three employees needed as well as the cost of changeovers. The cost of a changeover is composed by the salary for the three employees that need to work during the time of the changeover. The loss of product contents is fractional and hence not considered. The changeover times differ a lot why Arla is putting effort into making them both shorter and more uniform in-between products. This work has shown great potential and Arla assume they will reach changeover times of 30 minutes when changing within a product category, for example between two milk products, and 60 minutes when changing between categories, for example when changing from milk to cream products. Therefore, these are the changeover times used in this thesis. The salaries are derived from data obtained from Arla, as is the add on for working inconvenient hours that take place from 8:00 p.m to 7:00 a.m. which increases the cost for both production and changeovers during these times.

Chapter 3

Mathematical Background

The following section gives a brief overview and description of the most important mathematical concepts needed for the analysis and discussion of this thesis.

3.1 Optimization

Optimization is the the concept of approaching a complex decision problem of selecting the values for a number of interrelated variables by focusing on a single objective designed to quantify the quality of the decision.[1] The objective, also called the objective function, can either be minimized or maximized.[2] The optimization is also defined on whether it is constrained or not. Constraints are boundaries defining the set of feasible solutions, values that the variables can take in order to remain feasible. A general constrained optimization problem is mathematically defined as:[3]

$$\begin{array}{ll} \text{min} & f(\mathbf{x}) \\ \text{subject to} & h_i(\mathbf{x}) = 0, i = 1, 2, ..., m \\ & g_j(\mathbf{x}) \leq 0, j = 1, 2, ..., r \\ & \mathbf{x} \in S \end{array}$$

where $\mathbf{x}$ is an n-dimensional vector of unknowns, f, h_i and g_j are real-valued functions of the variables in $\mathbf{x}$ and S is a subset on an n-dimensional space composing the domain of $\mathbf{x}$. With this notation, f is the objective function and h_i and g_j are the constraints.

[1] David G. Luenberger and Ye Yinyo. *Linear and Nonlinear Programming.* Ed. by Fredrik S. Hillier. 3rd ed. New York: Springer Science+Business Media, LLC, 2008.

[2] Lars-Åke Lindahl. *Konvexitet och optimering.* Matematiska institutionen, Uppsala universitet, 2014.

[3] Luenberger and Yinyo, *Linear and Nonlinear Programming*, op. cit.

3.2 Optimal Solutions

There are generally two different definitions of optimal solutions (i.e minimizing solutions to an optimization problem). The differences in definitions are important since they are vital while analyzing the result from the optimization. Firstly, we define a *local minimum* as:

A point $x_0 \in X$ is a local minimum to $f(x)$ if there exists a $\epsilon > 0$ such that $f(x) \geq f(x_0)$ for all $x \in X$ that satisfies $\| x - x_0 \| \leq \epsilon$.

Furthermore, a *global minimum* is defined as:[4]

A point $x_0 \in X$ is a global minimum to $f(x)$ if $f(x) \geq f(x_0)$ for all $x \in X$.

For a convex objective function defined on a convex region it can be shown that a local minimum is also a global minimum.[5] Furthermore, for all convex optimizations a global minimum by definition must be unique and more specifically an optimal minimizing solution is unique if the function is strictly convex.[6]

3.3 Convexity

A subset X of R^n is called convex if $\lambda x + (1-\lambda)y \subseteq X$ for all $x, y \in X, \lambda \in]0,1[$.

In other words, the set X is convex if and only if it contains the line between every pair of points in X.[7] For a function, convexity is defined as:

A function $f : X \longrightarrow \bar{R}$ with a convex domain X is convex if and only if $f(\lambda x + (1-\lambda)y) \leq \lambda f(x) + (1-\lambda) f(y)$ for all $x, y \in X$ and $\lambda \in]0,1[$.

In mathematical optimization, the optimization is called convex if the domain is convex, the objective function is convex and the restricting functions are convex.[8]

It is generally hard to determine a minimum value for an arbitrary function. However, there exists many numerical methods for finding local minima to optimization problems. It can be proved that a local minimum is a global minimum to a convex optimization problem, hence the convexity concept is of great importance for mathematical optimization. Many algorithms use this fact and are guaranteed to find the global optimum if the optimization problem is convex.[9]

[4]Leif Appelgren, Daniel Sundström, and Lars Zachrisson. *Optimeringsmetoder*. Stockholm: Matematiska Institutionen vid Kungliga Tekniska högskolan, 2014.

[5]Ibid.

[6]E.M.L Beale and L. Mackley. *Introduction to Optimization*. John Wiley & Sons, Inc, 1988.

[7]Lindahl, *Konvexitet och optimering*, op. cit.

[8]Appelgren, Sundström, and Zachrisson, *Optimeringsmetoder*, op. cit.

[9]Lindahl, *Konvexitet och optimering*, op. cit.

3.4 Mixed Integer Programming

Mixed integer programming refers to linear programming with the feature that some of the variables only take integer values. Generally, the integer variables are binary and only take the value 0 or 1 indicating if an event occurred or not. Hence, a mixed integer program consists of both continuous and integer variables that both can be present in the objective as well as the constraints.[10]

Mixed integer programming is a widely used tool in operations research as it enables the incorporation of factors such as setup costs, fixed costs and other economies of scales.[11] Compared to linear programming, large instances of mixed integer programming require a large amount of computational capacity, see Section 3.5.[12]

3.5 Complexity

Complexity is an important concept for analyzing the choice of problem formulation as well as solving algorithm when performing mathematical optimization. By understanding what factors drive complexity for the solving algorithm, an appropriate problem formulation can be chosen for minimizing the time consumed or vice versa. The very definition of complexity is not measured in time but rather the number of elementary operations needed to be performed.[13]

Within the field of mathematical optimization, complexity is often used as a measure of how running time is proportional to a factor in the problem. The running time is commonly either considered as *asymptotic worst case running time* or as a *distribution of running times*, the latter more often used by practitioners.[14]

For general linear programs solved by the Simplex algorithm, the worst case running time is $O(n^{\mathrm{d}})$ where d is number of variables and n number of constraints assuming $d < n$. For mixed integer programs no worst case running time can generally be guaranteed except exponential on the size, i.e. $O(2^{\mathrm{n}^{\mathrm{k}}})$ where k is some positive constant.[15] However, there are multiple different methods that practitioners apply to solvers for reducing running time of a particular problem.[16]

[10] Beale and Mackley, *Introduction to Optimization*, op. cit.

[11] Yves Pochet and Laurence A Wolsey. *Production planning by mixed integer programming.* Springer series in operations research and financial engineering. New York: Springer, 2006. ISBN: 0387299599 (hd.bd.) URL: `http://www.loc.gov/catdir/enhancements/fy0663/2005935294-d.html`.

[12] Ibid.

[13] Ibid.

[14] Nimrod Megiddo. *On the Complexity of Linear Programming.* Cambridge University Press, 1987.

[15] Pochet and Wolsey, *Production planning by mixed integer programming*, op. cit.

[16] Ibid.

Chapter 4

Introduction to Production Planning and Scheduling

The following section gives a comprehensive overview of the area of production planning and scheduling, a highly relevant topic in order to understand and develop production scheduling tools.

4.1 The Context and Purpose of Production Planning and Scheduling

The importance of production planning has been widely recognized in a large variety of manufacturing businesses since the 1960s.[1] At the time, Japanese and European firms often outperformed North American companies regarding inventory levels giving a competitive advantage concerning both flexibility and lower costs of inventory.[2] This put pressure on firms in the United States and Canada necessitating an expanded focus on production development combining the previous focus on optimizing the present production with a new focus on change of the present conditions.[3] This change in the structure of the management set new requirements on the production planning as well as on the research field of mathematical scheduling.

Production planning and scheduling are management tools in the context of strategic decisions in corporate strategy, more specifically as a management lever in operations strategy.[4] Hence production planning and scheduling contribute to the higher objectives defined by the corporate management.

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[1] Vangelis Th. Paschos. *Applications of Combinatorial Optimization*. Ed. by 2nd ed. New York: John Wiley & Sons, Inc, 2014.

[2] Edward A Silver, D.F. Pyke, and Rein Peterson. *Inventory management and production planning and scheduling*. 3rd ed. New York: Wiley, 1998. ISBN: 0471119474 (cloth : alk. paper). URL: `http://www.loc.gov/catdir/description/wiley031/97048609.html`.

[3] Ibid.

[4] Ibid.

Production planning and scheduling might be further divided into sub-components according to the *hierarchical planning approach*:[5,6]

1. **Strategic** production planning and design of the production system or process pattern is the long-term planning involving high level decisions based on the characteristics of the product, industry and market.[7]

2. **Tactical** production planning and inventory management is the medium-term planning concerning the product portfolio and is based on the decisions of the strategic planning. The uncertainty in the value chain during this phase is high making it beneficial to aggregate products into groups (hence the phase also is called aggregated planning[8]), allowing the management to make broad decisions concerning the production planning.

3. **Operational** production planning and scheduling optimizes the production order and allocation in order to meet the objectives of the operations strategy. The period taken into consideration (i.e. the planning horizon) is significantly shorter than in the tactical and strategic planning and the aggregated product groups are divided into individual products or batches. The following sections 4.2.1 - 4.2.3 of this thesis will discuss the mathematical models concerning operational planning and will be complemented with an applied case-study of Arla.

A common challenge for the mathematical models used in all three phases described above is the trade-off between accuracy and relevance.[9] A highly complex model with little aggregation of products might be well applied to the specific production, but imposes a hazard of presenting inaccurate estimates. In the converse situation, the obtained results might be consistent but useless due to lack of contextual relevance.

4.2 Mathematical Models within Production Planning and Scheduling

This section gives an overview of the existing mathematical models within production planning and scheduling. Due to the scope of this thesis, only short-term planning methods (i.e. operational planning methods, see Section 4.1) will be covered with an emphasis on batching problems.

[5] Paschos, *Applications of Combinatorial Optimization*, op. cit.

[6] R.N. Anthony. *Planning and Control Systems: A Framework for Analysis*. 1st ed. Boston: Division of Research, Harvard Business School, 1965.

[7] Edward A. Silver. *Decision Systems for Inventory management and Production Planning*. 2th ed. New York: John Wiley & Sons, Inc, 1979.

[8] Maxim Bushuev. "Convex optimisation for aggregate production planning". In: *International Journal of Production Research,* (2014).

[9] Carlos A. Méndez et al. "State-of-the-art review of optimization methods for short-term scheduling of batch processes". In: *Computers & Chemical Engineering* 30.6-7 (2006), pp. 913–946. DOI: `10.1016/j.compchemeng.2006.02.008`. URL: `http://dx.doi.org/10.1016/j.compchemeng.2006.02.008`.

4.2.1 Approaches in Short Term Production Scheduling

After an analysis of the industrial context to be optimized, which is preferably done through the framework by Méndez et al.,[10] see Appendix A.1, the fundamental components of the scheduling model can be conveniently determined using the framework in Figure 4.1 based on Méndez et al.:[11]

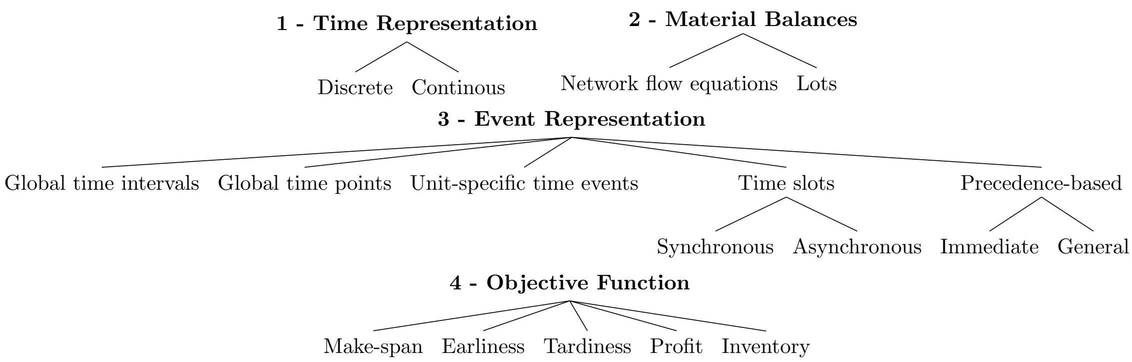

Figure 4.1: Model characteristics framework for scheduling algorithms

The choice of the framework's parameters largely impacts the performance of the scheduling algorithm and should be chosen based on the production characteristics and the goal of the scheduling.[12]

Firstly, a discrete *time representation* for the model requires setting time slots a priori when production and changeovers may occur. This approach is suitable when the precise time notation provided by continuous time representation is obsolete or if the demand pattern is complex. On the other hand, a large number of time slots increases the size of the optimization since the number of variables and constraints increase. Hence, if high time granularity is required or the planning horizon is extensive, continuous models might be preferable from a computational point of view.

The *material balance* parameter depends on if the number of batches of each size is known a priori executing the scheduling (i.e. lots). If this information is available, the scheduling reduces to allocation of the batches, reducing model complexity. Otherwise, both batch-sizing and allocation must be performed (i.e. network flow equations) which usually make the optimization computationally feasible only in a single stage production.

While a discrete time representation requires global time intervals as *event representation*, the variety of event representation concerned with the continuous models is large. When using global time points, those are determined in the optimization to be optimal events for every production unit of the schedule.

[10]Ibid.
[11]Ibid.
[12]Ibid.

Hence the time intervals do not need to be of equal size. The same determination procedure of optimal time points is executed while using unit-specific time events, although they are not consistent over the production units. The time slot approach allocates time slots (whose lengths are not defined a priori) to the production activities, synchronically (i.e. same time slots simultaneously on all units) or asynchronically over all production units. Precedence based event representation only considers the order of the production and if the precedence is immediate, allowing no pauses between production slots, or general where pauses are allowed.

