MASTER

Integrated planning and control of a multi-product, multi-echelon batch production-packaging system with an application to soap bars

Karakaya, S.

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Integrated Planning and Control of a Multi-product, Multi-echelon Batch Production-Packaging System with an application to Soap Bars

by

S. Karakaya (Senem)

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Student identity number 0668084

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Company Supervisors:

Prof. Dr. Ir. P. Bongers

Dr. C. Almeida-Rivera

Academic Supervisors:

Ir. Dr. S.D.P. Flapper, TU/e, OPAC

Prof. Dr. A.G. de Kok, TU/e, OPAC

TUE. School of Industrial Engineering

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I PREFACE

This document describes my research as the master thesis project finalizing the MSc. Operation Management and Logistics program in Eindhoven University of Technology, in sub-department of Operations, Planning, Accounting and Control. The master thesis project has been supervised by Ir. Dr. Simme Douwe Flapper and Prof. Dr. A.G. de Kok and conducted in cooperation with Unilever. The project is executed at Unilever Global Research and Development Centre in Vlaardingen, The Netherlands, in supervision of Prof. Dr. Ir. Peter Bongers and Dr. Cristhian Almeida-Rivera.

First of all, I want to present my special thanks to my supervisors in Unilever, Peter Bongers and Cristhian Almeida-Rivera, for their cooperation, starting the project, providing all the required information and sharing their insights and experiences. Their interest in the modeling has been inspiring and their help in debugging the model is really appreciated. I also want to thank Sander Dubbelman for sharing his knowledge and experiences as well as the details of his previous study on Mannheim Dove Soap Production Facility.

Furthermore, I would like to thank Bernd Kemptner and Bettina Volz for the cooperation, help and ideas they provided during and after the site visit to Mannheim. They shared very important information about the production system, parameter values and planning applications in the Mannheim Plant.

I owe many thanks to my first supervisor Dr.Flapper for motivating and aiding me in each step of the thesis and never hesitating to help to solve the problems faced during this period. His experience and academic knowledge as well as mathematical and modeling skills have been of tremendous help. I also want to thank my second supervisor Prof. De Kok for his help, valuable opinions from different angles and original point of view during the project.

I want to mention my thanks to Cor Hurkens for not sparing his time and help about software issues with his computer skills and modeling experiences.

I have to thank all my friends in Eindhoven, encouraging me to study, aiding me with their sincere friendship and making this difficult period easier and full of good memories. Finally, I am thankful to all my best friends and family for supporting me all the time.

II ABSTRACT

The aim of the study is designing a planning tool for integral planning and control of production and packaging stages in the Dove soap supply chain, where production and packaging take place at different physical locations with internal and external intermediate storage options and overtime possibilities, different capacities in the two facilities, sequence dependent setup times and costs, parallel non-identical packaging lines, minimum batch sizes and minimum safety stock requirements. The system has been modeled as a Mixed Integer Linear Problem and implemented. The modeling software used is AIMMS with optimization solver CPLEX 12.1. The objective is to minimize the total changeover, lost sale, handling, overtime, production loss and holding costs. The output of the model are production amounts on each reactor and line, inventory levels in intermediate and end product storage, delivery amounts, lost sale amounts, changeovers on each reactor and line and the total cost of the proposed production plan. The inputs are imported from Excel files and the outputs are displayed in Excel files. Scenario analyses have been conducted. Additionally, an extended version of the model including setup carryovers and a heuristic approach for solution has been proposed.

III MANAGEMENT SUMMARY

Planning in the process industry is problematic due to its specific features in production methods and facilities. The Dove Soap Bar Production Plant in Mannheim has a typical planning problem in process industry. First, raw materials are mixed and reacted in large tanks, with long cleaning and setup times when changing between intermediaries. These intermediaries are stored in finite storage spaces with different conditions. Then, intermediaries are converted to many end products by different equipments which have sequence dependent setup times and costs as well as different processing times. Despite the vast amount of studies, a generally accepted method is not yet found for planning problems existent in such complex systems. In this sense planners still have to find their own production planning methods, which are most of the time far from being optimal. Currently, planning is done via SAP and Excel sheets, relying highly on the experiences of the planners.

The aim of the study is: "Designing a planning tool for the integral planning and control of production and packaging stages in the Dove soap bar supply chain, where production and packaging take place at different physical locations with internal and external intermediate storage options and restrictions, different capacities of the two stages, sequence dependent setup times and costs, parallel non-identical packaging lines, minimum batch sizes, minimum safety stock requirements and overtime possibilities". The planning tool developed is to be used for medium-term planning problems, in which production plans are made with period length of at least one week, so daily scheduling of production lots on the lines and their sequences are not planned. The aim is to decide on the batch sizes, inventory levels and line allocations in order to satisfy the demand per period. It can be used to realize any capacity modification requirements, possible bottleneck processes and aggregate cost estimations for budgeting decisions based on demand forecasts available for the next 14 months. This ability would increase the flexibility and decrease the uncertainty involved in planning and control. It may also be used during the feasibility investigations for new investment decisions such as installing an additional line and what-if analysis with different demand scenarios. These analyses would help realizing the possible impacts of certain changes in capacity or other production parameters and understand the limitations of the system.

As the basis of such an analytical tool, a mathematical model of the system has been constructed. The objective of the model is to find the least costly production plan, considering the holding, handling, overtime, changeover and lost sale costs while constrained by technical capabilities, requirements and available capacities of production lines, packaging lines and storage locations. The model is solved with the optimization software AIMMS to find the optimal production plan for the next 14 months. The output of the model provides a more detailed planning for the first 3 months on a weekly basis and more aggregated monthly plans for the following 11 months. The input data is taken from an Excel spreadsheet so that it can easily be modified by the users for each period or during scenario analysis, whereas the output is written to a separate Excel sheet to provide plans, which are easier to use, check and modify. The planning tool is to be used on a rolling horizon basis.

The analysis performed for verification and validation showed that the model is reliable and usable to make least cost production plans in multi-echelon, batch production-packaging systems with changeover times and costs. Sensitivity analysis conducted with different values of the input parameters showed the expected changes in the plan and total cost depending on the relative values of the unit inventory holding, handling, last sale and efficiency loss cost coefficients. There is a

big difference in the total cost due to the relative magnitude of the cost coefficients of unit handling costs. Decreasing handling costs would not increase the efficiency of the production but increase the profitability of the plant considerably. Hence further studies can be done on how to decrease pallet and transportation costs. Inventory holding costs and lost sale penalty costs impact the production plan and the total cost as well as the solution time. Efficiency loss costs have larger impact on the total cost in case of high inventory costs, changeover costs and/or tight capacity restrictions in the production area.

Besides, the model can also be used to investigate the possible impacts of strategic decisions like increasing or decreasing the number of equipments as well as the values of the input parameters and costs. Possible demand scenarios can also be investigated to estimate the budget for following years and worst/best case total costs can be determined. These pre-investigations with what-if analysis can be done by changing the values of the related input parameters. Such analyses would provide valuable insights and flexibility to the company in case of uncertainties and enables being prepared for several possible scenarios. Scenario analysis with decreased number of reactors, different number of handling personnel in the storage locations, decreased number of storage options and dedicated packaging lines, in which each line is dedicated to certain product combinations, have been conducted. The recommendations for Mannheim, based on the results of the scenario analysis with the current input data values, can be summarized as follows:

- Line Dedication and fixed sequences should not be used since they decrease the flexibility of the system which is risky in a system with a large product assortment, fluctuating demands and parallel non-identical lines.
- The initial stock of intermediate soap bases should be decreased and the use of external stock locations should be reconsidered since they seem to be unnecessary under the current circumstances. The safety stock amounts should be calculated with care as they increase both changeover requirements and inventory levels.
- The bottleneck in the system is not the production area but the packaging area, especially the stamping lines. Capacity extension for reactors is not profitable for now, unless demand volumes are increased or product portfolio is enlarged requiring additional setups.

The analysis also revealed the importance of the unit changeover costs and changeover times on the proposed production plan. Modifications in these parameters can lead to large differences on the final plan and total cost. Including setup carryovers with some simplifying assumptions would enable more accurate changeover time and cost calculations. The upper bound on the overestimation in costs due to missing setup carryover consideration has been calculated. The maximum possible difference in total cost has been found to be 14 % of the total cost, which was substantial enough to make further investigation on the issue. So an extended model which allows setup carryovers has been constructed. The extended model cannot be solved in a reasonable time with a commercial solver with the current input parameters. A heuristic approach has been proposed for solving the model, which can be tested and used for large instances of the model. The further investigation on the model with set up carryovers is strongly suggested because it would increase the precision of the total cost estimates and cut down on the total cost up to 14%. It also provides more detailed production plans, including the last and first production lot on the lines for each planning period.

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1 INTRODUCTION

Planning in the process industry is problematic due to its specific features in production methods and facilities. In process industry, mostly raw materials are mixed, blended or reacted in large tanks, with long cleaning and setup times when changing between intermediaries or recipes. These intermediaries are stored in finite storage spaces with different conditions. Then, intermediaries are converted to many end products by different equipments which may have sequence dependent set up times and costs as well as different processing times.

Despite the vast amount of studies, experiments and many valuable researches, an optimal and widely accepted solution method is not yet found for dynamic capacitated lotsizing and scheduling problem. Systems with sequence dependent setup times, set up costs, multiple non-identical lines and many end products keeps adding complexities and are waiting for researchers to solve. In this sense planners working in this kind of environments still have to find their own methods, which are most of the time far from being optimal. Additional considerations such as overtime and intermediate storage options are not easy to integrate into the planning and scheduling problems which are already large sized and NP-hard problems. Furthermore, scenario analysis with different number of resources and capacities are not included together with the solution, though these are vital issues which can impact the performance of the systems significantly. Besides, contributing to the theoretical planning literature available, these analyses would help planners and practitioners to understand the system thoroughly and see the limitations and robustness of the plans better.

Based on this gap both in the literature and practice, the subject of this master thesis is determined as: "Integrated Planning and Control of a Multi-product, Multi-echelon Batch Production-Packaging System with intermediate storage restrictions, sequence dependent setup structure, non identical parallel lines and overtime option". The Dove Soap Bar Production Plant in Mannheim, which is one of the production facilities of Unilever, has been selected as the case study object. The plant produces both intermediates required to produce soap bars and packaged soap bars with production in the first stage and packaging in the second stage and intermediate storage options. Integrated planning of production and packaging stages efficiently while controlling the intermediate stock at the same time has always been a challenge for the planners. Planning the production using an analytical tool, being able to find the best plan, making some scenario analyses and realizing the possible impacts of certain changes in capacity or other production parameters would improve the performance of the system and increase the flexibility significantly. So, the output of the research is aimed to be a general and analytical tool to assist planning in such systems.

This thesis report summarizing the research is organized as follows. Chapter 2 explains the research method to be used and Chapter 3 gives the problem definition and the project scope. In Chapter 4 related organizations are described and in Chapter 5 the current situation is analyzed. As the basis of the planning tool, a Mixed Integer Programming (MIP) model of the system has been constructed in Chapter 6 and the input data requirements are listed in Chapter 7. The implementation of the model and software utilized are discussed in Chapter 8. The model has been verified and validated in Chapter 9. In Chapter 10, scenario analysis has been conducted and the outcomes of the analysis are provided. In Chapter 11, a further extension of the model with setup carryovers is presented and a heuristic approach is proposed. In Chapter 12 conclusions are given and in Chapter 13 recommendations are provided. Finally, in Chapter 14 reflections are presented.

2 RESEARCH METHOD

This Master Thesis Project is a Business Problem Solving (BPS) project and it is design-oriented, performance focused and client centered since it is conducted in collaboration with a company. Van Aken (2007) states that BPS project targets are designing sound solutions and realizing performance improvements by means of systematic planned changes. These are the relevance criteria. Additionally, rigour of the research is strengthened by being theory based and justified. The solution methods and tools used are based on the state of the art theoretical knowledge in the planning literature. It should be general enough to be adaptable to planning problems in similar environments. Based on Van Strien (1997) the steps of the project can be seen in Figure 1 below.

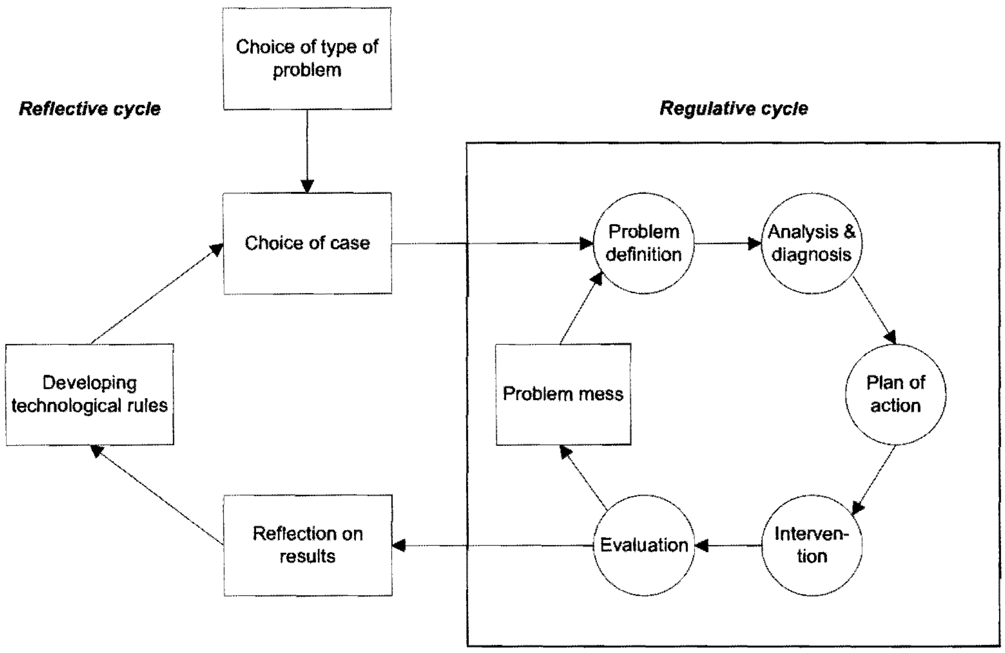

Figure 1: Research design (based on Van Aken et al., 2007 and Van Strien, 1997)

This project focuses on the first three stages, which is the design part. The aim is to propose a sound solution method. Since 5 months of time is not enough to both design and implement the solution, actual implementation is not feasible. Actual implementation would include using the production plan proposed by the model and seeing its impacts for 2 or 3 months in the intervention and evaluation step.

The problem type was chosen in the literature review conducted in the Master Thesis Preparation I about planning and scheduling issues in batch process industry and solution methods available in the literature. Growing rapidly and being capital intensive with some special characteristics this subject is a very interesting and open to improvements. In the previous study many planning and scheduling problems and optimization models and heuristics developed to solve them were examined. It was concluded that research in planning in process industries with multiple lines, many end products, complex setup structures, integrating multiple stages with limited intermediate storage, with overtime and service level considerations, supported with scenario analysis with different capacity and stock keeping options, is a promising research area, open to improvement and relevant for planners in the industry.

This choice led us in finding the suitable case in Unilever- Dove. Once the case was determined, the real situation in the company was investigated and the problems existing and reflected by the company supervisors were converted to a clear problem definition with a feasible project scope. This step has been taken during the Master Thesis Preparation II phase and the summary can be found in Chapter 3.

The second step is analysis and diagnosis. This step starts with thorough analysis of the production and packaging system of Unilever- Dove soap supply chain in Chapter 4 and 5. The current planning approaches and complicating technical and operational considerations have been discussed in detail. The parameters which are fixed and given, the variables which can be changed during the planning horizon and are determined by the model, the constraints imposed by the technical features and operational procedures can only be determined after a thorough investigation of the production system.

In the plan of action step, based on the analysis and diagnosis a Mixed Integer Programming model has been formulated with necessary definitions, adequate formulation of the constraints and objective function in Chapter 6. After the mathematical model was built, the actual quantities used in the Dove supply chain have been used to solve the model. This step requires detailed data gathering and requires close cooperation of the company, as discussed in Chapter 7.

Then, a feasible production plan can be proposed solving the model. The tool incorporates a solution method, designed for the model, which is practical and easy to use. The software used in Unilever is AIMMS, so the model has been re-written in adequate format for AIMMS optimization software and solved using the current input data. This is the intervention and evaluation step in the cycle feasible within the project scope, which can be seen in Chapter 8.

After an adequate model and solution approach was designed, the model has been modified with additional variables, parameters and constraints to make scenario analysis with different system designs. The impact of these modifications can be seen in the performance analysis and comparison with the base case. This step can be seen as shorter recursive regulative cycles. The comparison can be done both with optimizing the plan or using the data of the current planning. These steps can be found in Chapters 9 and 10.

3 RESEARCH PROJECT

In this chapter discusses the first two steps of the BPS cycle, providing the motivation in choosing this case study, the final problem definition and the defined scope of the research project.

3.1 Choice of Case

The complexity of the supply chain and production system makes the planning a very challenging and erratic task for the planners of the Dove Soap Bar production plant.

The soap production system includes most of the interesting and complicating characteristics in the planning literature, pointed out in the literature review conducted in the Master Thesis Preparation I, such as multiple stages, multiple items, parallel and non-identical lines, different capacities in two stages, intermediate storage restrictions, complex setup structures and overtime issues. The packaging lines have different capacities and technological capabilities. The intermediate storage feeding the packaging process is also problematic due to overflowing warehouse and high additional cost of external warehousing option. The Dove soap bar production system works according to a Make to Stock strategy and production is planned based on the forecast of future demand. The planning in such a complex production environment needs integration of production and packaging stages and intermediate storage in order to be more efficient and cost effective. However this assignment is not easy to handle without help of an analytical planning tool. This requirement is well in line with the research subject selected for the master thesis.

In the previous years there have been separate studies for the production planning and scheduling purposes in the plant. First, a study has been done to make the daily scheduling of the SKU s to the lines in the packaging stage. In another study, a production planning tool has been constructed combined in Excel and AIMMS. The optimization solver plans the daily amounts of DEFI bases to be produced on each reactor. Next, in an Excel sheet the demanded base amounts from the packaging stage is calculated by some spread sheet functions but not optimized. The results of this Excel calculation are the input to the planning model. Some drawbacks of this planning model are:

- No actual synchronization is attained between the production stages and packaging stages during the planning process, the decisions related to production and packaging are made at different points in time.
- Changeover decisions are not planned by the tool but given as input to the model based on the spread sheet calculations.
- The recently introduced product types are not considered.
- Changeover times between different flavors on packaging lines are not considered.
- Some packaging equipments are not considered at all.

Another study conducted was about short term scheduling in the packaging stage. A scheduling tool was designed using INFOR software. However, this tool requires availability of intermediates to be used as input, which is also a decision variable in reality.

Although outcomes of these studies were found helpful and promising by the company, they realized the need for an integrated planning tool which can include both production and packaging decisions taking onto account the storage options, cost tradeoffs involved and capacity differences of lines at the same time. The planners require an analytical tool to efficiently plan and control integrated production and packaging in the Dove soap bar supply chain, making this research relevant for the company.

3.2 Problem Definition

Based on the observations and discussions made with the company supervisors, the interested research area has been converted to a research assignment which is both rigorous for theoretical studies and future investigations, and relevant for the company used as a case study. The research assignment has been set as:

"Design a planning tool for integral planning and control of production and packaging in Dove soap supply chain, where production and packaging take place at different physical locations with different intermediate storage options and restrictions, different capacities in the two facilities, sequence dependent setup times and costs, parallel non-identical packaging lines, minimum batch sizes, minimum safety stock requirements and overtime possibilities in packaging lines"

The designed tool should be able to determine production batch sizes of each intermediate product and end product, to allocate determined batches to production and packaging lines and to determine the inventory levels in each storage point per period. The aim is to keep the total of lost sale, holding, handling, changeover and overtime costs at minimum during the planning horizon while satisfying the related constraints.

Additionally the company demands to know the impact of line dedication, different storage options and different resource capacities on the performance of the plant. Hence the tool designed should be usable with different parameters, additional constraints and variables required in such situations to make scenario analysis with different system designs.

3.3 Scope of the project

Dove supply chain can be visualized as in Figure 2 below. All parts of the supply chain drawn is in the outer scope of the study since all parts are somewhat related and neither of them can be fully ignored. On the other hand some parts are more important and are studied in detail. The part of the supply chain which will be in the main focus of the project is shown by the shaded area. The scope of the project is discussed in detail in this section.

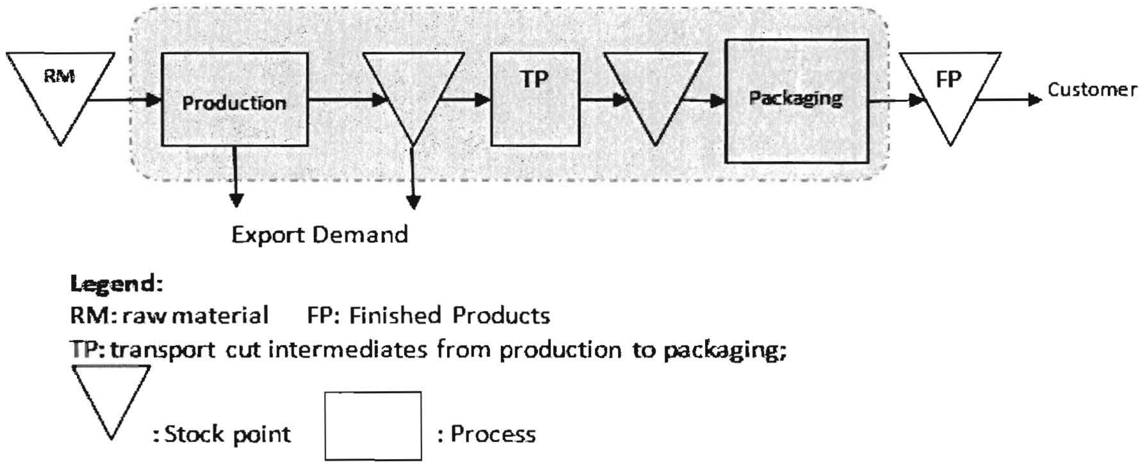

Figure 2: Goods flow Dove soap bars

Raw materials are assumed to be always available when required; hence raw material supply is out of scope. However some of the raw materials are kept in the same warehouse available in the production facility, together with the intermediate products. In order to handle this situation, a certain percentage of the available storage space in the warehouse will be allocated to the raw materials and deducted from the total capacity.