Lastly, the chosen *objective function* is selected based on the goals of the scheduling. In some cases additional objectives or variables might be added to enable the desired optimization.

4.2.2 Lot-Sizing Models

From the above classification framework in Figure 4.1 numerous scheduling models can be developed. For the purpose of this thesis only discrete time models, also called lot-sizing models, will be further explored. Lot-sizing models are defined as:

> *"...production planning problems in which the periods are fixed a priori, and production of an item in a given period implies some discrete event such as payment of a fixed cost or the loss of a fixed amount of production capacity, due to placement of an order, or the set-up, start-up, or changeover of a machine."*
> - Belvaux & Wolsey[13]

Hence with the above classification lot-sizing models are discrete time models with global time intervals. But even among lot-sizing models there are numerous different approaches. However, a commonly shared property is that they require mixed integer programming (MIP) (see Section 3.4) to be solved due to their discrete form. A common type of lot-sizing models are the *Capacitated Lot-Sizing Models (CLSM)*, which in literature often is used as an interchangeable notation for the general lot-sizing models.[14]

The basic assumptions for all lot-sizing models are:[15]

- Production resources are limited and they can only produce one product at the time.
- Demand is deterministic for all products.
- No backlogging (i.e. not completely meet customer demand) is allowed.
- The costs considered are changeover costs, inventory costs and production costs.[16]

[13] G. Belvaux and L.A. Wolsey. "Lot-Sizing Problems: Modelling Systems and a Speciaised Branch-and-Cut System". In: *Core Discussion Paper* (1998).

[14] Céline Gicquel, Michel Minoux, and Yves Dallery. *Capacitated Lot Sizing models: a literature review.* HAL Id: hal-00255830, 2008.

[15] Ibid.

[16] Laurence A. Wolsey. "MIP modelling of changeovers in production planning and scheduling problems". In: *European Journal of Operations Research* 99 (1997), pp. 154–165.

A common criticism towards lot-sizing models is focused on the assumption of deterministic demand.[17] Hence the models are often used based on forecasts of demand or when demand is relatively constant over time. Also the assumption concerning backlogging might be problematic in applications since it sometimes could be favorable to neglect some demand for economic reasons etc.

The primary breakdown of lot-sizing models is the separation of big respectively small bucket models. *Small Bucket models*, such as the Continuous Setup Lot-Sizing Problem (CSLP) which is the most fundamental of the small bucket models, include shorter time periods and only allow the setup of one (or possible two if model extensions are made) products during one time interval. If production of the same product is performed in two or more subsequent time intervals, no setup is needed. This feature allows the modeling of changeovers and start-up costs, but only at the edges of the time intervals. Amongst the small bucket models several simplifying assumptions might be drawn. As an example: if production is assumed to always produce at maximum capacity during the time slots (i.e. DLSP, Discrete Lot-Sizing Problem) a set of variables determining the amount of products produced is eliminated. Also, sequentially dependent or sequentially independent changeovers can be implemented. Small bucket models hence both perform lot-sizing as well as detailed scheduling on the resolution level set by the length of the discrete time intervals.

The **Large Bucket models** on the other hand allow several setups for production of different products during one time slot. Hence the intervals in general are longer. The most fundamental large bucket model is the Capacitated Lot-Sizing Problem model (CLSP), which determines the optimal amount of each product to be produced under each time period. However, it does not provide a detailed schedule within the time period. These properties also reduce the number of decision variables since not all production start-up times have to be determined explicitly. If the demand pattern to be implemented is volatile, the complexity of the model will increase rapidly, usually making a small bucket model more effective. Due to these characteristics the big bucket approach is used foremost when production resource allocation is in focus rather than changeover-costs or start-ups.

4.2.3 Selected Model from Literature

In order to perform an efficient and relevant modeling of Arla's production the chosen scheduling model must be well aligned with the production context. Classified by the framework in Appendix A.1, the Arla production is characterized by a single stage, multiple machine *process topology* with 14 production lines. The single stage property is due to that the scheduling optimization only considers the packaging process. The production of raw products (such as milk or cream) in the facility is a multiple stage process, although this is irrelevant for the scheduling. Twelve of the packaging machines are very similar, allowing a variable *equipment assignment* where products may be produced on variable machines, and the remaining two machines are used for specific big-pack packaging. While changing production from one product to another, the *changeover*

[17] Silver, *Decision Systems for Inventory management and Production Planning*, op. cit.

times are sequence dependent (i.e. changeover times depend on which products are involved in the change). The *demand pattern* consists of due dates formed by the truck deliveries to stores and industrial customers. The full classification of the Arla production by the framework by Méndez et al. is presented in Appendix A.2.

Based on the above defined production context and the scheduling model classification presented in Figure 4.1, Section 4.2.1, the appropriate model characteristics are identified. The **time representation** implemented is discrete due to Arla's complex demand pattern composed by a large variety of products and due dates. Also, the discrete approach is more suitable since changeover costs are considered in the optimization. Hence the **event representation** is composed by global time intervals. Also the **material balances** consist of network flow equations since the batch sizes are not known a priori. The **objective function** focus on changeover costs and labour costs.

Taking all these parameters into account combined with the literature study in Section 4.2.2, the chosen model to be implemented on Arla's production planning is a *single stage, multi-item, small-bucket, lot-sizing model* based on Wolsey,[18] solved as an MIP-optimization problem. The model considers a set of I products, $\mathcal{I} = \{1, 2, ..., I\}$, produced during a scheduling horizon of T discrete time intervals, $\mathcal{T} = \{1, 2, ..., T\}$ and aims to reduce the total production related costs of meeting demand without backlogging through an optimized production scheduling. The model notation is presented in the below Table 4.1 where $i, j \in \mathcal{I}$ and $t \in \mathcal{T}$.

Notation	Type	Description
x_t^i	Continous Variable	The volume produced of product i in time t
y_t^i	Binary Variable	Equals 1 if the production is setup for product i in the beginning of time t
z_t^i	Binary Variable	Equals 1 if there is a startup for product i in the beginning of time t
s_t^i	Continous Variable	The amount of product i held in the finished goods warehouse in time t
$w_t^{i,j}$	Binary Variable	Equals 1 if a product changeover occurs from product i to product j in time t
p_t^i	Coefficient	The cost of producing one unit of product i in time t
f_t^i	Coefficient	The cost setting up production of product i in time t
g_t^i	Coefficient	The cost starting up production of product i in time t
$c_t^{i,j}$	Coefficient	The cost of a changeover from product i to product j in time t
h_t^i	Coefficient	The cost of holding one unit of product i in inventory in time t

[18]Wolsey, "MIP modelling of changeovers in production planning and scheduling problems", op. cit.

d_t^i	Coefficient	The amount of product i that has to be delivered in time t
β_t^i	Coefficient	The startup time of producing product i in time t in units of lost capacity
γ_t^i	Coefficient	The changeover time from product i to product j in time t in units of lost capacity
C_t^i	Coefficient	The maximum production capacity of product i in time t

Table 4.1: Definitions of notation in model from literature

Objective function:

$$\min \sum_{t=1}^{T} \sum_{i=1}^{I} \left(p_t^i x_t^i + f_t^i y_t^i + g_t^i z_t^i + \sum_{j \in \mathcal{I} \setminus \{i\}} c_t^{ij} w_t^{ij} + h_t^i s_t^i \right) \tag{4.1}$$

Constraints:

$$s_{t-1}^i + x_t^i = d_t^i + s_t^i, \quad \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \tag{4.2}$$

$$x_t^i + \beta_t^i z_t^i, + \sum_{j \in \mathcal{I} \setminus \{i\}} \gamma_t^{ij} w_t^{ij} \leq C_t^i y_t^i, \quad \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \tag{4.3}$$

$$z_t^i \geq y_t^i - y_{t-1}^i, \quad \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \tag{4.4}$$

$$w_t^{ij} \geq y_{t-1}^i + y_t^j - 1, \quad \forall t \in \mathcal{T}, \forall i, j \in \mathcal{I} \text{ with } i \neq j \tag{4.5}$$

$$\sum_{i=1}^{I} y_t^i = 1, \quad \forall t \in \mathcal{T} \tag{4.6}$$

$$\begin{gathered} x_t^i, s_t^i \geq 0 \\ y_t^i, z_t^i, w_t^{ij} \in \{0,1\} \\ \forall t \in \mathcal{T}, \forall i, j \in \mathcal{I}. \end{gathered} \tag{4.7}$$

The objective function (4.1) aims to minimize the total cost of the production as defined by the cost structure of the scheduling model. In other words the *production costs* $p_t^i x_t^i$, the *setup costs* $f_t^i y_t^i$, the *startup costs* $g_t^i z_t^i$, the *changeover costs* $c_t^{ij} w_t^{ij}$ and the *holding costs* $h_t^i s_t^i$ summed over all products $i \in \mathcal{I}$ and time intervals $t \in \mathcal{T}$.

Constraint (4.2) ensures that all demand is met on time. Since demand can be met either by production or warehouse, the current warehouse level s_{t-1} plus the production during the time interval t, x_t^i, should equal the demand d_t^i plus the new warehouse level s_t. This should hold for all products $i \in \mathcal{I}$ and all times $t \in \mathcal{T}$.

Constraint (4.3) ensures that the produced volume, x_t^i, plus the capacity lost to start up, $\beta_t^i z_t^i$ and changeover, $\sum_{j \in \mathcal{I} \setminus \{i\}} \gamma_t^{ij} w_t^{ij}$, does not exceed the maximum production capacity C_t^i of product i at time t. This should hold for all products $i \in \mathcal{I}$ and all times $t \in \mathcal{T}$.

Constraint (4.4) updates the binary variable z_t^i that keeps track of if a production startup of product i occurred in time t. This variable is used in the objective function (4.1) in order to incorporate startup costs. The inequality should hold for all products $i \in \mathcal{I}$ at all times $t \in \mathcal{T}$.

Constraint (4.5) updates the binary variable w_t^{ij} that keeps track of if a production changeover occurred from product i to j in time t. This variable is used in the objective function (4.1) in order to incorporate changeover costs. The inequality should hold for all products $i, j \in \mathcal{I}$ where $i \neq j$ at all times $t \in \mathcal{T}$.

Constraint (4.6) ensures that the production is only setup to produce one product i at the time. This should hold for all products $i \in \mathcal{I}$ at all times $t \in \mathcal{T}$.

Constraint (4.7) ensures non-negativity of the continuous variables for production x_t^i and storage s_t^i. It also restricts the indicator variables y_t^i, z_t^i, w_t^{ij} to only take binary values. This should hold for all products $i, j \in \mathcal{I}$ at all times $t \in \mathcal{T}$.

Chapter 5

Methodology

The imposed research question in Section 1.3 is focused on the potential of mathematical optimization of production scheduling. Hence, multiple articles and models have been studied (see Section 4) with potential to describe and be further developed to model the specific production in the Arla facility. A model from literature has been selected (see Section 4.2.3), developed and refined in order to meet the requirements for modeling the Arla production processes.

Based on this model, data provided by Arla have been obtained and processed to fit the interface of the implemented model. For different reasons, some input data are based on assumptions or simplifications. The assumptions are based on discussions with Arla as well as observations from visits at the production site. Moreover, all assumptions are validated and commented in Section 5.1.2.2.

During the development of the methodology an iterative approach has been used aiming to secure the appropriability, validity and feasibility of the results. This includes communication with Arla as well as an iterative approach in the development of the optimization model, evaluating pros and cons with every extension and prototype.

5.1 Model Development

5.1.1 Model Extensions

Based on the model from literature presented in Section 4.2.3, a model more specifically suited for Arla's production was developed. The logics behind the extensions and changes made are presented below and the final model is presented in Section 5.1.2.

- **Multiple production lines:** While the original model only models one production line, a feature for multiple production lines is incorporated in the final model.

- **No variables for startup:** As Arla has no costs associated with the startup of production, the z_t^i variables and the associated constraint (4.4) can be removed for reduced complexity.
- **No product specific changeover costs:** Arla's production has the characteristic that all products can be categorized into four product categories; milk, sour milk, sour cream and cream. In terms of changeover costs, Arla has one cost for changes within such a category and another for changeovers between categories. Therefore, the changeover costs are not product specific why the w_t^{ij} variables are unnecessarily detailed increasing complexity. Due to this, these have been replaced with indicator variables, $w_t^{i,m}$, indicating if there is a change of product produced and other indicator variables, $u_t^{k,m}$, indicating if there is a change to product category k. This reduces the complexity considerably and speeds up the solving process. Following this, some new constraints regulating these variables have to be implemented, see constraint (5.5) and (5.6) in Section 5.1.2.
- **Constraint for finished goods warehouse:** A part of the problem picture at Arla is an overcrowded finished goods warehouse. A constraint ensuring that the maximum warehouse levels are not exceeded is built into the model.
- **Products in warehouse by the start of production day:** In a production where the planning horizon (i.e. the production day in the Arla case study) is rather short and in particular; when the time until the first delivery is short it is often required to have certain products in stock by the beginning of the production day (s_{-1}^i). If demand is reasonably homogenous over production days a suitable way to model this is to require certain stock levels by the end of the production day that will equal the levels in stock at the start of the day (a cyclical production day). The added constraint (5.8) in Section 5.1.2 enables this feature.