The company supervisors said that end product storage is not creating a bottleneck for the production and packaging operations and it can be assumed that there is always available storage space and personnel. So, the storage of end products and operations related to storage, including palletizing and stacking of the packages according to the customers, have not been taken into account. However, inventory levels of SKUs and costs to keep them in store should be considered in order to make realistic and efficient production plans. The tradeoff between holding costs and lost sale costs as well as the other production related costs should be included in the production planning decisions.

The capacities of the two facilities are fixed. The production lines work 7 days a week where as packaging lines operates 5 days a week. While the number of shifts and number of working days are fixed, the handling capacity of the intermediate storage can be extended with overtime options, considering the related costs and restrictions.

The pricing and impact of prices on the demand pattern is also out of scope. The selling prices of the products are not considered since the reaction of the demand to the pricing is not known and is not the subject of this study. Minimum safety stock requirements determined by the company are used as constraints in order to ensure the customer service level satisfaction. Although future demand is unknown, the demand forecasts provided by the company are used while making the plans. Hence the tool uses known demand data. The model is not stochastic. On the other hand including the impact of uncertainty in demand may provide a more robust production plans in the rolling horizon procedure. Because, once the plan is rolled for the next period, if the demand amounts has turned out to be considerably different than expected for the previous periods, the plan may be changed significantly which decreases the reliability of the plan for longer planning horizons. When the uncertainty considerations are included into the planning process, the variation in the demand is already taken into account while making the plans for next periods. But, stochasticity increases the complexity of the model significantly. The variance of the demand can be introduced to the model in terms of quadratic variables, in which case the model would not be linear anymore and far more difficult to solve in existence of thousands of decision variables, binary variables and constraints with recent commercial optimization software. So, the model is simplified by using the demand forecasts as constant parameters instead of random variables with a certain distribution.

The main scope of the project includes the production step of the intermediate soap flakes (DEFI bases), the intermediate storage with four different options and the sequential mixing, cutting and packaging processes referred as 'packaging step', in which the intermediates are converted to sellable end items, packages of soap.

3.4 Application Level of the Tool

The planning process in such complex supply chains are done at several levels, forming a hierarchy of decisions. In most of the Advanced Planning Systems (APS) a hierarchical planning approach is implemented with different decisions made at different planning levels. As discussed by Neumann et al. (2002) in detail, there are three planning levels, where strategic decisions are made at long-term planning level, tactical decisions are taken at mid-term planning level and detailed, operational decisions are made at short term planning level. Long term is defined in years, mid-term is defined in months or number of weeks and short term is defined in weeks or days.

The planning tool developed in this study can be used for mid-term planning problems, in which production plans are made with period length of at least one week. Daily scheduling of the production lots on the lines and their sequences have not been considered. The distribution of the end-items to customers, the routing during the transportation of the intermediate items from production to storage and from storage to packaging and the distribution of the exported intermediates have not been considered. The aim is to decide on the batch sizes, inventory levels and line allocations in order to satisfy the demand per period.

The decision levels and the use of the proposed tool in this planning hierarchy can be seen more clearly in the Figure 3 below.

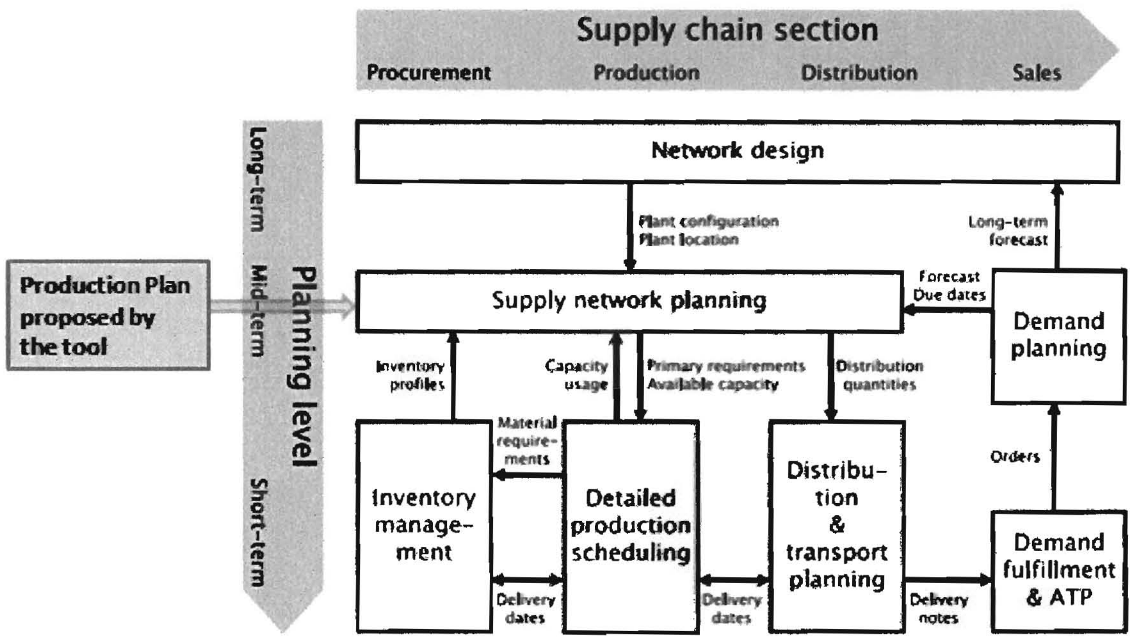

Figure 3: The location of the tool in a generic Advanced Planning System (Neumann et al. 2002)

This tool is not proposed to be used for operational purposes and daily scheduling and planning but more for tactical decisions, for doing some approximations about the production amounts, inventory levels and costs for the next 14 months. The planning tool is to be used on a rolling horizon basis. After the actual demand values, production amounts and inventory values are realized and the demand forecasts are updated, the related parameters should be modified and the model is rolled for next periods.

The rolling frequency depends on the robustness of the forecast and the requirements for tactical decisions such as frozen periods. For example, if the plans are frozen for the next 3 weeks, it does not make sense to roll the model each week because the plans cannot be totally changed but only small modifications can be made in the operational level. In this case, either the model can be rolled once in every 3 weeks or constraints should be added that are fixing the values of the variables for the frozen periods.

The plans provided by the tool can be used as input to the more detailed operational scheduling process. This planning model can provide some constraints for the detailed scheduling, making the scheduling easier. For example:

- The lot sizes should not be larger than the proposed by the model since longer periods are used in the model.
- The number of changeovers should not be larger than the number of changeovers proposed by the model since the setup savings due to the setup carryovers, i.e. when the same kind of lot is continued to be processed on the same line in the next period, are not deducted in the model
- The total changeover time should not be larger than the total changeover time proposed by the model because sequence dependent setup times and setup carryovers are not considered.
- The allocation of the lots to the lines is already done by the model.
- The total line usage hours found should be an upper bound for the scheduling model

When the uncertainty in demand is not included in the lotsizing calculations, in the rolling horizon, the lot sizes will be smaller in the first weeks in order to deal with the difference between the forecasted and actual inventory and demand amounts in the previous periods. The lot sizes gets larger in the later periods as the model takes the forecasts for the 14 months as deterministic data. However the lot sizes for these later periods are very prone to change and they can get smaller after rolling the model for several periods. The higher the certainty, the more robust are the plans. Hence only the first few weeks can be taken as input for the detailed scheduling. This explanation is one of the reasons why this model is not proposed to be directly used for operational purposes and weekly scheduling but only in terms of upper and lower bound constraints.

Another important use of the tool is making scenario analysis for the next 14 months for the system. Based on the current forecasts, scenario analysis can be conducted with different parameter values such as capacity values, safety stock levels or different production tactics like line allocation rules. The impact of these modifications on the system behavior, total cost and resource utilizations can be investigated.

The tool can be used for tactical decisions like rough cut capacity planning, MPS. These tactical decisions support strategic decisions and they tend to be medium level, medium significance, with moderate consequences. It can be used to realize any capacity modification requirements, possible bottle neck processes and aggregate cost estimations for budgeting decisions based on demand forecasts available for the next 14 months. It also helps to check the aggregate feasibility of the maintenance plans, investment plans like line installments and product portfolio modifications. This ability would increase the flexibility and decrease the uncertainty involved in planning and control.

In this mid-term planning problem, high level issues have not been considered. The supply chain network design, facility location and layout problems are out of the scope of this study. These long term and more strategic decisions, which are made in the higher level of the planning hierarchy, are taken as input to the tool.

4 COMPANY DESCRIPTION

This master thesis project has been done in cooperation with Unilever Global Research and Development Centre in Vlaardingen, The Netherlands. Dove soap production plant in Mannheim, Germany was chosen as the study object. This chapter gives a short description of the involved parties.

Unilever is one of the world's largest consumer goods companies with a strong portfolio of foods, home and personal care products which has turnover of € 30,164 million in 9 months of 2009 [1]. Unilever has 270 manufacturing sites across six continents, 100 countries, accommodating 174000 employees at the end of 2008 [2]. All organizations and R&D centers strive for improved performance on safety, efficiency, quality and environmental impacts, working to global Unilever standards and management systems [1]. The key facts about the portfolio categories can be seen in Figure 4.

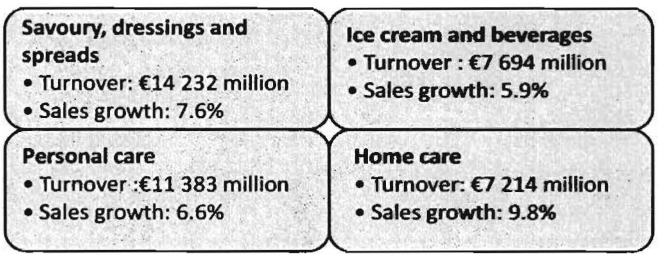

Figure 4: Portfolio categories [2]

Unilever holds the global market leader position in all the Food categories in which it operates such as Savory and Dressings, Spreads, Weight Management, Tea, and Ice Cream. It is also global market leader in Skin and Deodorants, and has very strong positions in other Home and Personal Care categories [1]. In January 2006, the Unilever Supply Chain Company AG (USCC) has been established as part of the new European supply chain organization, co-locating the supply chain key decision-makers in Switzerland. USCC is responsible for key decisions in the European Supply Chain including buying raw and packaging materials, production planning and manufacturing in the whole facility network. It also handles the logistics activities within Europe, including primary transport and warehousing operations in the network [3].Unilever, being very aware of the importance of innovation and improvement in existing products, has 31 major R&D centers all over the world. € 927 million was spent on research and development activities in 2008. The Global R&D center in Vlaardingen, the Netherlands has more than 1000 employees and over 40 nationalities focusing on the areas of bioscience, nutrition & health, sensation, perception & behavior, structured material and process sciences, advanced measurement and data modeling [1,2]. Dove is one of the top 13 brands of Unilever, which account for over 2.5 € billion annual sales over 80 countries [2]. It is the number one cleansing brand with a portfolio of soaps, body lotions, hair care products, deodorants; face care, body wash and hand wash products [4]. Soap bars constitute the 75% of the revenue of Dove in 2007. Dove soap bars are produced in the manufacturing plant in Mannheim, Germany. The distribution centre supplying Dove products to the whole German market is in Mannheim as well [5].

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1 www.unilever.com, last consulted on 02.01.2010
2 Unilever Annual Review 2008
3 www.wikipedia.com, last consulted on 02.01.2010
4 www.dove.com, last consulted on 03.01.2010
5 www.unilever.de, last consulted on 03.01.2010

5 CURRENT SITUATION

This chapter discusses the current situation of the system under consideration for analysis and diagnosis of the system. The system under consideration can be visualized as in Figure 5 below. The arrows represent the flows of goods.