5.1.2 Final Model

The final model is derived by converting the extensions mentioned in Section 5.1.1 into math and incorporating them into the model from literature. The final model considers the single stage production of I products, $\mathcal{I} = \{1, 2, ..., I\}$, produced on M independent machines, $\mathcal{M} = \{1, 2, ..., M\}$ during a scheduling horizon of T discrete time intervals, $\mathcal{T} = \{1, 2, ..., T\}$. Further the I products are sorted into a set of K mutually exclusive categories, $\mathcal{K} = \{1, 2, ..., K\}$. The set of products $\mathcal{I}_k$ within the same category is characterized by common production requirements, providing one common changeover time when changeovers occur within the category. The function $\zeta(i) : \mathcal{I} \rightarrow \mathcal{K}$ provides the category k of the considered product i. The model aims to minimize the production costs incurred by production and changeovers, within and between product categories. In the model below, $i \in \mathcal{I}, m \in \mathcal{M}, t \in \mathcal{T}$, and $\cup_{k=1}^{K} \mathcal{I}_k = \mathcal{I}$.

Objective function:

$$\min \sum_{m=1}^{M} \sum_{t=1}^{T} \sum_{i=1}^{I} \left(p_t^{\zeta(i),m} x_t^{i,m} + p_t^{\zeta(i),m} \alpha_t^{i,m} w_t^{i,m} \right) + \sum_{m=1}^{M} \sum_{t=1}^{T} \sum_{k=1}^{K} \left(p_t^{k,m} \gamma_t^{k,m} u_t^{k,m} \right) \tag{5.1}$$

Constraints:

$$s_{t-1}^{i} + \sum_{m=1}^{M} x_t^{i,m} = d_t^i + s_t^i, \quad \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \tag{5.2}$$

$$x_t^{i,m} + \alpha_t^{i,m} w_t^{i,m} + \gamma_t^{\zeta(i),m} u_t^{\zeta(i),m} \leq C_t^{i,m} y_t^{i,m}, \quad \forall i \in \mathcal{I}, \forall m \in \mathcal{M}, \forall t \in \mathcal{T} \tag{5.3}$$

$$w_t^{i,m} \geq y_t^{i,m} - y_{t-1}^{i,m}, \quad \forall i \in \mathcal{I}, \forall m \in \mathcal{M}, \forall t \in \mathcal{T} \tag{5.4}$$

$$u_t^{k,m} \geq \sum_{i \in I_k} y_t^{i,m} - \sum_{i \in I_k} y_{t-1}^{i,m}, \quad \forall m \in \mathcal{M}, \forall t \in \mathcal{T}, \forall k \in \mathcal{K} \tag{5.5}$$

$$\sum_{i=1}^{I} y_t^{i,m} = 1, \quad \forall m \in \mathcal{M}, \forall t \in \mathcal{T} \tag{5.6}$$

$$\sum_{i=1}^{I} s_t^i \beta^i \leq \theta, \quad \forall t \in \mathcal{T} \tag{5.7}$$

$$s_{-1}^i = s_T^i = D^i, \quad \forall i \in \mathcal{I} \tag{5.8}$$

$$\begin{aligned} x_t^{i,m}, s_t^{i,m} \geq 0 \quad & \forall i \in \mathcal{I}, \forall m \in \mathcal{M}, \forall t \in \mathcal{T} \\ y_t^{i,m}, w_t^{i,m}, u_t^{k,m} \in \{0,1\} \quad & \forall i \in \mathcal{I}, \forall m \in \mathcal{M}, \forall t \in \mathcal{T}, \forall k \in \mathcal{K} \end{aligned} \tag{5.9}$$

In Section 5.2 this model, its components and variables are presented and interpreted separately in the Arla case study context.

5.1.2.1 Definition of Decision Variables and Coefficients

The decision variables and coefficients used in the model are presented and described in Table 5.1 below:

Notation	**Type**	**Description**
$x_t^{i,m}$	Continous Variable	The volume produced of product i on production line m in time t
s_t^i	Continous Variable	The amount of product i held in the finished goods warehouse in time t
$y_t^{i,m}$	Binary Variable	Equals 1 if production line m is setup for product i in the beginning of time t
$w_t^{i,m}$	Binary Variable	Equals 1 if a product change to product i on production line m has occurred in time t
$u_t^{k,m}$	Binary Variable	Equals 1 if a change to product category k has occurred on production line m in time t
$p_t^{k,m}$	Coefficient	The cost of producing one unit of a product in category k on production line m in time t
$\alpha_t^{i,m}$	Coefficient	The number of units lost to startup producing product i on production line m in time t, not taking a change of product group into account
$\gamma_t^{k,m}$	Coefficient	The number of units lost when a changeover to producing product category k on production line m in time t
d_t^i	Coefficient	The amount of product i that has to be delivered in time t
$C_t^{i,m}$	Coefficient	The maximum production capacity of product i on production line m in time t
β^i	Coefficient	The area that one unit of product i occupies in the finished goods warehouse
θ	Constant	The maximal area of the finished goods warehouse
D^i	Constant	The amount of product i to be stored in warehouse by the end of production day

Table 5.1: Definitions of notation in the final model

5.1.2.2 Model Assumptions

Following are the most important assumptions incorporated in the model:

- **Changeover times:** The model assumes that products can be aggregated into several product categories. The total changeover time is in the model computed as the the time taken for changing to a new product plus the extra time taken for changing to a new product category if such a change occurred.

- **Only one changeover every time period:** The model can only handle one changeover in every time period. If more frequent changeovers are needed the time granularity can be decreased. This is however associated with increased complexity.
- **The day starts and ends with the same volume in warehouse:** In order to supply demand in the beginning of the day a certain level in the warehouse is necessary. The model hence assumes that this level has to be retained at the end of the day so that the entire demand of the day actually is produced. This assumption is not very drastic especially if the demand pattern is homogenous and cyclical over production days.
- **No backlogging:** All demand must be met on time. If there is no way to achieve this, no solution to the optimization will exist.
- **Cost structure only dependent on variable production costs**. All costs modeled are driven by production volumes and changeover times.

5.2 Model Implementation

This section covers an overhaul on how the final model presented in Section 5.1.2 was applied on Arla's production and implemented in an optimization solver.

5.2.1 Objective Function

$$\min \sum_{m=1}^{M}\sum_{t=1}^{T}\sum_{i=1}^{I}\left(p_t^{\zeta(i),m}x_t^{i,m} + p_t^{\zeta(i),m}\alpha_t^{i,m}w_t^{i,m}\right) + \sum_{m=1}^{M}\sum_{t=1}^{T}\sum_{k=1}^{K}\left(p_t^{k,m}\gamma_t^{k,m}u_t^{k,m}\right)$$

The objective function (5.1) comprises of three different kind of terms. The first kind is $p_t^{\zeta(i),m}x_t^{i,m}$, representing *the cost of producing x liters of a product in category k on line m in time t.* For the applied example the cost coefficient $p_t^{k,m}$ is the labour cost for producing one liter of product i at production line m. This is derived from hourly salaries and production capacities.

The second terms, $p_t^{\zeta(i),m}\alpha_t^{i,m}w_t^{i,m}$, represent *the cost of changing to product i on machine m in time t regardless of i's product category.* In the Arla case study the coefficient, $\alpha_t^{i,m}$, is the changeover time multiplied by production capacity of machine m.

The third terms, $p_t^{k,m}\gamma_t^{k,m}u_t^{k,m}$, represent *the extra cost of a changeover if the change is to a new product category k.* In the Arla case study $\gamma_t^{k,m}$ is the changeover time for changing to category k multiplied by the maximum production capacity. Arla has four product categories: milk, sour milk, sour cream, and cream.

5.2.2 Constraints

Constraint (5.2)**:** The first constraint ensures that the production and inventory held are at least as large as the volume to be delivered in each time period. It can be interpreted as *the inventory from previous time period plus the volume produced on each machine equals what is delivered in time t plus what is held in inventory at the end of the period*

$$s_{t-1}^i + \sum_{m=1}^{M} x_t^{i,m} = d_t^i + s_t^i, \quad \forall i \in \mathcal{I}, \forall t \in \mathcal{T}.$$

Constraint (5.3)**:** The second constraint ensures that no machine is producing more than its maximum capacity during each time period. The interpretation of the constraint is *the volume $x_t^{i,m}$ produced plus the capacity lost for changing product, $\gamma_t^{k,m} u_t^{k,m}$, plus the capacity lost due to change of product group, $\gamma_t^{k,m} u_t^{k,m}$, must be less than or equal to the maximum capacity, $C_t^{i,m} y_t^{i,m}$*

$$x_t^{i,m} + \alpha_t^{i,m} w_t^{i,m} + \gamma_t^{\zeta(i),m} u_t^{\zeta(i),m} \leq C_t^{i,m} y_t^{i,m}, \quad \forall i \in \mathcal{I}, \forall m \in \mathcal{M}, \forall t \in \mathcal{T}.$$

Constraint (5.4)**:** The third constraint requires the $w_t^{i,m}$ variables to be 1 when there has been a changeover to product i on production line m in time t

$$w_t^{i,m} \geq y_t^{i,m} - y_{t-1}^{i,m}, \quad \forall i \in \mathcal{I}, \forall m \in \mathcal{M}, \forall t \in \mathcal{T}.$$

Constraint (5.5)**:** The fourth constraint requires the $u_t^{k,m}$ variables to be 1 if there has been a changeover to a new product category k on production line m in time t

$$u_t^{k,m} \geq \sum_{i \in I_k} y_t^{i,m} - \sum_{i \in I_k} y_{t-1}^{i,m}, \quad \forall m \in \mathcal{M}, \forall t \in \mathcal{T}, \forall k \in \mathcal{K}.$$

Constraint (5.6)**:** The fifth constraint ensures that every production line is only setup for the production of one product i in time t

$$\sum_{i=1}^{I} y_t^{i,m} = 1, \quad \forall m \in \mathcal{M}, \forall t \in \mathcal{T}.$$

Constraint (5.7)**:** The sixth constraint concerns the finished goods warehouse's limitations. The interpretation of the constraint is *the sum of the volume of all products, i, multiplied by the how much floorspace one unit of each product needs, β^i, has to be less than or equal to the total area of the warehouse, θ*

$$\sum_{i=1}^{I} s_t^i \beta^i \leq \theta, \quad \forall t \in \mathcal{T}.$$

Constraint (5.8)**:** The seventh constraint defines the requirement of product i in warehouse by the end and beginning of the production day. Under the assumption that the production day is seen as cyclical, the warehouse levels at T should equal those at $t = -1$ (i.e. warehouse level at the start of production day)

$$s^i_{-1} = s^i_T = D^i, \quad \forall i \in \mathcal{I}.$$

Constraint (5.9)**:** The eighth group of constraints ensures non-negativity of the continuous variables, neither the produced volume, $x_t^{i,m}$, or the volume held in finished goods warehouse, $s_t^{i,m}$, can be negative

$$x_t^{i,m}, s_t^{i,m} \geq 0 \quad \forall i \in \mathcal{I}, \forall m \in \mathcal{M}, \forall t \in \mathcal{T},$$
$$y_t^{i,m}, w_t^{i,m}, u_t^{k,m} \in \{0,1\} \quad \forall i \in \mathcal{I}, \forall m \in \mathcal{M}, \forall t \in \mathcal{T}, \forall k \in \mathcal{K}.$$

5.2.3 Properties of the Implemented Optimization Problem

When implementing the Arla production context into the final model presented in Section 5.1.2 the variables and constraints are built from the following properties:

- The number of products, $|\mathcal{I}| = I = 43$, reduced from 59 products due to simplifications, see Section 5.2.5.1.
- The number of machines, $|\mathcal{M}| = M = 12$, after removing production line 13 and 14, see Section 5.2.5.1.
- The number of categories, $|\mathcal{K}| = K = 4$, namely milk, sour milk, cream, and sour cream.
- The discrete time representation, $|\mathcal{T}| = T = 24$, i.e. one interval equals one hour.

The number of constraints considered in the final model in Section 5.1.2 hence is $IT + IMT + IMT + MTK + MT + T + I = 27307$, where each term is the contribution from the constraints (5.2) to (5.8). The number of binary variables incurred, defined in Constraint (5.2.2) is $IMT + IMT + MKT = 25920$, where each term is the contribution from the variables $y_t^{i,m}, w_t^{i,m}, u_t^{k,m}$. Similarly, the number of the continuous variables $x_t^{i,m}, s_t^{i,m}$ is $IMT + IMT = 24768$. The computational running time for this implementation is approximately 4 hours.

5.2.4 Implemented Assumptions

Following are the most important assumptions implemented;

- **Similar production lines:** In the implementation similar production lines are assumed. This is not entirely true since Arla's production lines have slightly different capacities and cannot produce all products. However, this only implies minor differences as they are rather similar and the optimization will only assign to generic production lines.

- **Changeover times:** Changeover times are considered equal when changing within product categories and equal when changing between product categories. In reality, these times vary a lot but Arla are working on making them more uniform why this assumption is legitimate. However, the model presented in Section 5.1.2 has the ability to model different changeover times for different products and product categories.
- **Only one changeover every hour:** The model can only handle one changeover every hour. This is of course theoretically unrealistic but does not imply much in practical terms as changeover times vary between 30 and 60 minutes at Arla.
- **The day starts and ends with products in warehouse:** In order to be able to supply demand in the beginning of the day some levels in the warehouse in the beginning of the day is necessary. The model was implemented with 8 hours of demand in warehouse in the beginning and end of the day. This assumption is not very drastic especially as the demand pattern of Arla is homogenous and relatively cyclical over production days. Today Arla has about 10 hours of demand in warehouse on average.
- **Skewed production day:** Since this thesis evaluates the potential of introducing a second night shift starting at 6:00 p.m. this hour is set as the beginning of the production day in the optimization and the output.
- **System washing:** As of today, the production system has to be cleaned during 6 hours each day. Although, in other Arla facilities this feature is built away and this is an initiative that also the Kallhäll facility considers. Hence the optimization assumes that production might be performed during all 24 hours of the day.