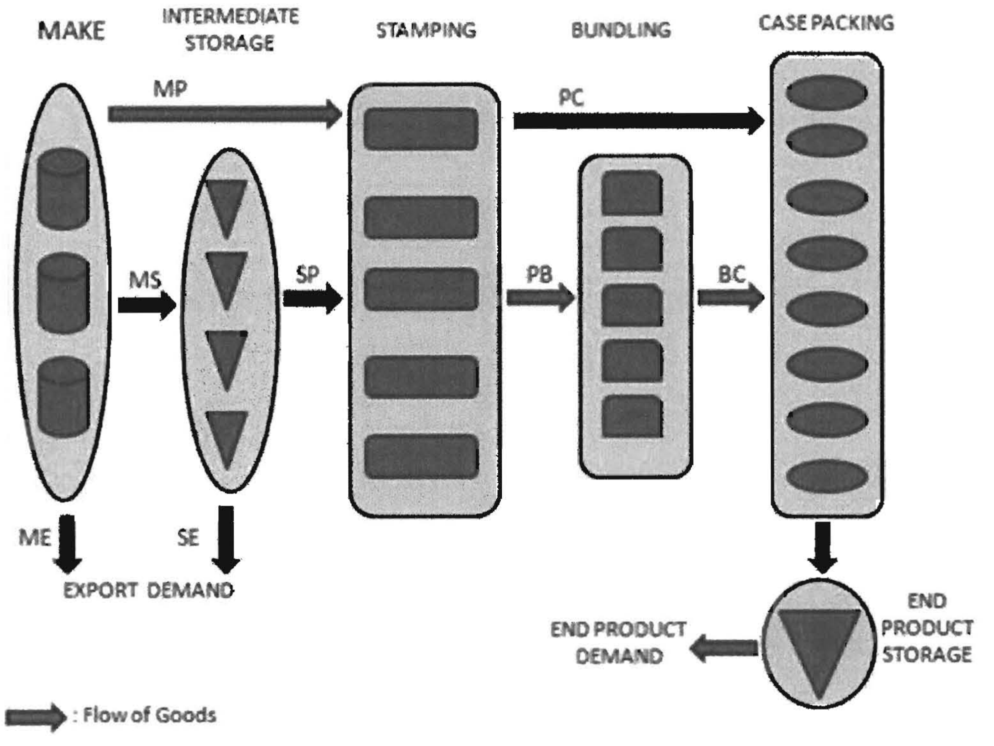

Figure 5: System and the good flows representation

The production of soap bars is done in two stages. The first stage, referred as "production step", involves production of soap flakes (DEFI bases) from raw materials. There are 3 kinds of bases (HEBE, GEAR and TALLOW) which are produced in the make area in 3 reactors. These bases are the intermediate products used for the soap bar production. The bases produced in reactors can be used directly to satisfy export demand (ME), directly sent to packaging without storage (MP) or kept in storage locations (MS). There is intermediate storage between make and packaging stages. There are 4 possible storage locations with different holding and handling costs, where all bases can be stored. Bases stored in the storage locations can be used to satisfy the export demand (SE) or can be directed to the stamping lines (SP) to be converted into end products. The second stage which is called as "packaging", involves mixing of flakes, adding color and fragrance, cutting the block into bars and packaging the bars in various ways. In the stamping lines bases are mixed with certain chemicals to have different flavors and can be stamped (cut) in different bar sizes (grams). There are 5 stamping lines with different technical capabilities. The stamped bars are packed. They can be packed in bundles or in singles. To have multiple bundles in a package, the bars are sent from the stamping lines to the bundlers (PB) and after that, primary packaged goods are sent to the case packers (BC) for secondary packaging. The products to be packed in singles are directly sent from the stamping lines to the case packers (PC). There are 5 bundlers and 8 case packers with different capabilities and production rates. There is no storage possibility after the stamping lines. The end items are sent to end product storage to satisfy end product demand.

5.1 Production Processes

5.1.1 Raw Materials

The raw materials used in the production are mainly oils, chemicals and a certain additive used to make GEAR. There are different kinds of oils, cheaper ones increase the number of bases produced. The raw materials used in stamping lines are additives for color and fragrance, such as *fillers, colorants, preservatives, perfume etc.* and packaging materials used in bundlers and case packers. Raw materials can be assumed to be always available for use and raw material supply is left outside of the problem boundaries. Some of the raw materials are stored in liquid form in special tanks or containers. However some are kept in the same warehouse with the intermediates, so restrict the available storage capacity. In order to simplify the situation, it will be assumed that a certain percentage of the warehouse is dedicated for raw material storage. There is no storage time limitation for raw materials

5.1.2 Production of Soap Flakes (Bases)

In the production, the raw materials are put into dosing systems in front of the reactors. Currently, there are 3 reactors with same capacity, 2 of which are connected to the same dosing system. The raw materials are heated up to 230°C degrees in these reactors. Then materials passes through water, additives are added between 15-30% percent according to which kind of base to produce and finally cooled to 30-40°C in the cooler. The output of the production step can be 3 kinds of intermediate soap bases (flakes), namely HEBE, GEAR and TALLOW.

HEBE is the mostly used base and GEAR is used to make only 2 flavors, which constitute the 10% of the total demand. TALLOW is recently included in the product range and can only be produced in one of the reactors. There is limited information about its demand but it will be included into the analysis for further use. These are flakes with no color and no flavor and they are intermediate products to be input to the stamping lines.

5.1.3 Intermediate Storage

There are multiple options for intermediate storage of the flakes. Certain amount of the flakes is exported to the other plants in abroad, since this manufacturing site is one of the 3 factories producing flakes all over the world for Dove. Also, some amount of flakes can be directly transported to the stamping lines without storage. The flakes for later use can be stored:

- In production facility(re-pack area)
- In warehouse(Internal Storage)
- Off site in another location(External Storage I and II)

The capacities and holding costs related to each option differ. The efficient management of the storage is important since the capacity in the warehouse is not enough in current situation and high costs are involved in off-site storage.

These bases are stored in Big Bags and on pallets. In addition to the Big Bag and pallet costs there are also costs related to the handling of these bags into and out of the storage locations. There is regular Big Bag handling personnel with certain handling capacity. However making overtime and hiring additional personnel is possible with certain costs.

5.1.4 Transportation

Although the transportation of the end products to the customers and raw materials from suppliers to the production area has not been considered, the transportation within the production area and between storage and lines should be considered. The transportation of the goods within the plant and in the warehouse is done by forklift. The transportation of the intermediates to the offsite storage point is done by trucks which is costly. This offsite storage location is close to the production facility, at the other side of the city and transportation does not take much time. It takes less than a day or maybe couple of hours so the cost item is not related to the routing of the transportation but more to the administrative costs, rents etc. The capacity of transportation, number of trucks, drivers etc. is assumed to be unrestricted, as soon as the related costs are paid.

5.1.5 Mixing & Cutting & Packaging

There are multiple stamping lines with different capabilities in use. The line starts with a mixer in which flakes are mixed with many different additives for color and fragrance according to the recipe of end items required. Some bars in certain sizes can only be produced in certain stamping lines. After the mixture goes through more consecutive processes on the line, they are cut into one of the 3 different sizes of bars in stamping process. The bars are fed to one of the bundlers by the help of a transportation belt and a junction. The bars are bundled in a bundle consisting of 1, 2, 4 or 6 bars. There are multiple bundlers in use with different capabilities. This is called the primary pack. After that, 48, 24 or 12 bars are packed in a case, which constitutes the secondary pack, by a case packer. There are multiple case packers, parallel non-identical lines, and primary packs are fed through them again by the help of a transportation belt and a junction. Finally they are taken to end product storage. Figure 6 summarizes the process flow in this stage.

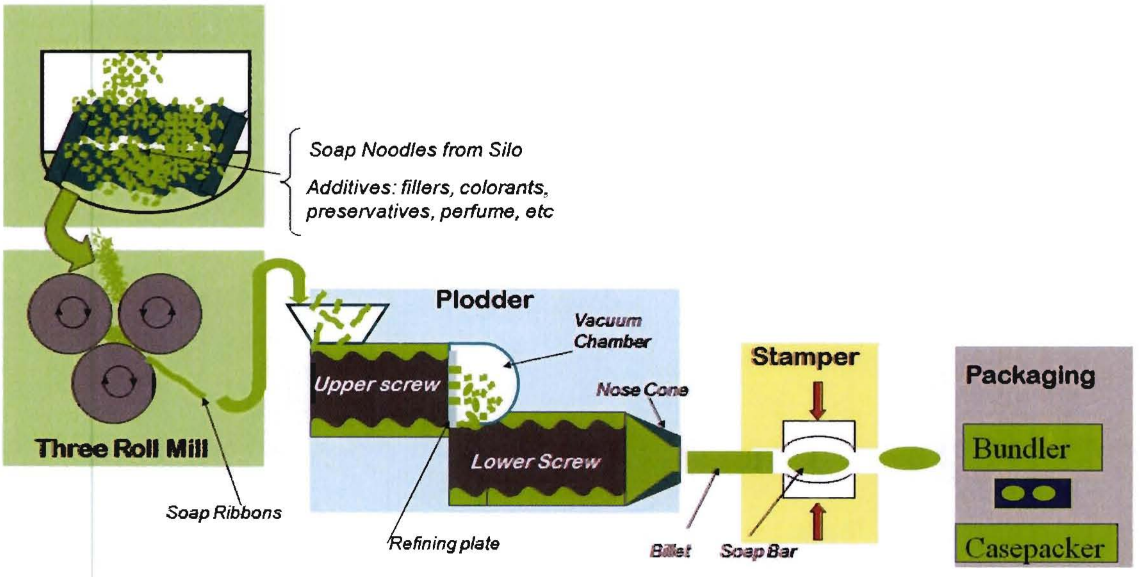

Figure 6: Process flow of flakes to become end products [6]

Processing rates of the equipments differ based on the process they are involved in. Also the equipments doing the same process have different rates based on the technological capabilities. Hence there are non-identical parallel lines in each step. While changing between flavors and sizes,

[6] Power point presentation, "2010.01.12 Soap bars" by Peter Bongers, January 2010

certain setup times and costs are incurred. Changeover times between flavors differ between lines and production rates change based on both the line and the bar size.

The packaging lines operate 5 days a week and 24 hours per day all year long. The numbers of shifts are fixed. The difference in operation hours available per week in two stages makes it inevitable to keep substantial amount of intermediate storage and makes it harder to integrate planning and control of these two stages.

5.1.6 Labor

The production of flakes is almost completely automated since it involves very high temperatures and hazardous chemicals. Mixing and cutting are automated as well but big bag handling can be said to be labor dependent. Also set up operations are highly labor dependent. The workers in a department can do different works in that department but cannot change department. For example in packaging a worker can work in different bundlers and case packers but cannot work in production.

After discussing the situation with the company supervisors, it has been decided that the available capacity and the number of shifts should be taken fixed for the packaging stage since the lead time to apply these changes is too long and cannot be based on mid-term plans. On the other hand capacity expansion is possible for Big Bag Handling Personnel, working in the intermediate storage locations, within certain limits by means of overtime and external hiring.