5.2.5 Data

The data supplied for this thesis is provided by Arla and is not manipulated in any sense. This fact increases the validity and enhances the real world alignment of the thesis. In this section all obtained data is presented and commented as well as discussed on how it has been processed to fit the optimization algorithm. Following are the different data types:

- **Three months of historical deliveries:** An excel sheet containing all unique deliveries of all products during the last three months. Every row corresponds to the delivery of one product at a specific time a specific day. The information supplied with every such delivery is among others; product, date, delivery time, article number and volume.
- **Production capacities:** Data of the capacities and capabilities of the production lines, including information of how many employees that are needed to run one production line.
- **Area multiples and warehouse limits:** The area that one unit of every product occupies in the warehouse for finished goods as well as the total area for the latter.

- **Changeover times:** The changeover times from each product to every other. In Arla's case, these are uniform for a change to any other product and doubled if the change also implies production of a new product category.
- **Salaries:** Excel sheet of the salaries for the people working in the production. This was used to compute an average hourly salary.

5.2.5.1 Data Pre-Processing

Data preprocessing was performed on the following data:

- **Production capacities:** Arla's production consists of 14 production lines out of which two are for packages larger than 1 liter and the rest are for 1 liters. Following the model restrictions these cannot be optimized together. Therefore, the optimization was performed on only the twelve one liter lines and some pre-processing was performed in order to remove the larger package products from the delivery file.
- **Three months of historical deliveries:** The optimization performed in the thesis is on a daily basis and a typical day had to be derived from the historical deliveries data. An average of all days would imply that most products have to be delivered in every hour of the day why this would not illustrate a typical day. Therefore the 5 of February 2015 was picked as a representative busy Thursday which is the day with highest demand. The deliveries this day were collapsed into a histogram with the same resolution as the time intervals of the optimization in order to correspond to the d_t^i term in Constraint (5.2.2).
- **Salaries:** From the data of the salaries of the production employees an average hourly salary was computed as well as an average salary increase for those working inconvenient hours.

5.2.6 Software

The software used for the optimization was IBM's module CPLEX. The optimization model was implemented into CPLEX using its Python interface. One logic behind the choice of CPLEX is its flexibility when it comes to different optimization problems, handling everything from regular linear programs to mixed integer programs. Also, the software has been continuously improved and is efficient when solving MIP problems which is important for this thesis.

For handling the data in Python several modules have been used. Most importantly, Scipy has been used to vectorize computations, Pandas has been used to read from the Excel files provided by Arla and Xlsxwriter has been used to post the result of the optimization directly in Excel.

5.2.7 Model Output

Due to the large amount of variables in the optimization problem it is hard to establish an overall interpretation based on the values of the variables themselves. Due to this, a visual interface is vital and developed such that the result is presented in an Excel sheet. The files consisted of three different charts:

- **Chart of levels in the finished goods warehouse:** During every hour, the chart presents the current area in the warehouse used by every product as well as the cumulative occupied area. This enables a visual aid to ensure that no excess levels occur at any time.
- **Production schedules:** One chart for every production line showing what product and volume that should be produced in every time interval.
- **Demand chart:** The optimization produces a histogram chart containing all deliveries during the production day.

Chapter 6

Results

6.1 Results from the Arla Case Study

The result of the scheduling optimization performed is presented in Figure 6.2 - 6.13 illustrating the schedules for each production line in Arla's facility. During non-production time, the production line is either unused or a changeover is performed. The interpretation of the schedules is that production in column 6:00 p.m. is performed during the period 6:00 p.m. - 7:00 p.m. and so on.

Generally, the result obtained from the production schedules suggests that it to a large extent is possible to avoid producing during the expensive night hours, 8:00 p.m. - 7:00 a.m., without overcrowding the finished goods warehouse. Hence, the optimization succeeds to remedy Arla's problematics while minimizing costs according to the used cost structure, this is further discussed in Section 7.2.

Figure 6.1: Legend corresponding to production schedule 1 - 12 in Figure 6.2 - 6.13

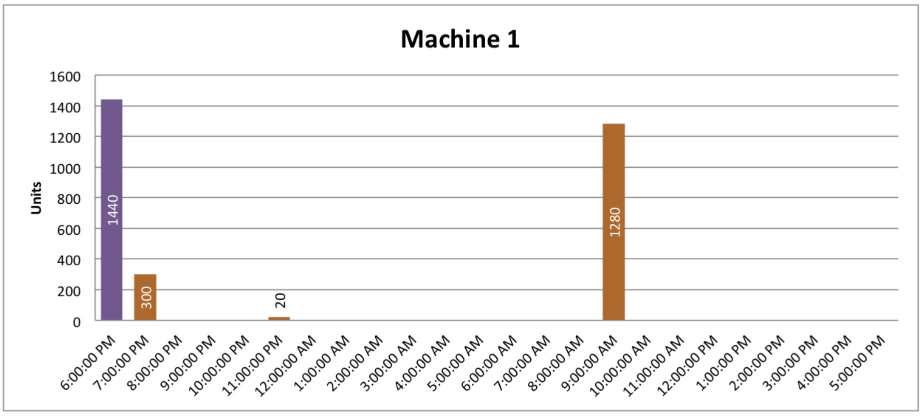

Figure 6.2: Production Schedule Machine 1

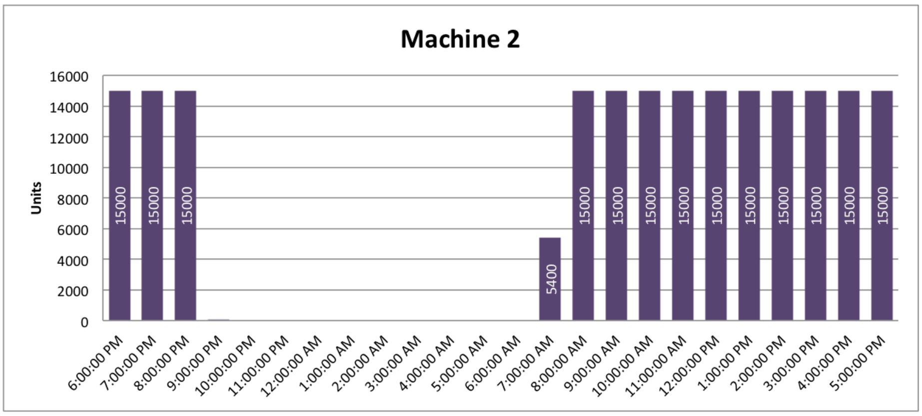

Figure 6.3: Production Schedule Machine 2

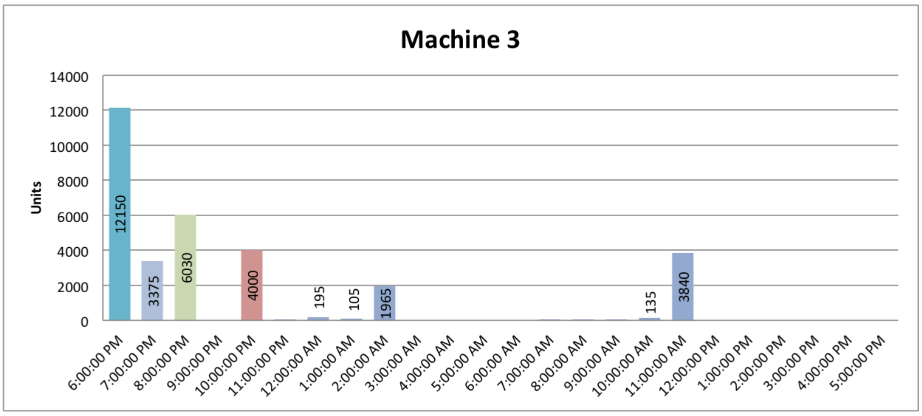

Figure 6.4: Production Schedule Machine 3

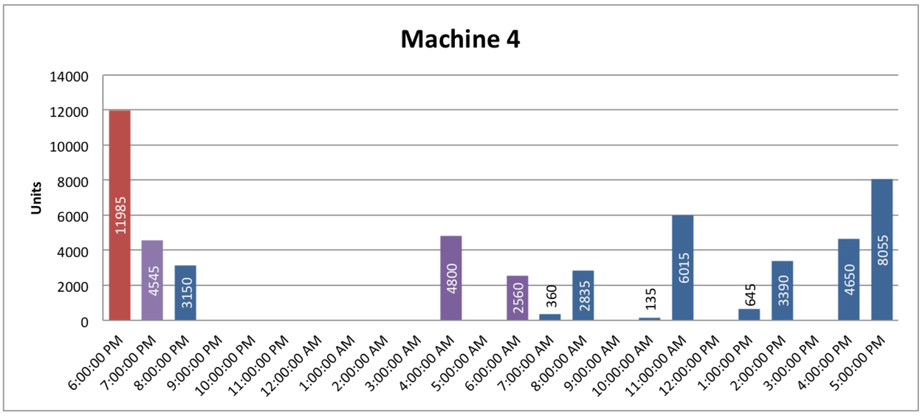

Figure 6.5: Production Schedule Machine 4

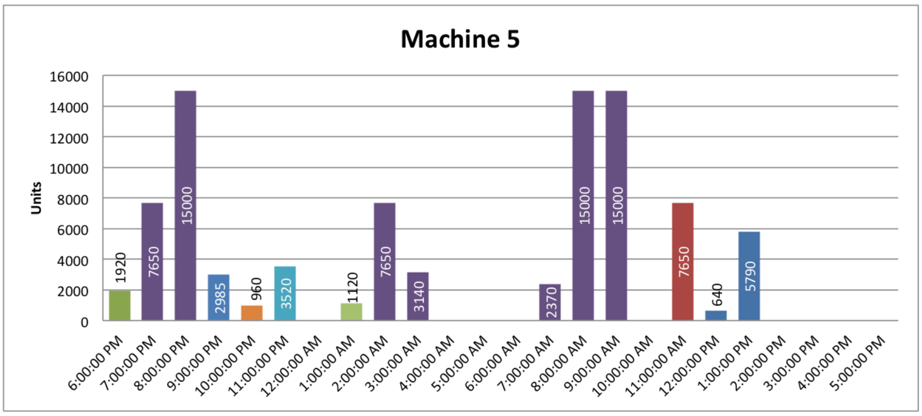

Figure 6.6: Production Schedule Machine 5

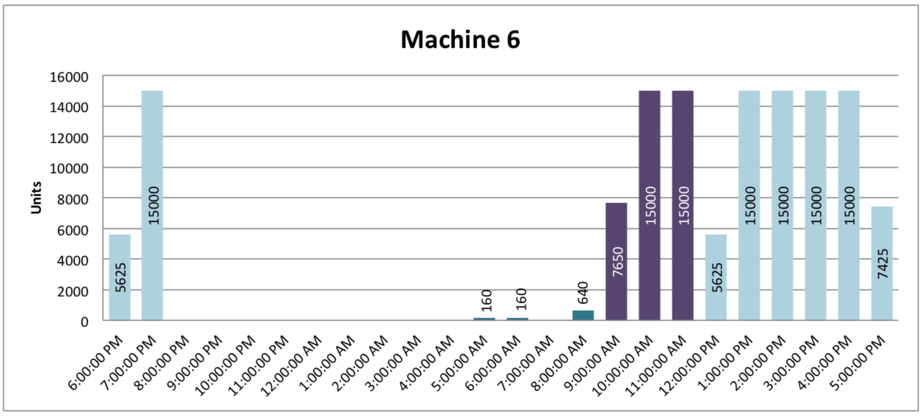

Figure 6.7: Production Schedule Machine 6

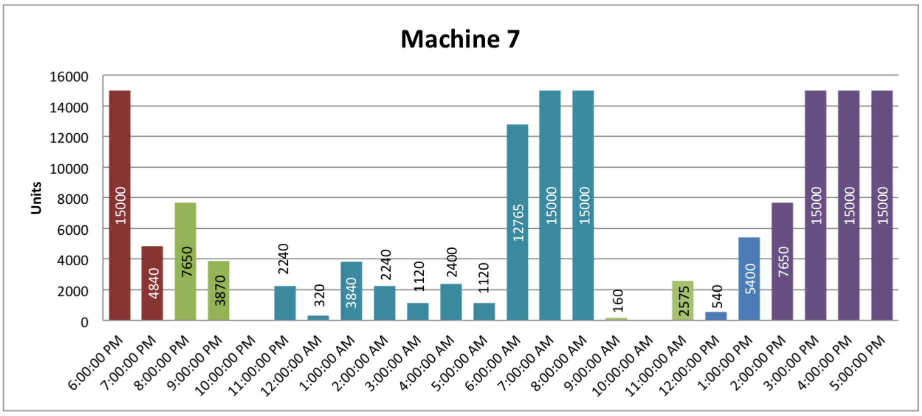

Figure 6.8: Production Schedule Machine 7

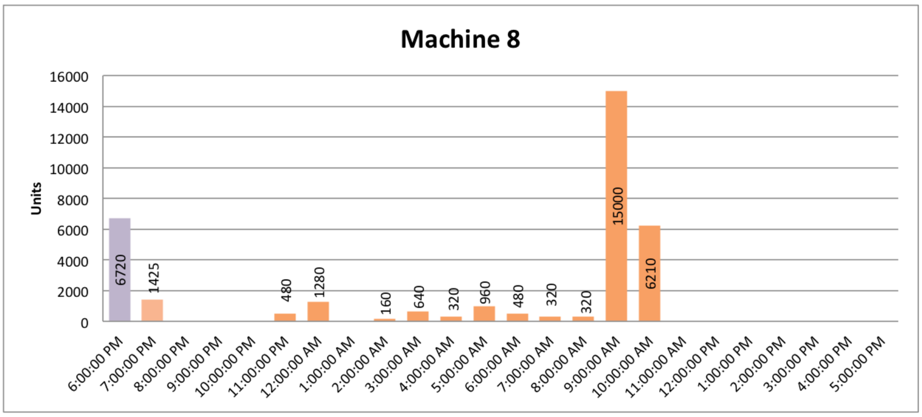

Figure 6.9: Production Schedule Machine 8

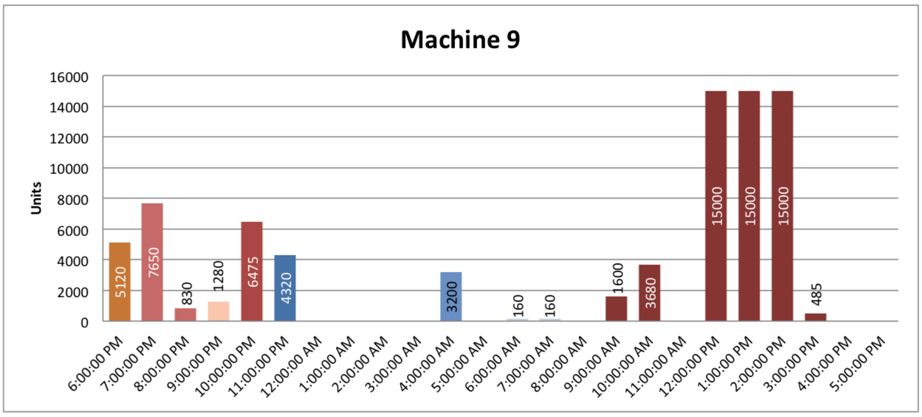

Figure 6.10: Production Schedule Machine 9

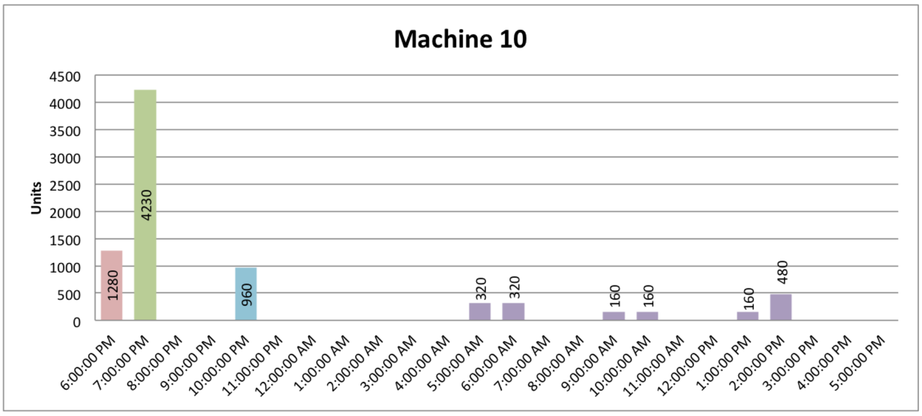

Figure 6.11: Production Schedule Machine 10

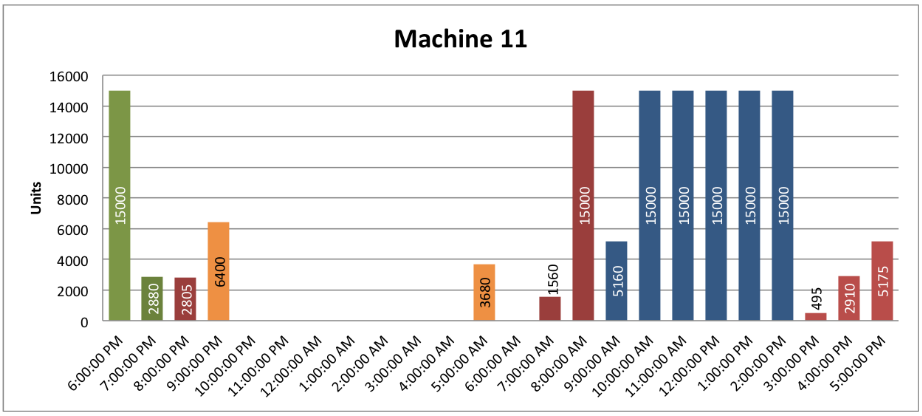

Figure 6.12: Production Schedule Machine 11

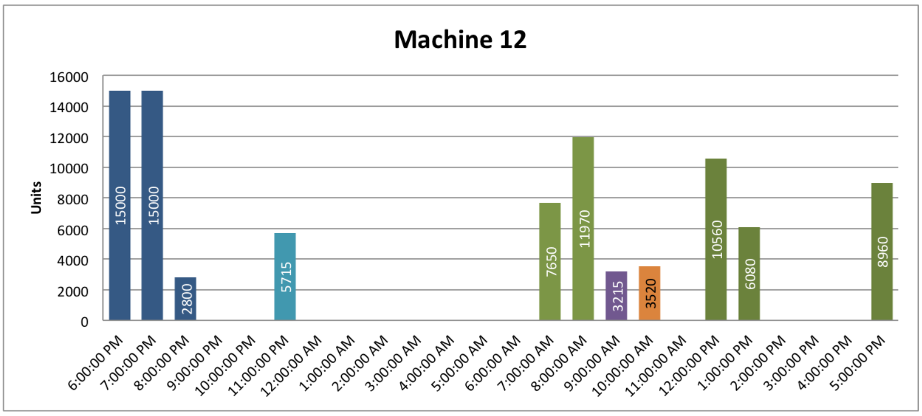

Figure 6.13: Production Schedule Machine 12

As one of Arla's main production challenges is limited warehouse capacity and one part of the research question of this thesis is to examine whether an optimized production schedule can remedy the associated problematics one of the constraints of the optimization is about maintaining acceptable levels in the warehouse for finished goods. The result of the optimization provides warehouse levels during the production day as displayed in Figure 6.14. The total storage capacity is approximately 1200 m^2 for the considered products. As seen in Figure 6.14, the optimization suggests maximum warehouse levels of about 750 m^2 over the day, eliminating the risk of overcrowding with great margin, even when considering a Thursday which is the day with the highest demand.

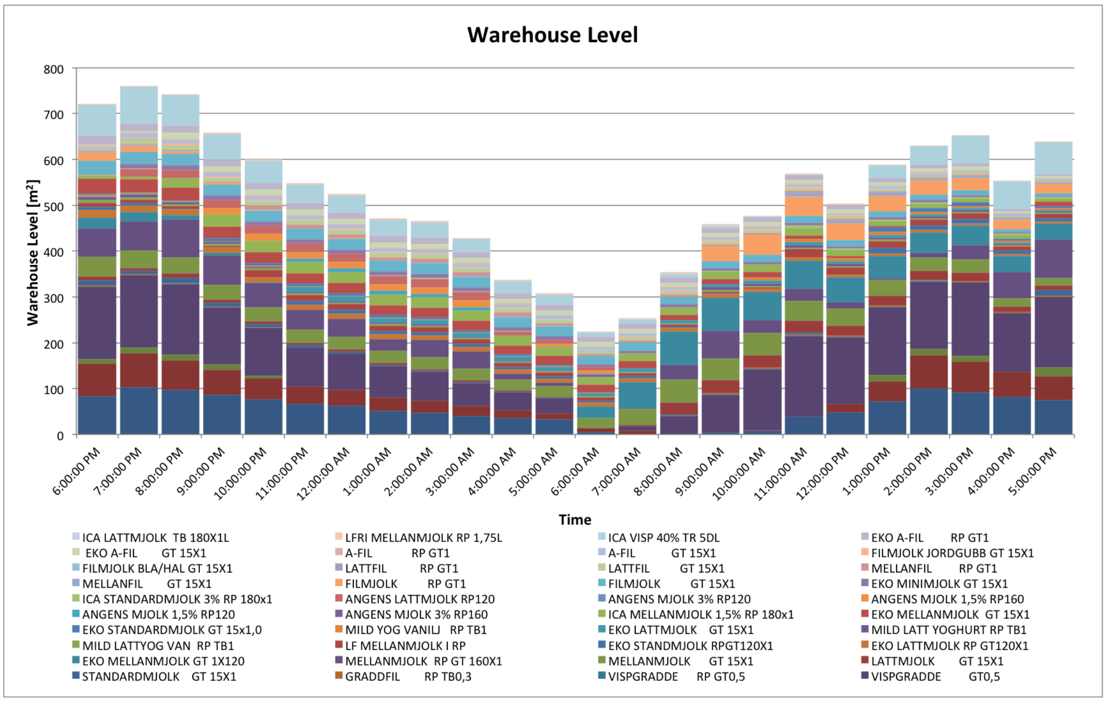

Figure 6.14: Inventory levels of the finished goods warehouse

As a complement to the above warehouse levels, the demand pattern for each product during the *production day* 5 of February is displayed in Figure 6.15. The day is skewed as by the assumption in Section 5.2.4. The demand pattern is the foundation of the scheduling algorithm since the model requires all demand to be met on time. Also, in order to secure deliveries met on time despite the discrete time representation, the demand is shifted one interval earlier. As an example; what has to be delivered in period 7:00 p.m. to 8:00 p.m. i considered to have a due date *for the production* at 7:00 p.m. and are included in the 6:00 p.m. demand column.

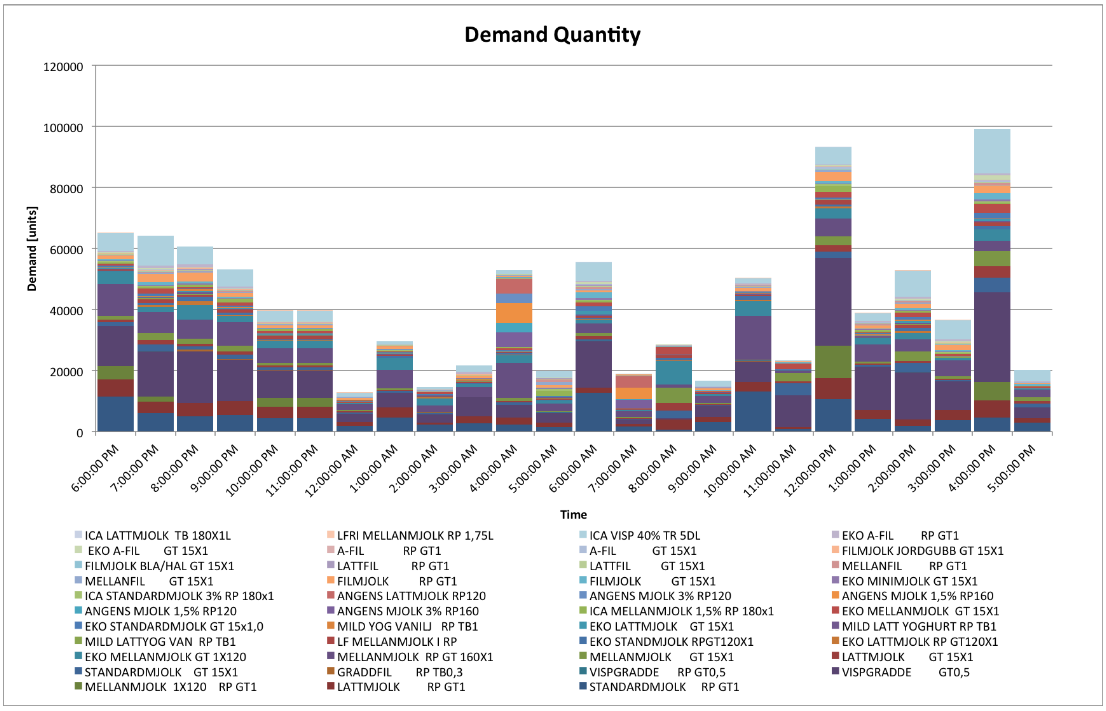

Figure 6.15: Demand quantities to be met by the production during the production day of the 5 of February 2015.

6.2 Mathematical Modeling Results

The major scientific contribution of this thesis is the development of the optimization model performing the scheduling in the Arla case study and which can be applied in similar production systems with only minor adjustments. The model is a powerful tool while optimizing production schedules in contexts where products can be grouped into a handful of categories with similar production characteristics. Also the complexity is considerably reduced allowing implementation of larger instances than general models. In order to determine if the model is suited for a production context, please consider the classification framework in Appendix A.1. The model is presented and described in detail in Section 5.1.2.

Chapter 7

Discussion

7.1 Development of the New Scheduling Model

The new model formulation developed in this thesis is based on a general MIP-optimization formulation for single stage-production with discrete time representation (see Section 4.2.3). Based on this, the model has been refined with the overall goal to establish a general model for production contexts similar to Arla's while keeping complexity low. From this foundation, five main extensions have been added to the original model obtained from literature (see Section 5.1.1). The following section will cover a discussion on these extensions' impact on complexity and overall applicability of the model.

7.1.1 Discussion of Model Extensions

While converting the literature single machine model into a model considering multiple production lines, the complexity of the model increases substantially. Although, this extension is necessary in order to obtain detailed production schedules and important in order to avoid suboptimal schedules in productions with parallel machines. The extended model allows differentiated capacities on the machines and products, increasing adaptability to industry context. This feature is not used in the implemented case study since the actual difference are small and lack significant relevance in the result interpretations.