5.2 Demand

The customers of the production system are:

- Warehouses belonging to Unilever for end items
- Distribution Centers of Retailers for end items
- Other production plants of Unilever for intermediates

There are two kinds of demands involved in the system. Intermediate DEFI bases are demanded by other soap production plants all over the world. These bases are forwarded to these plants in big bags either from storage or directly from make area. The second type of demand is the end product demand by warehouses and distribution centers of retailers all over the Europe. The end products are delivered in secondary packages, mostly consisting of 48 or 24 bars bundled in several combinations.

The demand distribution is not known with a defined mean, standard deviation and distribution type. Demand stochasticity is handled by making forecast based on the historical data, the forecasts provided by the customers and via interactive communication and data sharing channels within Europe. The data sharing is very intense and provide robust forecasts for the customers in Europe due to the Vendor Managed Inventory Planning system. The planning is made based on these forecasts. The forecasts are used as deterministic data. However the company supervisor mentions that there is a kind of seasonality which is not as obvious as in an ice cream demand. It is not certain if this seasonality is real or due to the planning. The planning is done by disaggregating requirements to quarters, then to months, then to weeks. This disaggregating can affect the utilizations.

The detailed production planning for a week determining the line allocation, lot sizes and sequencing is done 19 days before the start of that week based on the information from SAP and demand forecasts. The production lots are allocated based on changeover requirements, ideal combination of bundler and case packer and 100% utilization of the stamping lines. The planners rely on some rough and frequent schedules that are used and defined cycle times based on experiences. The planning is done in excel sheets manually. The required modifications on the plans are done manually on excel sheets based on urgency, customer lead times of different SKUs and customers.

The end products are controlled in terms of Stock Keeping Units (SKUs), with distinctive SKU codes for each base type, flavor, bar size, bundle size, package size as well as the country to be exported and pallet sizes. There are more than 150 types of different SKUs currently being produced in Mannheim Plant. However in this study the pallet sizes and the country to be exported does not play a role in the production planning process, since they do not change the equipments to be used, processing times or production amounts. Pallet sizes and export countries are important for stock keeping of end products which is not the main point of this study. So, in the following pats of this thesis an SKU is representing a combination of flavor type, bar size, bundle size and secondary package size. Types of flavors, bundle sizes and package sizes can show differences between years.

6 MATHEMATICAL MODEL

In order to find the least costly production plan for the planning horizon, a mixed integer programming model has been constructed. This section gives the summary of the studies in the planning literature utilized during the modeling stage, the assumptions and simplifications made, the extensions added step by step and finally the explanations of the constraints and objective function formulated.

6.1 Literature on Planning in the Process Industry

As the first step to develop a production planning and control tool, a broad literature study has been conducted, reviewing the planning and scheduling issues and solution methods available in the literature during Master Thesis Preparation I. Growing rapidly and being capital intensive with some special characteristics this subject is a very interesting and open to improvements. Among many valuable and inspiring researches available in the literature and reviewed, only a few studies which are intensely used during the model building stage are discussed very shortly in the following paragraphs.

The studies of Kallrath (2002, 2005) have provided valuable insights on the points to consider in the modeling stage of MILPs, specifically the planning models in Process Industry, such as the general framework and characteristics of the problem to be included in the modeling stage. The main focus of this study is medium-term production planning. According to Kallrath (2005), the medium-term planning is involved with making decisions on material requirements planning (MRP) and deciding on production quantities or lot sizing over the planning period, considering the capacities decided in long term planning as constraints and try to optimize some performance criteria such as minimize make-span or costs, while satisfying the demand. The increasing product variety, reduced order sizes, shorter delivery times and pressure on flexibility and quality, increase the need for efficient lotsizing and scheduling decision making as stated in Dam et al. (1998).Mostly, dynamic multi level multi item capacitated lot sizing problem (MLCLSP) with setups and multiple capacitated resources have been investigated. MLCLSP has finite number of discrete periods, known dynamic demand, constant processing times, multiple items, multiple non-identical machines with different capacities, sequence independent setup times and costs and no setup carryover, which shares many common characteristics with the system under investigation in this master thesis. Therefore, the review has been narrowed down to focus mostly on studies about MLCLSP.

In addition to sequence dependent set-up structures, multiple end items, multiple machines with different features or abilities, most of the systems compose of multiple production stages and finite storage spaces in between. Most models with intermediate storage involve two stage production systems, with processing in the first level and packaging in the second level and also incorporate time restrictions on storage time due to deterioration. Ferreira et al. (2008) built an MIP model for a system in which raw materials are stored and mixed in tanks and then soft drinks are bottled in the following step. Each line is fed by a single tank and tanks feed multiple lines. This type of system is defined as "make and pack". The problem studied in this thesis can also be classified as a "make and pack" problem and his formulation served as a general framework for the integration of production and packaging stages. Günther et al. (2007) studied a similar make and pack problem and introduced an MILP based method to solve it optimally. The well known approach of dividing the planning horizon into small equal sized periods and fitting the setup times into a discrete time grid may cause infeasibilities. The use of a continuous representation of time can be thought alternatively. The approach used by Günther et al. (2007, 2009) is based on block planning. Several variants of a product type are integrated into a block and assigned to a macro period. The block has to be finished before the end of that period but the production of a single lot cannot be assigned to a specific date. Within each block a fixed or natural sequencing exists, mostly based on the sequence dependent set up structure, such as from light color to the dark color. The composition of single block can be changed between periods. Since demand is dynamic, the production amount of each product within a block is dynamic as well as the total completion time of a block. This approach has been used in formulation of the setup constraints of the production stage to reduce the complexity of the setup structure on reactors.

Almada et al (2009) studied the multiple machine continuous lotsizing problems (CLSP) with sequence dependent set ups including the production loss costs. First the problem is formulated as MILP. Then the formulation is reduced to a network flow type problem with nodes representing product types produced in a period and arcs corresponding to the set up between products. Arc weights are calculated based on setup time and cost. Then the problem is decoupled by machine using Lagrangean Relaxation. The formulated MILP in their study has been used to formulate the relationship between the production and packaging stages and OEE loss sale costs in the objective function in this thesis. There are few studies in which overtime decisions are stated explicitly. The previously discussed work of Günther et al. (2007) integrated overtime decisions explicitly into capacity constraints and overtime cost is included in the objective function. Only single kind of overtime is allowed which is during the weekend. Özdamar and Birbil (1998) defined two kinds of capacity which is overtime capacity and regular time capacity for each resource. While incorporating the overtime and regular capacity of the BBH personnel in the intermediate storage area these researches have been utilized.

Meyr (2002) studied the non-identical, parallel production lines with sequence dependent setup times. The problem studied is called General Lotsizing and Scheduling Problem for Parallel Production lines (GLSPPL). The planning horizon is first divided into macro periods, in which the number of lots produced is not restricted. Then a macro period is divided into non-overlapping micro-periods for each line separately. A sequence of micro-periods where the same item is produced on the same line constitutes a lot. In a micro-period only one setup is allowed. Setup carryovers are allowed. The article by Meyr (2002) and the master thesis of Budé (2008), in which an MIP model for Ice cream Production Planning is proposed, have been consulted while different lengths for planning periods are incorporated to the model. Their formulations of changeovers in parallel machines and minimum number of batch requirements have also been very helpful. Lukac et al. (2008) solved the single level, two-machine problem with sequence dependent set up time but sequence independent set up cost problem, using a bi-level MIP approach. Two machines have different cost, capacity and process times and can process all kinds of products. At the first level the products are assigned to the machines while total sequence dependent set up time is minimized. In the second level the production, storage and set up costs are minimized. Although this basic problem instance can be solved in relatively short time, the authors concluded that the biggest burden lies in the solution of the MIP at the second level, which can be problematic for larger size problems. The study by Lukac et al. (2008) and the master thesis by Budé (2008) have been frequently consulted while the changeover and changeover saving constraints are formulated for the reactors in production stage. Doganis and Sarimveis (2008) solved a MILP model for single stage yogurt production plan in short time to optimality using the customized model, including some machine-product dedication, due dates, job mixing and splitting. Since the model is highly customized for the specific industry it is not proved to be applicable for general problems. Although their study considers only single level, it has been very helpful while constructing the capacity and changeover constraints in the packaging stage.

6.2 Model Specifications

The system to be modeled is quite a large and complicated system with many related flows, changeover requirements, different processing times on equipments etc. Hence the mathematical model cannot be constructed fully in the first attempt but some parts have been refined and handled specially with specific simplifications and assumptions.

6.2.1 Incorporating Changeovers on the Reactors

In the production stage when there is a changeover between bases there is a changeover time requirement of several hours. However setup carryovers are not allowed in the model and the last base type produced at the end of the previous period is not known. When the demand structure is examined, it is seen that one of the base types, HEBE, constitute more than 75% percent of the total demand in average. So, it has been assumed that a reactor is set up for HEBE in default and a changeover to and from TALLOW or GEAR should be made in the same period if a production takes place. For the sake of practicality, it has been assumed that there is no changeover time and cost related to production of HEBE but the changeover time and cost are twice the real value for GEAR and TALLOW since both changing over from HEBE and to HEBE is done in the same period. Accordingly, the most efficient way to produce TALLOW and GEAR during the same period in the same reactor is producing them consecutively. In that case, there would be a single changeover from HEBE, a changeover between other bases and a changeover to HEBE again instead of two changeovers from and to HEBE. Hence a changeover saving time and cost have been introduced which are equal to the half of the parameter values whenever TALLOW and GEAR are produced during the same period in the same reactor. This assumption has been modeled using non negative variables which can take only 0 or 1 depending on the related binary changeover variables.

6.2.2 Incorporating Changeovers on the Stamping Lines

Having sequence dependent set up times is one of the most complicating characteristics of the system. On the other hand the scope of the project is providing a medium-term planning tool with a relatively long planning horizon. The sequence dependent setup structure can be modeled in short term scheduling models but not in medium-term planning models. Hence changeover times in stamping lines have been modeled with the help of some assumptions and simplifications.

The change over time on the stamping lines depends both on the flavor of the bar, size of the bar, type of the base used and the stamping line. Sequence dependent setup times between the flavors have not been taken into account. Instead, average changeover times have been used based on the flavor type and stamping line (ct_{fl}). These changeover times include the time required for base type changes as well since each flavor is produced using a single type of base. The calculations have been made with the help of the company supervisors, having the average of the sequence dependent setup times to a product type on a line, adding the base changeover time for the flavors stamped from GEAR and TALLOW and tuning them comparatively. These changeover times are independent of the bar size but additional size changeover times and costs are incurred when multiple bar sizes are produced on the same stamping line during a period. Since the model does not keep track of the sequences, there are some assumptions about the sequence. It has been assumed that when multiple bar sizes are stamped on the same stamping machine, all flavors having the same size are stamped sequentially. So, after having the first flavor setup for one size, the bars with different flavors but the same size will be produced after the flavor changeovers and then there will be a size changeover after which all bars with this second size but different flavors will be stamped having the flavor changeovers in between.

At this moment in time only 2 lines are configured to stamp two different sizes. Line 2 is the only line which is capable of stamping 75 gram bars and line 5 is the only line which is capable of stamping 135 gram bars. Although these sizes have relatively small demands, they are demanded and produced almost in each period. Hence it has been assumed that these lines are set up for these specific sizes in default and there is size changeover requirement whenever 100 gram bars are produced on these lines. At the beginning of each period, there is a setup no matter what was the last item produced at the end of the previous period. Setups cannot be carried over to the next period since additional binary variables are required to represent this situation, which will lead to a further increase of the model size and complexity. This default setup assumption also helps to decrease the additional changeovers due to the missing setup carryovers.