In many manufacturing contexts the products end up in a warehouse with limited capacity. Hence the incorporation of a warehouse constraint is highly relevant. In the Arla case study, this constraint was one of the main components since the production today struggles with overcrowded warehouses and associated problematics. The extension adds some constraints but the impact on model complexity is very low.

The model extension concerning the requirement to keep certain product levels in warehouse by the end of the production horizon is important in production contexts where the production due dates occur during the entire planning horizon. In the Arla case study, the constraint is crucial in order to meet the first deliveries of the production day. For example, one hour after the start of the production day, certain amounts of approximately 40 products are to be delivered while only 12 can be produced due to the number of production lines and relatively long changeover times. Hence it is both more feasible and often more optimal to keep a certain level in stock between production days.

7.1.2 Reducing Complexity

The largest initiative in order to reduce model complexity is the introduction of *product categories*. This enables a drastic reduction of the number of variables and constraints, from $O(n^2)$ to approximately $O(n)$ relative to the number n of products considered in the optimization. This extension is hence very useful when products can be sorted into categories and when changeover times are mainly dependent on if a production change occurs between or within a product category. The larger and fewer the product categories are, the lower the complexity of the model. In the Arla case study, this remodeling did not result in any loss of detail.

7.1.3 Solving the Scheduling Problem

While solving the final scheduling model presented in Section 5.1.2 the software used was CPLEX. As a highly powerful, but also very flexible optimization tool, CPLEX can be tuned in order to obtain relevant results during feasible running times. The first measure taken was the change of the solvers emphasis (i.e. which solution characteristics the solver primary pursues) to focus on feasibility rather than optimality. This is motivated by that even if the obtained results are not the most optimal they are sufficient given the quite harsh precision in the production modeling. In an applied situation where this algorithm maybe is to be run on every production day, it is much more prioritized to obtain feasible solutions within reasonable time rather than one slightly more optimal solution much to late. Also, in the Arla case study, the main problematic was overcrowded warehouses rather than cost optimization.

It is sometimes more efficient to solve the dual of large MIP systems rather than the primal. As a rule of thumb, this is reasonable when the number of variables exceeds the number of constraints. Although, in the Arla case study the obtained solutions are derived by solving the primal since the dual did not solve in shorter time.

7.1.4 Impact of Limitations

The primary limitations of the derived scheduling model are due to the discrete time representation. The discrete time representation does not allow more detailed schedules than the resolution of the time intervals (one hour in the case study) and neither it is possible to model changeover times larger than one time interval. If either of these features is required a different approach, such as continuous time models, should be implemented. In the Arla case study, the discrete time representation were suitable considering the detail requirements concerning production schedule and changeover times. Hence the impact of these limitations are judged to be insignificant.

7.2 Arla Case Study Results

The result from the scheduling optimization of Arla's production primarily consists of production schedules for the different machines, Figure 6.2 - 6.13, as well as a warehouse level graph, Figure 6.14. Regarding the production schedules one notices three main themes: Firstly, the same products tend to be produced in sequence on the same machine (example Figure 6.3), rationally derived from the objective to minimize the cost of changeovers. Secondly, production tends to avoid production during the hours 8:00 p.m. to 7:00 a.m. when the salaries are higher due to inconvenient hours. Thirdly, products of the same category tend to be produced in sequence on the same machine since the changeovers within a category are shorter than between categories. An example of this is Figure 6.7 where only cream products are produced, Figure 6.4 where only sour-milk products are produced or Figure 6.8 where only different milk products are produced. All these three trends are in line with the expectations imposed by the objective function.

The reader might be struck by the fact that the production schedules look quite sparse although it probably should be cheaper to produce on fewer production lines. This observation is valid, although the issue is not incorporated in the model. There is no extra cost modeled for the startup of an extra production line, the only costs considered are labour costs proportional to the time spent on production and changeovers. Hence the solver does not favor a solution where the number of active machines is minimized but rather favors sparser schedules as total changeover times might be even lower. One should keep in mind that today there is no ongoing production between 18:00 p.m. and 12:00 a.m., hence the schedules are not considerably more sparse than the current ones.

The validity and applicability of the results highly depend on the simplifications. One of those is the underlying reasons for the sparseness mentioned above. If the schedules were to be implemented in the production, a manual compression of the schedules probably would be favorable, reducing the sparseness. Another model simplification greatly affecting the outcome of the model is that demand always has to be met regardless of the costs incurred. In reality, this is not always the best priority, rather a more complex balance considering customer satisfaction, costs evoked from not delivering on time and production costs. Further, simplifications have been made concerning production capacities and capabilities which are assumed to be equal even though they in reality are slightly different. The effect of this simplification is however mitigated by the fact that the schedules might be assigned to the most appropriate machine in the Arla factory. Lastly, due to the discrete time representation all deliveries are set due the hour before they are actually shipped. This could result in unnecessarily high warehouse levels but does also provide resilience in delivery precision in the case of production failure.

The most influential simplification concerns the cost structure and the fact that the model only considers costs as proportional to the time spent on production and changeovers. In reality, the employees will have to be paid not only while the machines are running, but during the entire shift where production takes place. This effect might be remedied by concentrating the production periods by hand as a post-processing as much as possible, similarly to discussion concerning sparse production schedules above. A different objective function might also be chosen, such as minimizing the total timespan for production.

7.3 Transformation of Production Shift Proposed by the Optimization

One of the questions posed by this thesis is wether it would be favorable for Arla to start production on an additional night shift, namely from 18:00 p.m. to 12:00 a.m. The results obtained by the scheduling optimization suggest that this initiative is favorable in order to remedy the warehouse problematics. At the same time it suggest a significantly decreased production during the existing night shift from 12:00 a.m. to 7:00 a.m. Of course this would be a radical turn for Arla and cause substantial changes in the operations. Although it is important to consider the total cost structure and evaluate the limitations in the cost modeling due to the simplifications mentioned in Section 7.2.

7.4 Suggestions on Further Research

For the purpose of this thesis, emphasis has been put on developing a lot-sizing model to solve the problematics at Arla. Lot-sizing models are generally more well suited for situations containing warehouse constraints and batch characteristics in the production. However they are also associated with disadvantages; for example restricted number of changeovers within a period, maximum changeover duration of one time interval, and that no detailed scheduling is provided within each time interval. Based on this, an interesting research field would be to develop the continuos models to incorporate features such as complex demand patterns, batch production and maximum warehouse levels.

Another area for further research would be to look into the incorporation of a more comprehensive cost structure in the existing models. As of now, the cost of producing is strictly proportional to the amount produced and factors such as sparse production schedules, which obviously incur costs, are not taken into consideration. The implementation of such components would align the model further to reality and therefore radically increase the usefulness.

Lastly, the optimization on Arla's production is already proceeding towards being unsolvable in short enough time. Therefore, in order to make the model applicable to even larger productions, serious efforts have to be put into reducing the complexity and speed up the solving of the optimization model.

Chapter 8

The Impact of Shift Work on Life Quality - perceived effects and possible remedies

8.1 Introduction

According to the mathematical scheduling optimization presented in Section 6.1 a solution to Arla's problems caused by high levels of inventory in the finished goods warehouse is to begin production on an additional night shift (6:00 p.m. - 12:00 a.m.). Although, before considering such a solution, one should investigate the effect on the employees working in the production since literature shows this might impact their physical and psychological health. The health issues might impose problems for Arla risking a damaged employer brand, decreased productivity, injuries in the production and increased costs. From this background, the purpose of this section is to investigate how night shift work affects the employees social life, sleep and stress as well as how to work with remediating actions concerning these issues.

The research field of employer health and working environment is large and divergent and focus varies from pure medical to management perspectives.[1] Due to this, restrictions are necessary for the relevance and accuracy of this thesis. Hence, the research performed will exclude pure medical issues and solely focus on the perceived effects of night shift work on mental and sociological matters as well as remediating actions for them.

[1] Göran Kecklund, Michael Ingre, and Torbjörn Åkerstedt. *Arbetstider, hälsa och säkerhet – en uppdatering av aktuell forskning.* Vol. Stressforskningsrapport 322. Universitetsservice Frescati i Stockholm, 2010.

8.2 Methodology

In order to address the stated research question concerning night shift work's effects on mental and sociological matters two main approaches have been used. Firstly, a literature study focusing on current research and general consensus on how shift work affects social life, sleep disruption, and stress. Secondly, a qualitative employee survey among Arla employees regarding the presence and perception of these issues.

The literature study was performed through the collection of articles and books judged to be reliable, mainly through searches in different databases. A majority of the articles have been collected through the search tool "Primo" provided by The Royal Institute of Technology which combines several databases for scientific publications. In some cases, Google has been used to find important articles referred to in the literature. Although, when articles have been found through Google the publishing details have been verified through reliable catalogues such as PubMed or the Library of Congress catalog. The main keywords used in the Primo database searches are; "shift work", "stress research", "sleep disturbance", "shift work management", "work life balance" etc.

The qualitative employee survey was performed on 55 Arla employees working in the production or the finished goods warehouse. The survey was performed through an anonymous questionnaire of 14 multiple choice questions that were given to the employees in the beginning of their shift. The first set of questions asked was about the characteristics of the employee followed by questions about the perceived effects of working night shift. Among the respondents, 44 out of 55 had experience of working night shift and 32 out of 55 had at least one child. For the complete questionnaire, see Appendix A.3.

Together they form the base for an analysis of how Arla can work with remediating actions from management level in order to avoid and mitigate the associated negative effects.

8.3 Literature Study of Shift Work Research

This section will introduce three aspects related to night shift work that have an impact on life quality; social life, sleep disruption, and stress. The literature study performed within each of these areas investigates the current research and raises key aspects to be considered in the development of remediating actions.

8.3.1 Shift Work Impact on Social Life

Employees working night shift or abnormal hours can experience a disruption of social activities since the rhythm of the general population is oriented around the day. Examples of this are difficulties to participate in sporting or religious activities. Furthermore, nightshift can affect the relationship to the family and marriage as duties such as grocery shopping, child care and general domestic duties can be hard to fulfill. This general problem picture of working night shift can lead to social marginalization.[2]

The negative effects of night shift work on the social life can seem obvious but are often hard to quantify and difficult to determine the extent of their impact. However, Harriet B. Presser,[3] put emphasis on this problem and studied the impact of shift work on marriage through a logistic regression. Presser's study based on 3476 married couples found that couples where at least one was working shift are between three to six times more likely to end up in separation of marriage within five years depending on the conditions for the shift work. Other studies declare the existence of positive effects of shift work. One example is Williams[4] whose study claims that employees working night shift have the possibility of spending more time with their children and considers the night shift work as a possibility for parents to juggle with day care. On the other hand, the same study clarifies that the same group on average spends less time with their spouse than day workers which definitely could be considered a tradeoff from spending more time with their children.[5]

On the positive side, employees working night shift who have solitary leisure pursuits have relatively more opportunities to schedule their activities in their everyday life.[6] However, according to Williams,[7] employees working night shift more often claim they have too little time with their family and friends.

8.3.2 Shift Work Impact on Sleep

Maybe the most obvious consequence of night shift work is sleep disruption including both reduced sleep duration as well as reduced sleep quality. The human sleep pattern is determined by the circadian rhythms[8] which also controls other vital systems in the body such as hormonal balances and body temperature.[9] From this background, it is not surprising that working during the body's natural sleeping hours might cause sleep disturbances. This intuition is also confirmed by Haus & Smolensky[10] who observes several effects (such as hormonal disturbances and insomnia) amongst night shift workers who consequently violated their circadian rhythms (i.e. circadian disharmony[11]). Due to circadian disharmony night shift workers in general experience more sleep dis-

[2] J.M. Harrington. "Health Effects of Shift Work and Extended Hours of Work". In: *Occup Environ Med* 58 (2001), pp. 68–72.

[3] H.B. Presser. "Nonstandard Work Schedules and Marital Instability". In: *Journal of Marriage and the Family* 62 (2000).

[4] Cara Williams. "Work-life balance of shift workers". In: *Statistics Canada* 75-001-X (2008).

[5] Ibid.

[6] Harrington, "Health Effects of Shift Work and Extended Hours of Work", op. cit.

[7] Williams, "Work-life balance of shift workers", op. cit.

[8] D.S. Minors and J.M. Waterhouse. "Circadian rhythms in general". In: *Occupational Medicine* 5.2 (1990), pp. 165–182.

[9] Harold A. Thomas. *Circadian Rhythms and Shift Work - Policy Resource and Education Paper*. American College for Emergency Physicians, 2010.

[10] Haus E. and Smolensky M. "Biological clocks and shift work: circadian dysregulation and potential long-term effects". In: *Cancer Causes and Control* 17.4 (2006), pp. 489–500.

[11] Thomas, *Circadian Rhythms and Shift Work - Policy Resource and Education Paper*, op. cit.

turbance than day workers.[12] Beyond the disturbance of the circadian rhythms, sleeping during day is less restorative due to external factors such as daylight, domestic duties, noise etc.[13]

The largest impact on sleep quality occurs when the employee tries to change the circadian rhythm. The Swedish Stress Research Institute[14] and Haus & Smolenskyl[15] argue that a complete change of the circadian rhythm, resulting in a complete adaption to night shift work, is impossible. They stress the importance of shift schedules in order to reduce those effects, see Section 8.5. The primary reason for the difficulty of adjusting circadian rhythms is that employees tend to readjust the circadian rhythms during weekends to facilitate social activities or family life.