6.2.3 Incorporating Different Period Lengths

First, monthly planning periods were used for midterm production planning. The version of the model having 14 monthly planning periods can be seen in Appendix I. However it was seen that a production plan optimal for the monthly periods is not necessarily optimal or even feasible for weekly periods. When monthly periods are used, the weekly demands are aggregated into monthly demand and the capacities of the lines are aggregated to monthly capacities. In this case the demand of any week during the month is satisfied at the end of the month. This enables having larger production lots leading to fewer changeovers and less capacity usage. On the other hand, when weekly demands are considered, the production lots get smaller, causing more changeover time requirements. In such a system with long changeover hours this makes a huge difference in terms of the available time for processing. Using monthly periods would not make a difference if the orders were given at the beginning of the month and the customer lead time was 4 weeks. However, this is not the case for Mannheim Plant. Orders are accepted at the beginning of each week and the lead time is assumed to be one week. In that case, weekly planning periods provide more realistic and detailed plans.

On the other hand an MIP model with weekly periods for 14 months would be impossible to be solved to optimality by commercial optimization software. Hence, after the situation is discussed with the company supervisors weekly planning periods have been introduced for first N months and monthly periods thereafter. It is assumed that months have 4 weeks. Weekly periods have been used for first 12 weeks, in order to be able to have more detailed and precise production plans for shorter term but aggregate plans for the long term. Only the numbers of parameters, variables and constraints have been increased due to the additional 9 periods (12 weekly - 3 monthly). The value of the cost and capacity parameters is different for first 12 weekly periods and 11 monthly periods.

This means t represent different lengths of periods for different values. It represents a week for t<=12 and represents a month for t>12. This enables the user to have a more detailed planning for the first 3 months and rough cut capacity and aggregate monthly plans for the rest of the planning horizon. In Figure 7, index "n" has been introduced to represent the monthly period for the first 3 months which have weekly periods and used for demand calculations.

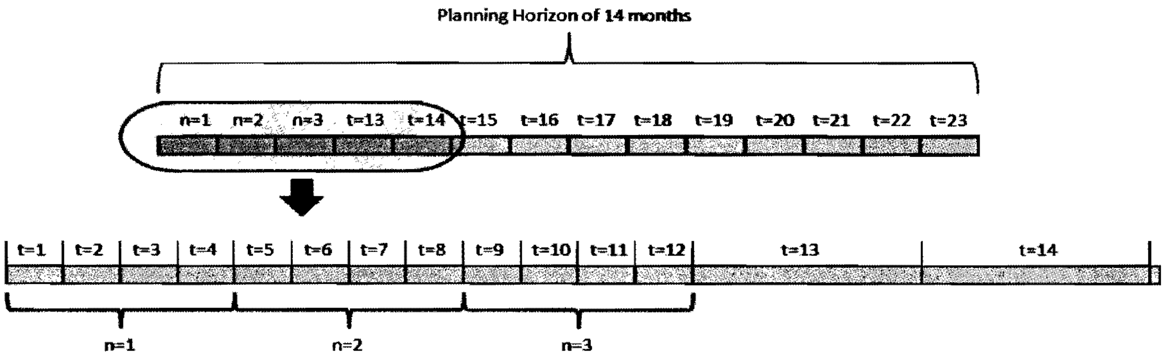

Figure 7: Planning Horizon and Periods

6.2.4 Incorporating Lost sales

Lost sales have been allowed in a later refinement for the sake of feasibility. Lost sale variables per period and penalty cost parameter per product have been included in the model. Lost sales of end products and export demand are represented with different parameters and have different penalty costs per lost sale. Actually, lost sales are not desirable for export demand of the intermediate bases since this would impact the production in the related factories. Lost sale for end products are not desirable either, because in a retail industry the pressure is high from retailers and lost sales would impair the long term relationships with the customer. Although lost sales are allowed, penalty costs have been set relatively high to ensure that demand will be satisfied as long as it is feasible.

6.2.5 Incorporating Processing Times

Different processing times are introduced for fresh and stocked bases on stamping lines because stocked bases take longer time to stamp. Additional variables have been introduced to the model for bars stamped from fresh base and additional parameters have been defined for time required to stamp a bar using fresh base. The number of constraints has been increased, dividing the inflow constraint for stamping lines into two parts.

Additionally, processing times per bar are the same on stamping line l, bundler m and case packer c which is equal to the maximum time required per bar on any of these line. A bar is processed with processing time t_{ilmc}^{fresh} or $t_{ilmc}^{stocked}$ which depends on the freshness of the base, type of SKU, allocated stamping line, bundler and case packer combination. There is no storage possibility after the stamping lines. Stamped bars are directed to the bundlers and case packers on a transportation belt with certain junction points. Since there are no stocking possibilities in between and all the stamped bars have to be bundled and packaged, the flow variables (PB_{fslmt}, PC_{fs1lct}, and BC_{fsemct}) between these stages have been merged into two different allocation variables ($FPack_{ilmct}$ and $SPack_{ilmct}$) keeping track of the freshness of the base, SKU(Stock Keeping Unit=end product) type and stamping line, bundler and case packer combination visited by this SKU. An SKU i is composed of flavor type f, bar size s, bundle size e and secondary package size p. Furthermore, there is no need to use the separate production amount variables for the bundlers ($Bundle_{fsemt}$) and the case packers

($CasePack_{fsepct}$) since now these amounts can easily be calculated using the introduced allocation variables. Now the system modeled became like the one in Figure 8 below.

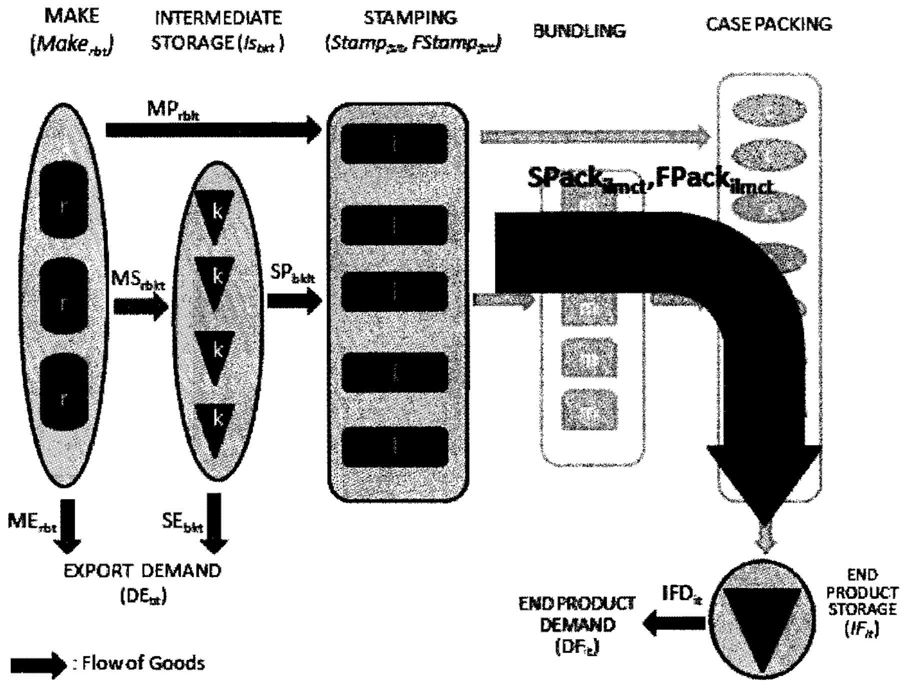

Figure 8: System and the good flows re-modeled

The arrows represent the flows of goods and the names on the arrows represent the variables used in the model to denote these flows. The variables in the parenthesis have been used to denote the production amounts in that process or inventory amounts in the storage locations. The parameters in parenthesis next to the demand points have been used in the model to denote the demanded amounts. The letters on the equipment and storage locations are the indices used in the model.

6.3 Model Assumptions

A mathematical model is an abstract representation of an actual entity which is the Dove Soap Bar production system in this study. Since it is impossible to model a system with all its real characteristics, assumptions have been made to simplify the system and represent it in a mathematical format. The main assumptions and simplifications made during the modeling phase are listed and explained in the following subsections, classified based on the related part of the system. Some of these assumptions related to the extensions are already explained in more detail in the previous section.

6.3.1 Period Length

- Weekly periods have been used for first N months and monthly periods thereafter. It has been assumed that all months have 4 weeks.

6.3.2 Objective Function

- The only costs minimized have been inventory holding, inventory handling, overtime, changeover and OEE loss costs.
- Production cost of processing a single unit on a machine has not been taken into account

- Average costs have been used for each ton of additional big bag handling used as overtime by existing personnel or hired externally.
- The cost differences between overtime cost of regular workers during the weekdays and weekends, as well as the differences between cost of hiring additional personnel during the weekdays and weekends have not been taken into account.
- There are no changeover costs on bundlers and case packers, while changing over from one product to the other one.
- There is a single term to account for the 5% of efficiency loss during production on the stamping lines due to using stored bases instead of fresh bases. The same single loss cost has been assumed to be incurred per ton of base received from storage irrespective of how much time it spent in storage and which storage location supplies the base.
- It has been assumed that no production loss cost is incurred for the bases received from reactors, irrespective of the transportation time spent in between.

6.3.3 Raw Material

- The raw materials have been assumed to be always available and not taken into the project scope.

6.3.4 Production Area

- The reactor is setup for HEBE in default, but whenever GEAR or TALLOW is produced in the same period as HEBE, the changeover to and from HEBE is done in the same period.
- It has been assumed that when TALLOW and GEAR are produced in the same period and in the same reactor, they will be produced consecutively and there is a changeover time saving of 6 hours and changeover cost saving of one setup.
- Maintenance shifts are planned and deducted from the available capacity of reactors during the period. They are parameters given to the model instead of variables decided by the model.

6.3.5 Stamping Lines

- When multiple bar sizes are stamped on the same stamping machine, all flavors having the same size are stamped sequentially. So, after having the first flavor setup for one size, instead of doing the size setup each time, there will be one changeover for format (size) change.
- Size change over is only possible on line 2 (75 gram and 100 gram) and line 5 (135 gram and 100 gram). Size changeover occurs when 100 gram bars are produced on these lines
- Sequence dependent set up times are not taken into account. Instead, an average setup time ct_{fl} has been used.
- At the beginning of each period, there is a setup no matter what was the last item produced at the end of the previous period. Setups cannot be carried over to the next period.
- Sequencing of the lots on machines has not been incorporated. Only the aggregate feasibility can be checked in terms of flows.
- Maintenance shifts are planned and deducted from the capacity during the period for stamping lines, a shift in every two weeks. Corrective maintenances have not been taken into account since they cannot be predicted beforehand.

- Part of the order for a flavor and size combination for a period is produced in one batch in a stamping line, which means that a flavor-size combination can be produced at most once on a line during a period.
- Packaging can only operate 5 days a week and this number is not a decision variable but fixed, i.e. working during the weekend is not an option. Overtime is not possible on the stamping lines.

6.3.6 Bundlers and Case Packers

- Setup time required in bundlers and case packers have not been considered since they were found to be negligible (less than 10 minutes).

6.3.7 End Product Storage

- The final products are kept in a different storage location than the intermediates with a given holding cost. The end product demand is satisfied from stock since the system operated Make to Stock.
- There is no backordering. All of the demand for a certain period should be satisfied at the end of that period. If not, lost sale costs occurs.
- It has been assumed that there is no capacity restriction for end product storage
- Safety stock requirements stay constant over time.

6.4 Formal Mathematical Model

In this section, final version of the mathematical model after all of the specifications mentioned in section 6.2 are applied, based on the assumptions listed in the previous section 6.3 is provided. First, the formal representation of the constraints and objective function together with sets, parameters and variables used is given. Then, the objective function and constraint formulations are explained in more detail.

6.4.1 Declarations and Formulation of the Mathematical Model

Sets

B	= Types of intermediate soap bases, index b, b', B= {HEBE, GEAR, TALLOW}
C	= Case packers, index c, C= {1, 2, 3, 4, 6, 7, 8}
F	= Types of flavors, index f, F= {None, Angelic, ... , ProAge}
F_b	= Set of flavors f, which are made using base b, e.g. F_{GEAR} = {Pacifica, Phuket Bar}
I	= Type of SKU, index i, I= {1, 2, ... , 52}
$I_{(f,s)}$	= Set of SKU's having flavor type f and bar size s, s', e.g. $I_{(None,\ 100)}$ ={1,2,3}
K	= Intermediate storage location, index k, K= {Internal, Repack, Ext 1, Ext 2}
L	= Stamping lines, index l, L= {1, 2, 3, 4, 5}
M	= Bundlers, index m, M= {0, 3, 4, 6, 7}
P	= Periods, (weekly for t<=4N, monthly for t>4N), index t, P= {1, 2, ... , 23}

R =Reactors, index r, R= {1, 2, 3}

S = Sizes of the bars, index s, S= {75, 100, 135}

Parameters

$AllowedRoute_{ilmc}$= 1 if the SKU I can be processed on stamping line l, bundler m and case packer c based on the technical capabilities on the equipments, 0 otherwise

$batch_b$ = Batch size of base b (tons)

BB_t = Available capacity of regular big bag handling personnel during period t (tons)

CB_{mt} = Available capacity of bundler m during period t (hours)

CL_{lt} = Available capacity of stamping line l during period t (hours)

CM_{rt} = Available capacity of reactor r during period t (hours)

$cost_b^{Bchange}$ = Cost of changeover for base b in reactors (€)

$cost^{Fchange}$ = Cost of changing over between flavors in stamping lines (€)

$cost^{hire}$ = Cost per ton of base in big bags handled by additional personnel hired (€/ton)

$cost^{overtime}$ = Cost per ton of base in big bags handled during overtime hours by regular personnel (€/ton)

$cost^{pallet}$ = Cost per ton transferred on pallets including big bag handling cost (€/ton)

$cost^{Save}$ = Cost saving when a changeover saving occurs on a reactor (€)

$cost^{Schange}$ = Cost of changing over between bar sizes in stamping lines (€)

$cost_k^{transFrom}$ = Cost per ton of base transferred from storage location k including big bag handling cost (€/ton)

$cost_k^{transTo}$ = Cost per ton of based transferred to the storage location k excluding big bag handling cost (€/ton)

CP_{ct} = Available capacity of case packer c during period t (hours)

CS_k = Available capacity of storage location k (tons)

ct_b = Changeover time required to start producing base b (hours)

ct_{fl} = Changeover time required to start producing flavor f on stamping line l (hours)

DE_{bt} = Export Demand for base b for period t (tons)

DF_{it} = Demand of SKU i for period t (bars)

h_{kt} = Holding cost of a ton of base in intermediate storage location k during period t including IWC cost (€/ton)

hf_t = Holding cost of a single bar of SKU in end product storage during period t including IWC cost (€/bar)

IF_{i0} = Initial Inventory level of SKU i at the beginning of period 1 (bars)

IS_{bk0} = Initial Inventory level of base b at storage location k at the beginning of period 1 (ton)

$Loss_l$ = Unit loss cost per each ton of stocked base used on stamping line l (€)

$MaxOvertime_t$= Maximum tons of base that can be handled by regular workers during overtime shifts in period t (tons)

$MinBatch_b$ = Minimum number of batches of base b that should be produced each period once the changeover is done (batches)

N = Number of months planned in terms of weekly periods (months)

$penalty_i^{lostsale}$= Penalty cost incurred per unit of unsatisfied demand of SKU i at the end of each period (€)

$penalty_b^{lostexport}$= Penalty cost incurred per ton of unsatisfied export demand for base b at the end of each period (€)

SS_b = Safety stock requirement of base b (tons)

SS_i = Safety stock requirement of end product I (bars)

t_b = Time required to produce a batch of base b (hours)

t_{ilmc}^{fresh} = Time required to process a single bar of SKU i using fresh bases which goes through stamping line l, bundler m and case packer c, which is equal to maximum processing time on any of these 3 stages (hours)

$t_{ilmc}^{stocked}$ = Time required to process a single bar of SKU i using stocked bases which goes through stamping line l, bundler m and case packer c, which is equal to maximum processing time on any of these 3 stages (hours)

ct_l^{size} = Changeover time required when multiple bar sizes are produced on stamping line l in the same period (hours)

ton_s = Conversion factor used to convert number of bars of size s into tons

tr^{save} = Changeover hours saved if base GEAR and TALLOW are produced in the same reactor during the same period t (hours)

$ts^{average}$ = Average processing time per a single bar stamped on any stamping line (hours)

Dependent Variables

$FStamp_{fslt}$ = Amount of bars having flavor f and size s and stamped on stamping line l using fresh bases during period t (bars)

IF_{it} = Inventory level of SKU i at the end of period t (bars)

IS_{bkt} = Inventory of base b at storage location k at the end of period t (tons)

$Lostexport_{bt}$ = Amount of base b demanded by export customers that cannot be satisfied at the end of the period t (tons)

$Make_{rbt}$ = Number of batches of base b produced in reactor r during period t (batches)

$Stamp_{fslt}$ = Amount of bars having flavor f and bar size s stamped on stamping line l using stocked bases during period t (bars)

<u>Other Variables</u>

BBO_t = Amount of additional capacity worked overtime during period t in order to handle big bags (tons)

BBH_t = Amount of additional capacity hired externally during period t in order to handle big bags (tons)

CO_{lt}^{size} = Shows whether multiple sizes of bars are stamped on line l during period t or not (forced with constraints to take a value of 1 if yes, 0 otherwise)

CO_{rt}^{save} = Shows whether base GEAR and TALLOW are produced in reactor r during the same period t or not (forced with constraints to take a value of 1 if yes, 0 otherwise)

$FPack_{ilmct}$ = Amount of SKU i produced from fresh base, which goes through stamping line l, bundler m and case packer c during period t (bars)

$Lostsale_{it}$ = Amount of SKU i, which cannot be satisfied from stock at the end of the period t (bars)

ME_{rbt} = Amount of base b sent from reactor r to satisfy export demand during t (tons)

MP_{rblt} = Amount of base b sent from reactor r to stamping line l during t (tons)

MS_{rbkt} = Amount of base b sent from reactor r to storage location k during t (tons)

SE_{bkt} = Amount of base b sent from storage location k to satisfy export demand during t (tons)

SP_{bklt} = Amount of base b sent from storage location k to stamping line l during t (tons)

$SPack_{ilmct}$ =Amount of SKU i produced from stocked base, which goes through stamping line l, bundler m and case packer c during period t (bars)

$$W_{rbt} = \begin{cases} 1 \text{ if reactor r is set up for base b during period t,} \\ 0 \text{ otherwise} \end{cases}$$

$$Z_{flst} = \begin{cases} 1 \text{ if stamping line l is set up for flavor f and size s during period t,} \\ 0 \text{ otherwise} \end{cases}$$

Objective Function

$$Min\ TotalCost = \sum_t \Bigg\{ \sum_r \left[\left(\sum_b W_{rbt} \right) * cost_b^{Bchange} - CO_{rt}^{save} * cost^{Save} \right]$$
$$+ \sum_k \left(\sum_b \sum_r MS_{rbkt} \right) * (cost_k^{transTo} + cost^{pallet}) + \left(\sum_r \sum_b ME_{rbt} * cost^{pallet} \right)$$
$$+ \sum_k \left[\sum_b \left(\sum_l SP_{bklt} \right) + SE_{bkt} \right] * cost_k^{transFrom} + \sum_k \left[\left(\sum_b IS_{bkt} \right) * h_{kt} \right]$$
$$+ (BBO_t * cost^{overtime} + BBH_t * cost^{hire}) + \sum_l \left(\sum_b \sum_k SP_{bklt} \right) * Loss_l$$
$$+ \sum_l \left(\sum_f \left(\sum_s Z_{fslt} \right) * cost^{Fchange} + CO_{lt}^{size} * cost^{Schange} \right) + \sum_i IF_{it} * hf_t$$
$$+ \sum_b Lostexport_{bt} * penalty_b^{lostexport} + \sum_i Lostsale_{it} * penalty_i^{lostsale} \Bigg\} \quad (1)$$

Constraints

- *Production Stage*

$$\sum_k MS_{rbkt} + \sum_l MP_{rblt} + ME_{rbt} = Make_{rbt} * batch_b \qquad \forall b, \forall r, \forall t \ (2)$$

$$Make_{rbt} \geq MinBatch_b * W_{rbt} \qquad \forall b, \forall r, \forall t \ (3)$$

$$Make_{rbt} * t_b \leq CM_{rt} * W_{rbt} \qquad \forall b, \forall r, \forall t \ (4)$$

$$\sum_b (Make_{rbt} * t_b + W_{rbt} * ct_b) \leq CM_{rt} + CO_{rt}^{save} * tr^{save} \qquad \forall r, \forall t (5)$$

$$CO_{rt}^{save} \geq W_{rbt} + W_{rb't} - 1 \qquad b = GEAR, b' = TALLOW, \forall r, \forall t \ (6)$$

$$CO_{rt}^{save} \leq W_{rbt} \qquad b = GEAR, \forall r, \forall t \ (7)$$

$$CO_{rt}^{save} \leq W_{rb't} \qquad b' = TALLOW, \forall r, \forall t \ (8)$$

- *Intermediate Storage*

$$IS_{bkt} = IS_{bk0} + \sum_r MS_{rbkt} - \sum_l SP_{bklt} - SE_{bkt} \qquad \forall b, \forall k, t = 1 \ (9)$$

$$IS_{bkt} = IS_{bkt-1} + \sum_r MS_{rbkt} - \sum_l SP_{bklt} - SE_{bkt} \qquad \forall b, \forall k, \forall t > 1 \ (10)$$

$$\sum_b (IS_{bkt-1} + \sum_r MS_{rbkt}) \leq CS_k \qquad \forall k, \forall t (11)$$

$$\sum_k IS_{bkt} \geq SS_b \qquad \forall b, \forall t \ (12)$$

- *Big Bag Handling*

$$\sum_r \sum_b \sum_k MS_{rbkt} + \sum_b \sum_k \sum_l SP_{bklt} + \sum_r \sum_b ME_{rbt} + \sum_k \sum_b SE_{kbt} \leq BB_t + BBO_t + BBH_t \qquad \forall t \ (13)$$

$$BBO_t \leq MaxOvertime_t \qquad \forall t \ (14)$$

- *Export Demand*

$$\sum_r ME_{rbt} + \sum_k SE_{kbt} = DE_{bt} - Lostexport_{bt} \qquad \forall b, \forall t (15)$$