Ursin et al.[16] conclude through a large statistical study that night shift workers in general have shorter sleep durations than day workers. According to Harold,[17] sleep duration is approximately 0.5 - 2 hours shorter in general for employees working night shift. Shorter sleep duration may result in a sleep debt making it difficult to stay awake and maintain concentration, especially during the circadian rhythms natural sleep hours.[18] Research also shows that shorter sleep duration affects the composition of the different phases of sleep, resulting in lower sleep quality.[19]

Consequent disruption of the natural sleep cycle and shortage of restorative sleeping hours may result in the condition of fatigue, especially if the tasks performed by the employee are complex, monotonous or under general high workload.[20] Fatigue is the decrease of mental and physical capability for an individual, for example in terms of coordination, attention, strength or speed.[21] Fatigue is highly correlated to the risk of accidents[22] in the production, but also during for example transportation between home and workplace,[23] and might result in long term health conditions.

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[12] Torbjörn Akerstedt. "Shift work and disturbed sleep/wakefulness". In: *Occup Med (Lond)* 53.2 (2003), pp. 89–94.

[13] Timothy H. Monk and Simon Folkard. *Making shift work tolerable*. London: Taylor & Francis, 1992. ISBN: 0850668220. URL: `http://www.loc.gov/catdir/enhancements/fy0917/92220017-d.html`.

[14] Kecklund, Ingre, and Åkerstedt, *Arbetstider, hälsa och säkerhet – en uppdatering av aktuell forskning*, op. cit.

[15] E. and M., "Biological clocks and shift work: circadian dysregulation and potential long-term effects", op. cit.

[16] Reidun Ursin, Bjørn Bjorvatn, and Fred Holsten. "Sleep duration, subjective sleep need, and sleep habits of 40- to 45-year-olds in the Hordaland Health Study". In: *Sleep* 28.10 (2005), pp. 1260–9.

[17] Thomas, *Circadian Rhythms and Shift Work - Policy Resource and Education Paper*, op. cit.

[18] Y. Harrison and J.A. Horne. "The impact of sleep deprivation on decision making: a review". In: *J Exp Psychol Appl* 6.3 (2000), pp. 236–49.

[19] Kecklund, Ingre, and Åkerstedt, *Arbetstider, hälsa och säkerhet – en uppdatering av aktuell forskning*, op. cit.

[20] E. Grandjean and Karl H.E. Kroemer. *Fitting the task to the human: A textbook of Occupational Ergonomics*. Ed. by 5th ed. CRC Press, 1997.

[21] Philippa Gander et al. *Managing shift work to minimise workplace fatigue*. ISBN 978-0-478-28161-3. Wellington: The Department of Labour, 2007.

[22] D.F. Dinges. "An overview of sleepiness and accidents". In: *J Sleep Res* 4.S2 (1995), pp. 4–14.

[23] Kecklund, Ingre, and Åkerstedt, *Arbetstider, hälsa och säkerhet – en uppdatering av aktuell forskning*, op. cit.

8.3.3 Shift Work Impact on Stress

Working night shift can be a cause of stress for the employee.[24] However, beyond this connection it is difficult to understand in detail what factors in shift work that actually drive stress, but research point out sleep and social distress as important causes.[25,26] Harrington,[27] argues that other complicating factors in understanding this relationship are the vague definition of stress as well as the fact that night shift work is often self selected. Hence, according to Harrington, one cannot know if people that are generally stressed more frequently go into night shift work or if they become stressed from their work.

On the other hand, there is no consensus about the magnification of stress due to night shift work. Some research claim there is no obvious connection between the two while others claim the opposite. For example, the study performed by Williams[28] means that general life stress defined as the feeling that there is not enough time in the day to do everything applies to 26.6% and 26.8% of day workers and night shift workers respectively, i.e. an insignificant difference. At the same time, a study performed on 4962 workers in the Japanese steal industry researched the connection between work related stress and shift work and found that there is a significant difference.[29] The study performs a logistic regression based on a questionnaire answered by the workers and addresses some interesting drivers of stress. The multivariate regression reveals that night shift work includes more stress generating factors such as increased amount of over time, less holidays and decreased job control. Hence, the study claims that these are important factors for the increased stress among night shift workers rather than shift work itself, a view that is shared by Halpern.[30]

8.4 Employee Survey

In this section the most important takeaways from the employee survey will be highlighted and discussed. A complete description of how the qualitative employee survey was performed is presented in Section 8.2.

Firstly, the employees answered questions on the perceived effects of night shift work. As seen in Figure 8.1 the vast majority, 80%, associates night shift work with something negative and expects negative impact on social, sleep and stress aspects. One can see that the effect on sleep quality is the most commonly expected, although the differences are small. Change in sleep is also the main driver for perceived increased stress. Another interesting trend is that 65%,

[24] Diane F. Halpern. "How Time-Flexible Work Policies Can Reduce Stress Improve Health and Save Money". In: *Stress and Health* 21 (2005), pp. 157–168.

[25] J. Rutenfranz et al. "Biomedical and psychosocial aspects of shift work. A review". In: *Scand J Work Environ Health* 3.4 (1977), pp. 165–82.

[26] Y Victor et al. "The mediating role of work-to-family conflict in the relationship between shiftwork and depression". In: *Work & Stress* 22.4 (2008), pp. 341–356.

[27] Harrington, "Health Effects of Shift Work and Extended Hours of Work", op. cit.

[28] Williams, "Work-life balance of shift workers", op. cit.

[29] H. Harada et al. "Three Shift Systems Increases Job-Related Stress in Japanese Workers". In: *J Occup Health* 47 (2005), pp. 397–404.

[30] Halpern, "How Time-Flexible Work Policies Can Reduce Stress Improve Health and Save Money", op. cit.

which is low compared to other perceived effects, expect to face a decrease in time spent with family and friends.

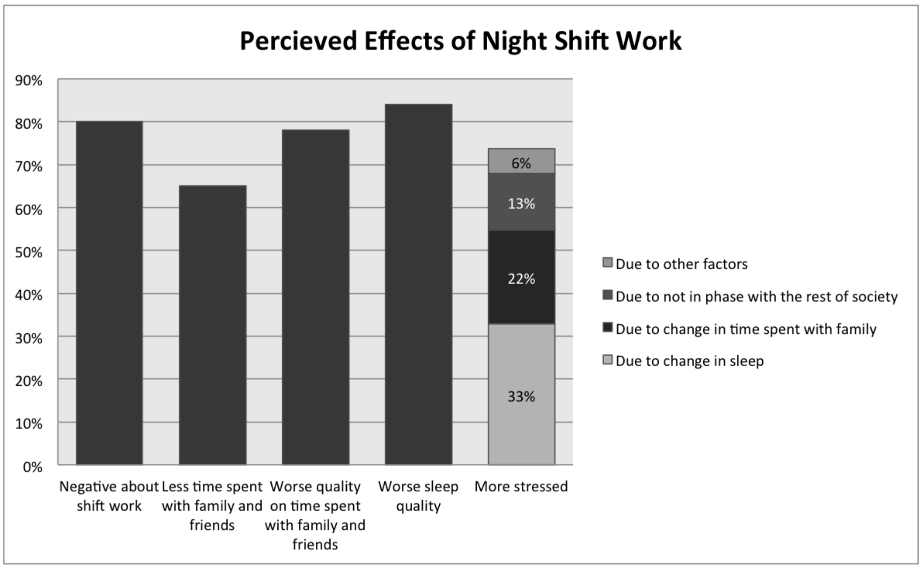

Figure 8.1: Perceived effects of night shift work by Arla employees

To those who had negative opinions about working night shift another set of questions was asked regarding what compensations that would make them change opinion, see Table 8.1. The results suggest that salary increase and working shorter weeks stand out as the most appreciated compensations. In more detail, about 81% of the workers that answered "increased salary" as an appreciated compensation asked for more than a 20% increase in salary, compared to about 12% that Arla offers today.

Appreciated compensations among workers originally negative about working night shift	**Fraction**
Would be positive if salary increase	61%
Would be positive if working shorter weeks	59%
Would be positive if more holidays	34%
Would be positive if offered healthcare programs	16%

Table 8.1: Presenting different compensations and what fraction that could change opinion on night shift work if offered any of them.

Based on the survey a brief analysis was conducted regarding the difference between employees with and without children, see Table 8.2. Of the 55 respondents, 32 had one child or more while the remaining 23 had none. Based on the results from the survey it is not possible to identify any general differences between the two groups. However some interesting differences should be mentioned and discussed. Firstly, the employees having children expressed less concerns regarding the social aspects. This could be due to the possibility of interacting with children during day time while people without children probably not have such opportunity as their social network are at work during the day. Secondly, workers with children raised larger concerns about sleep and stress. A possible explanation for this could be more family related duties that have to be done during day time disrupting the workers sleep and increasing stress levels. This logic together with less flexibility associated with working night shift might be a reason behind the somewhat larger skepticism towards night shift work among parents.

Perceived effect of night shift work	If having children	If not having children
Negative about night shift work	84%	74%
Less time spent with family and friends	63%	70%
Worse quality on time spent with family and friends	72%	87%
Worse sleep	88%	78%
More stress	78%	65%

Table 8.2: Comparison of perceived effects for workers with and without children.

8.5 Management Remedies

Although it is important to be aware of the negative effects of night shift work, it is possibly even more important for Arla as an employer to work proactively with remediating actions to minimize the negative effects. This section covers possible management remedies obtained from literature.

8.5.1 Increased Flexibility

Issues regarding social stress, disruptive sleep and employees that do not thrive at work might negatively affect a company through increased health costs, absence, high workforce turnover, fatigue issues and a less committed workforce. According to Halpern[31] this can imply severe economic effects for a company why reducing these events is of mutual importance for employees and employers. Halpern's research also claims that increased flexibility for the worker generally solves issues associated with social stress and that the savings are larger than the costs. Possible initiatives enhancing flexibility are allowing employees to work from home or to give the employees more influence over their working hours. A more structure-changing initiative would be the possibility of taking a day off when needed for personal issues, if announced beforehand.

[31] Ibid.

8.5.2 Overtime and Vacation

Less overtime and more holidays might remedy the negative effects of working night shift. Harada's et al.[32] studies show that the increased stress levels among shift employees are correlated with fewer holidays and more overtime. The opinion that overtime is negatively related to health is shared by The Swedish Stress Research Institute[33] who presents a review of current research. The same review also emphasize the importance of vacant days in between two blocks of night shift. A company which experiences these patterns among their employees could benefit from changed policies regarding overtime and holidays equalizing the differences between employees working day and night respectively.

8.5.3 Compressed Work Week

The Swedish Stress Research Institute's review[34] looks into the importance of the shift work schedule regarding negative effects of working night shift. The general conclusions are though a bit vague as there exists lots of research making contradictory conclusions regarding issues such as; weekly continuity of shift work, shift work rotation, length of the shift, daily rest, and vacant days between shifts. However, one trend that is emphasized is that night shift employees increasingly want to compress their working week i.e. work longer shifts some nights in order to get more vacant days. This could be designed in multiple different ways depending on the industry and personal desires. Bambra et al[35] performs an extensive review of the current research of the compressed work week schedule and concludes that it generally improves work life balance.

8.6 Discussion

The conducted literature study and employee survey form a rigid base for the analysis of the research question. While the employee survey effectively shows the presence of perceptions about negative effects of working night shift on social life, sleep and stress it does not reveal the underlying reasons. It is therefore well complemented by the literature study showing on possible causes for these perceptions as well as offering a theoretical foundation for understanding how the associated issues can be prevented.

The results from the employee survey are in terms of absolute numbers not claimed to be very accurate. However, general trends identified as well as the presence of negative perceptions in these questions at Arla are considered having high validity due to the univocality of the answers. The same reasoning is legitimate for the validity of the literature study. It is not very extensive, but

[32]Harada et al., "Three Shift Systems Increases Job-Related Stress in Japanese Workers", op. cit.

[33]Kecklund, Ingre, and Åkerstedt, *Arbetstider, hälsa och säkerhet – en uppdatering av aktuell forskning*, op. cit.

[34]Ibid.

[35]C Bambra et al. ""A hard day's night?" The effects of Compressed Working Week interventions on the health and work-life balance of shift workers: a systematic review". In: *J Epidemiol Community Health* 62.9 (2008), pp. 764–77. DOI: 10.1136/jech.2007.067249.

is deep within the narrow research field and hence rather extensive in the area of the research question.

Our study performed through literature and empirical research clearly shows a strong relationship between night shift work and issues concerning social life, stress and sleep as well as that they are present at Arla. While this relationship is established in previous research as well as in the qualitative study at Arla the implications are up to this point not yet evaluated. However, for Arla as a company, it should rather be emphasized to establish an understanding of how and to what extent these issues affect the company and what actions that can be taken in order to prevent them. As our scheduling results presented in Section 6.1 suggest increased production during inconvenient hours, the negative effects of night work is leveraged and hence requires more attention.

Our qualitative study among Arla employees is in many cases aligned with the theories proposed by the literature consulted. In Table 8.2, one can see that employees with children are less concerned about the negative effects on time spent with their families while working night compared to employees without children. This trend is also supported by Williams[36] who claims that employees working night shift have the possibility to spend time with their children during daytime. A possible trade-off is consequently that parents will experience less sleep during daytime hours but also less restorative sleep due to domestic duties and noise from children etc. This conclusion is supported by the qualitative study in Table 8.2 showing that parents perceive larger negative impact on sleep than employees without children and is in line with theories by Monk & Folkard.[37]

Concerning the possible remedies presented in Section 8.5 we recommend Arla to focus on remediating actions within *Overtime and Vacation* and *Compressed work week* to be further explored and developed in order to fit the production context at Arla. *Increased flexibility* on the other hand as proposed by Halpern[38] could be difficult for Arla to implement on the shift employees since it is a producing unit requiring continuous attention. Flexibility, in terms of being able to work from home and flexible hours is hence not applicable at Arla. However, less drastic actions promoting flexibility, such as facilitating taking a day off when needed for personal issues, could be both beneficial for Arla from an employer brand perspective as well as concerning the associated economical aspects.

Generally, Arla should be well aware of the existence of the perceptions raised in the employee survey and work remediating with the actions proposed. Although, the recommendations above should be further evaluated before being implemented. An interesting field for further research would be to look into if certain remedies are more applicable to industries such as Arla's. Such an evaluation has not been performed in this study but the literature reviewed is performed on specific industries that we judge to be representative for Arla, although not identical. Also, an even more exhaustive qualitative analysis including more extensive interviews would give Arla a deeper insight of the opin-

[36]Williams, "Work-life balance of shift workers", op. cit.

[37]Monk and Folkard, *Making shift work tolerable*, op. cit.

[38]Halpern, "How Time-Flexible Work Policies Can Reduce Stress Improve Health and Save Money", op. cit.

ions and perceptions among the employees allowing the development of custom fit solutions of remedies specifically for Arla. Further research could also be done regarding the identification of more remedies than those stated in Section 8.5.

It should be noted that the most appreciated compensation for working night shift is increased salary, see Table 8.1, and 81% of the employees answered that they would require a salary increase of more than 20% as a full compensation. This should be compared to the average salary increase of 12% that is applied today during the night shift. This result is also interesting since it emphasizes the economic importance of effective remedies. Since production during inconvenient hours is important for Arla, and is proposed by the results from the production schedule optimization in Section 6.1, increasing costs for compensation to employees is a probable consequence if the same employee satisfaction is to be maintained. Therefore, Arla should consider the trade-off between increased costs for making night shift work more tolerable and the requirements of economic compensations. Also, economic compensation does not solve the actual health issues cased by night shift work and should not be implemented as a substitute for other initiatives.

One should keep in mind that the remediating actions proposed are only concerned with the narrow field of stress, sleep disruption and social life even though the possible effects of working night shift are even more diverse, especially including more medical issues such as heart diseases, ergonometric and production related injuries. Those issues, although not developed in this thesis, should be considered and incorporated while developing remediating initiatives.

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Appendix A

Appendix

A.1 Framework for Classification of Industrial Context

In order to develop and apply a relevant and efficient scheduling algorithm it is crucial to define the considered production context. The structure given below highlights the most important production characteristics, based on a framework by Méndez et al.:[1]

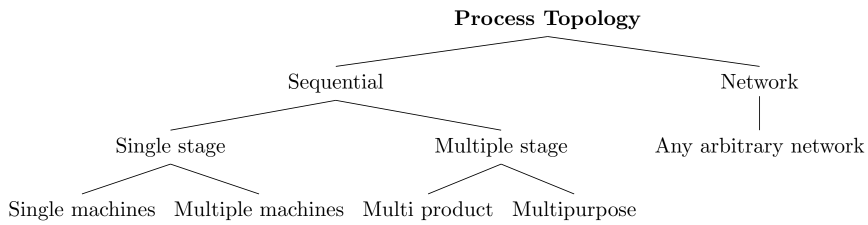

Figure A.1: Process topology characteristics tree

In a sequential process topology the products are produced by a pre-determined sequence of one (single stage) or multiple (multiple stage) processes or operations.[2] The network topology is more frequently used in low volume manufacturing[3] where the number of operations needed for each product unit is high.

[1] Méndez et al., "State-of-the-art review of optimization methods for short-term scheduling of batch processes", op. cit.

[2] Peter Brucker. *Scheduling algorithms.* 2th ed. Berlin: Springer-Verlag, 1995. ISBN: 3540600876 (hardcover : acid-free paper).

[3] Silver, *Decision Systems for Inventory management and Production Planning*, op. cit.

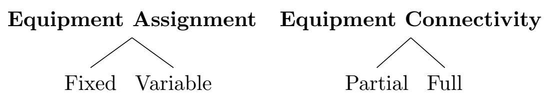

Figure A.2: Equipment assignment and connectivity characteristics tree

The equipment assignment and connectivity describe the flexibility of the machine arrangement and the machine capabilities. In a fully connected variable production the interaction between machines and operation stages is high (full connectivity) and all products can be produced on any machine (variable assignment).

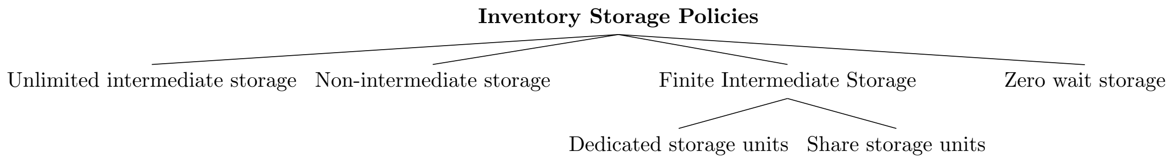

Figure A.3: Inventory storage policies characteristics tree

The inventory storage policies describe the structure of the intermediate storage in the production, the space designated for storage and if the available space is shared by production units.

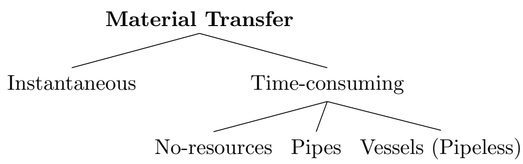

Figure A.4: Material transfer characteristics tree

Material transfer describe how material is transported within the production, to storage or between operations.

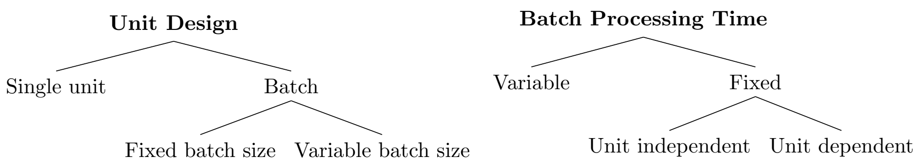

Figure A.5: Unit design and Batch processing time characteristics tree

The unit design and batch processing times describes if the production of units is performed in batches (i.e. if series of the same product produced on the same machine is produced jointly[4]). The batch processing time might be variable or fixed.

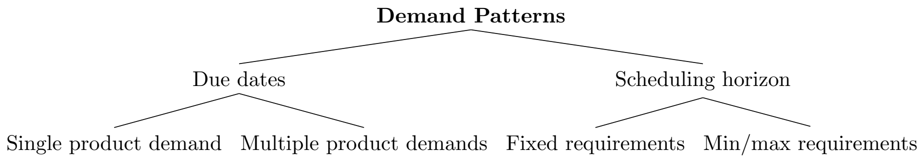

Figure A.6: Demand pattern characteristics tree

Demand pattern with due dates requires certain amounts of products to be produced at certain times (ex. to meet deliveries). Scheduling horizon demand defines what must be produced by the end of the scheduling horizon.

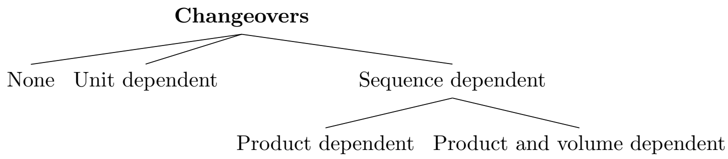

Figure A.7: Changeover characteristics tree

Changeover times might be sequence dependent or product dependent (i.e. determined by the product that is to be produced). The changeover times might also depend on the amount of units to be produced on the machine.

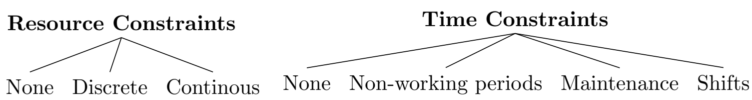

Figure A.8: Resource and Time constraint characteristics tree

Resource and time constraints define the limitations of the scheduling. Continuous resources are for example liters of crude oil whilst discrete resources are for example number of operators available.

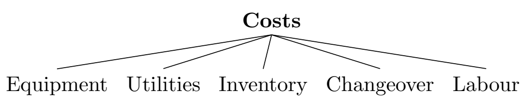

Figure A.9: Cost characteristics tree

[4]Brucker, *Scheduling algorithms*, op. cit.

The cost structure's relevance is highly dependent on the objective of the scheduling. Although, in many cases cost minimization is part of the objective function.

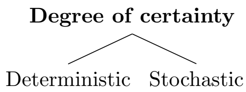

Figure A.10: Degree of certainty characteristics tree

The degree of certainty mainly concerns the demand pattern. The choice of stochastic or deterministic models is determined by the demand structure and the purpose of the scheduling.

A.2 Classification of the Arla Production Context

Parameter	Choice	Motivation
Process Topology	Single stage, multiple machine	The process considered in the scheduling is solely the packaging of the dairy products, hence the model is single stage. There are 14 production lines working in parallel.
Equipment Assignment	Variable	This contains a slight simplification of the Arla production since one of the 14 production lines are designated for one specific type of products. All other production lines are completely interchangeable.
Equipment Connectivity	Full	Since the production is single stage, the connectivity is high.
Inventory Storage Policy	Non-intermediate storage	Although this is a slight simplification, the single stage production implies no need for intermediate storage.
Material Transfer	Instantaneous	No material transfer due to single stage production. The transfer to finished goods warehouse is assumed to be instantaneous.
Unit Design	Variable batch size	The dairy products are produced in batches of variable sizes.
Batch Processing Time	Fixed unit dependent	Each product is associated with an individual capacity factor, but is assumed not to be variable over time or machine.
Demand Patterns	Due date, multiple product demand	Over the course of the day (i.e. the scheduling horizon) certain products must be delivered at certain times with specified quantities.
Changeovers	Product sequence dependent	Changeover times in Arla's production is dependent on the sequence of products to be produced on a specific machine, although product specific setup times is assumed to be included in the sequential setups.
Resource Constraints	None	The scheduling optimization only concerns the packaging process, the dairy products are assumed to be available at any given time (not a heuristic assumption according to Arla management).
Time Constraints	None	We assume for the purpose of the thesis' investigation of shift work potential that no time constraining factors are active a regular production day.
Costs	Labour	The costs taken into account are the labour cost associated with production and changeover times.

Table A.1: Classification of Arla's production system according to Appendix A.1

A.3 Employee Survey Questionnaire

Enkät om arbetsmiljö och nattarbete

Denna enkät utförs som ett **examensarbete på KTH** (Kungliga Tekniska Högskolan) och är alltså **inte beställd av eller kopplad till Arla**. Svaren är anonyma och kommer användas till forskning om arbetsmiljö.

Svara på frågorna utifrån din egen tolkning av frågeställningen. Fyll i det svarsalternativ som stämmer bäst in. Välj enbart **ett alternativ** per fråga.

Man ☐ Kvinna ☐ **Ålder:** <30 år ☐ 30-45 ☐ 45-55 ☐ >55 ☐

Högsta utbildning:
Grundskola ☐ Gymnasium ☐ Universitet/högskola ☐ Annat ☐

Relationssituation
Singel ☐ Sambo/särbo ☐ Gift ☐ Annat ☐

Barn:
Inga barn ☐ 1 barn ☐ Mer än 1 barn ☐

Arbetar eller har du tidigare arbetat nattskift:
Ja ☐ Nej ☐

Tänk dig följande situation:
Du har tidigare arbetat dagskift (08.00-17.00) men ska framöver arbeta nattskift (00.00 – 07.00), **observera att detta är en fiktiv situation.** Nedan kommer du få besvara frågor kring hur du skulle påverkas av denna omställning.

1. Hur skulle **tiden** du umgås med familj och vänner påverkas i den givna situationen?
Mycket mindre tid ☐ *Något mindre tid* ☐ *Oförändrat* ☐ *Något mer tid* ☐ *Mycket mer tid* ☐

2. Hur skulle **den upplevda kvalitén** på ditt umgänge med familj och vänner påverkas i den givna situationen?
Mycket sämre ☐ *Något sämre* ☐ *Oförändrat* ☐ *Något bättre* ☐ *Mycket bättre* ☐

3. Hur skulle **din sömnkvalité** påverkas i den givna situationen?
Mycket sämre ☐ *Något sämre* ☐ *Oförändrat* ☐ *Något bättre* ☐ *Mycket bättre* ☐

4a). Hur skulle **din upplevda stressnivå** påverkas i den givna situationen?
Mycket mer stressad ☐ *Något mer stressad* ☐ *Oförändrat* ☐ *Något mindre stressad* ☐ *Mycket mindre stressad* ☐

4b). Vilken faktor skulle **mest** påverka din upplevda stressnivå? (Om du svarat "oförändrat" på fråga 4, hoppa till fråga 5)
Förändrad sömn ☐ *Förändrat umgänge med familj och vänner* ☐ *Samhällsfunktioner ej anpassade för nattarbete* ☐ *Annat* ☐

5a). Sammanvägt, vad är din inställning till nattarbete?
Mycket negativ ☐ *Något negativ* ☐ *Neutral* ☐ *Något positiv* ☐ *Mycket positiv* ☐

5b). Om du är negativt inställd, vilken kompensation skulle få dig att få en positiv syn på nattarbete?
(Välj ett eller flera alternativ)
Ekonomisk kompensation ☐ *Utökad semesterledighet* ☐ *Förkortad arbetsvecka* ☐ *Friskvårdsprogram* ☐ *Annat* ☐

5c) Om du valt **ekonomisk kompensation ovan**, vilken procentuell löneökning anser du skulle få dig att få en positiv syn på nattarbete?
0-10 % ☐ *10-20%* ☐ *20-30 %* ☐ *30-40 %* ☐ *> 40 %* ☐

Figure A.11: Employee Survey Questionnaire

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