- *Stamping Lines*

$$\sum_k SP_{bklt} = \sum_{f \in F_b} \sum_s Stamp_{fslt} * ton_s \qquad \forall b, \forall l, \forall t \ (16)$$

$$\sum_r MP_{rblt} = \sum_{f \in F_b} \sum_s FStamp_{fslt} * ton_s \qquad \forall b, \forall l, \forall t \ (17)$$

$$\left(Stamp_{fslt} + FStamp_{fslt}\right) * ts^{average} \leq CL_{lt} * Z_{flst} \qquad \forall f, \forall s, \forall l, \forall t \ (18)$$

$$CO_{lt}^{size} \geq Z_{flst} \qquad \forall f, s = 100, l \in \{2,5\}, \forall t \ (19)$$

$$CO_{lt}^{size} \leq 1 \qquad \forall l, \forall t \ (20)$$

$$FStamp_{fslt} = \sum_{i \in I_{(f,s)}} \sum_m \sum_c FPack_{ilmct} \qquad \forall f, \forall s, \forall l, \forall t \ (21)$$

$$Stamp_{fslt} = \sum_{i \in I_{(f,s)}} \sum_m \sum_c SPack_{ilmct} \qquad \forall f, \forall s, \forall l, \forall t \ (22)$$

$$FPack_{ilmct} + SPack_{ilmct} \leq AllowedRoute_{ilmc} * \inf \qquad \forall i, \forall l, \forall m, \forall c, \forall t \ (23)$$

$$\sum_i \sum_m \sum_c (FPack_{ilmct} * t_{ilmc}^{fresh} + SPack_{ilmct} * t_{ilmc}^{stocked}) + \sum_f \left(\sum_s Z_{fslt}\right) * ct_{fl} \leq CL_{lt} - CO_{lt}^{size} * ct_l^{size} \qquad \forall l, \forall t \ (24)$$

- *Bundlers*

$$\sum_i \sum_l \sum_c \left(FPack_{ilmct} * t_{ilmc}^{fresh} + SPack_{ilmct} * t_{ilmc}^{stocked}\right) \leq CB_{mt} \qquad \forall m, \forall t \ (25)$$

- *Case Packers*

$$\sum_i \sum_l \sum_m \left(FPack_{ilmct} * t_{ilmc}^{fresh} + SPack_{ilmct} * t_{ilmc}^{stocked}\right) \leq CP_{ct} \qquad \forall c, \forall t \ (26)$$

- *Final Product Demand*

$$IF_{it} = IF_{i0} + \sum_l \sum_m \sum_c (SPack_{ilmct} + FPack_{ilmct}) - (DF_{it} - Lostsale_{it}) \qquad \forall i, \forall t = 1 \ (27)$$

$$IF_{it} = IF_{it-1} + \sum_{l}\sum_{m}\sum_{c}(SPack_{ilmct} + FPack_{ilmct}) - (DF_{it} - Lostsale_{it}) \qquad \forall i, \forall t > 1 \; (28)$$

$$IF_{it} \geq SS_i \qquad \forall i, \forall t \; (29)$$

- *Variable Types*

$$Make_{rbt} \in N \qquad \forall r, \forall b, \forall t (30)$$

$$W_{rbt} \in \{1,0\} \qquad \forall r, \forall b, \forall t (31)$$

$$Z_{fslt} \in \{1,0\} \qquad \forall f, \forall s, \forall l, \forall t (32)$$

$$MS_{rbkt}, MP_{rblt}, ME_{rbt}, CO_{rt}^{save}, IS_{bkt}, SP_{bklt}, SE_{bkt}, Lostexport_{bt}, BBH_t, BBO_t, Stamp_{fslt},$$

$$FStamp_{fslt}, CO_{lt}^{size}, FPack_{ilmct}, SPack_{ilmct}, IF_{it}, Lostsale_{it} \geq 0 \qquad (33)$$

6.4.2 Explanation of the Objective Function

The objective of this model is to find the production and flow amounts per period during the planning horizon, which leads to minimum set up, overtime, production loss, lost sale and inventory costs. The production costs have not been taken into account since there is no information available about production cost per unit base or SKU. On the other hand, when the production is not punished in the objective function in terms of cost coefficients, unnecessary production amounts can be found by the model. In order to prevent this situation, equality constraints are used in the model.

The first term in the objective function is the total changeover cost on the reactors. The total number of setups minus the number of saved changeovers is multiplied by the setup cost for a base change. Note that only the setup variables for GEAR and TALLOW will be added up since it has been assumed that no setup time and cost is incurred for HEBE.

The second term accounts for the handling costs of the bases flowing from production area to the intermediate storage, including the big bag costs and related pallet costs. The third term accounts for the pallet and bag costs incurred during the handling of the bases transferred directly from make to satisfy export demand. The fourth term adds the costs incurred to handle the bases flowing from the storage locations to the stamping lines and export demand. The fifth term calculates the holding cost of the intermediate storage, total tons stored times holding cost per ton in that storage location per month whereas the sixth term accounts for the cost of using additional handling capacity for Big Bag Handling by making permanent personnel work overtime and/or hiring temporary personnel.

The seventh term calculates the efficiency loss costs on stamping lines due to the inefficiencies caused by using stored bases with lower initial temperatures, instead of fresh ones just out of the reactors. The eighth term accounts for the total changeover costs incurred on the stamping lines. At first, only the setup costs due to flavor changes are summed up then the setup costs for format (size) changeovers are added. The ninth term accounts for the holding cost of end products in storage. The tenth term adds the penalty costs for lost export sales that cannot be satisfied at the end of the demanded period and the eleventh term adds the penalty cost for lost sales of the end products that cannot be satisfied till the end of the demanded period. Finally, all these terms are summed over planning periods over the planning horizon.

6.4.3 Explanation of the Constraints

Constraints (2)-(8) are related to the production of intermediate soap bases in the reactors and flow out of the production area. Constraint (2) shows that the flow of bases out of a reactor to storage, to packaging area and to export demand during a period should be equal to the total production amount of each base in that reactor during that period. Constraint (3) ensures that if there is a production of a certain base in a reactor, the produced amount should be at least as large as the minimum number of batches required. Constraint (4) shows that the capacity of a reactor can only be used for a certain base if the reactor is set up for that base during that period. Constraint (5) restricts the total time spent on a reactor for production time of batches and changeovers to be less than or equal to the total available capacity of that reactor for that period. The setup time savings occurring when GEAR and TALLOW are produced in the same reactor during the same period are added to the total available capacity. As explained in more detail in section 6.2, the most efficient way to produce GEAR and TALLOW in a reactor during the same period is producing them in sequence, so that there is no need to change over to HEBE and from HEBE twice. In that case, there is only a single change over between GEAR and TALLOW instead of two changeovers (to HEBE and from HEBE), leading to a time saving of tr^{save} for that reactor. Constraint (6) assigns the value of the changeover saving variable to be positive when base GEAR and base 3 TALLOW are produced in the same reactor during the same variable with the inequality:

$$CO_{rt}^{save} \geq W_{rbt} + W_{rb't} - 1$$

Equality sign cannot be used in order to prevent infeasibilities due to negative values when none of the bases are produced. Since positive values of the saving variable leads to a decrease in the total costs in terms of setup cost savings in addition to the capacity increase in the reactors, the model would always assign the largest possible value to the variable. But in that case, this variable can take positive values even when none of the bases are produced if there were not any additional restrictions. Constraints (7)-(8) ensure that changeover saving is only possible when GEAR and TALLOW are produced during the same period in which case CO_{rt}^{save} takes a value of 1 and it is 0 if the reactor r is not setup for either GEAR ($W_{rbt} \neq 1$) or TALLOW ($W_{rb't} \neq 1$) during period t. . In order to decrease the number of binary variables CO_{rt}^{save} has been kept as a non-negative variable. But it can take only 1 and 0 since it depends on the binary changeover variables.

Constraints (9)-(12) are related to the intermediate storage limitations. Constraint (9) is the inventory balance equation for the first planning period taking into account the initial stock in the intermediate storage location plus the inflow from reactors minus outflow to the packaging area and export demand. Constraint (10) is the inventory balance equation for the later periods till the end of the planning horizon. Constraint (11) restricts the capacity usage in each storage location per period. The maximum tons of bases stored during the period can be the total of inventory form the previous period and the total amount sent to the storage during this period in worst case which should be smaller than or equal to the storage capacity of that location. Constraint (12) states that for each period, the total amount stored in all storage locations for each base should be equal to or larger than the safety stock requirement of that base.

Constraint (13) restricts the capacity usage of Big Bag Handling Personnel, handling the flow from make to storage, from production to satisfy export demand, from storage to satisfy export demand and from storage to packaging area. The total amount handled to and from storage locations cannot be larger than the sum of regular Big Bag Handling capacity, overtime capacity used and the additional capacity hired. Furthermore, constraint (14) ensures that amount of overtime hours used is not larger than the maximum overtime hours allowed per period.

Constraint (15) ensures the export demand per period is satisfied or lost sales occur at the end of the period. The total amount sent from make and storage should be at least as large as the demanded amount during that period minus the lost export sale amount.

Constraints (16)-(24) are related to the production, goods flow and setup requirements on the stamping lines. Constraint (16) states that production on a stamping line from stocked bases during a period should be equal to the flow of bases to that line from storage whereas (17) states that production on a stamping line from fresh bases during a period should be equal to the flow of bases from reactors to that line during that period because there is no storage in between. Since the total flow into the lines is in terms of tons and the produced amount variables $Stamp_{fslt}$ and $FStamp_{fslt}$ are in terms of number of bars, they are converted to tons using the parameter " $tons_s$" , based on the size (gram) of the bars. Constraint (18) allows the capacity usage of a line for a certain flavor-size combination only when the corresponding setup is done. The total amount of production can be at most 0 bars if the changeover variable Z_{flst} is zero. The average stamping time has been used to restrict the capacity usage roughly in this constraint since the capacity constraint already takes into account the total processing and changeover times in more detail. Note that total production includes both bars made from stocked and fresh bases and production times are different.

When multiple sizes of soap bars are to be produced on the same line during the same period, the most efficient way is to produce all flavor of a size successively so that additional setup for format (size) is done only once for the first size changeover and then flavor setup is applied changing between the flavors of the same size, which costs less. In that case, there is a setup time requirement of ct_l^{size} and cost of $cost^{Schange}$. Constraint (19) ensures that the size changeover is applied whenever 100 gram bars of any flavor are stamped on the same line on which 135 gram or 75 gram bars are processed by default. The reasoning behind has been discussed in section 6.2. Constraint (20) is used to assign this changeover variable to 1 whenever it will be positive. This constraint is necessary because the size changeover variable, CO_{lt}^{size}, is nonnegative instead of binary in order to decrease the number of integer variables.

In order to be able to prevent blocked transportation belts, all the packaging stages should have the same processing time on the packaging lines for a production lot, which should be the smallest processing time of the single lines for that product. So the model should keep track of the specific stamping line, bundler and case packer a batch of the end product having flavor f, bar size s, bundle size e and case pack size p goes through during its packaging processes. Also the processing speed differs depending on the freshness of the base used. So two variables have been introduced keeping track of the SKU i produced form fresh and stocked base processed on stamping line l, bundler m and case packer c. For the SKUs not bundled, m would be zero and the bundler m=0 would have no capacity restriction. Constraint (21) and (22) converts the total number of bars having flavor f and size s, stamped on stamping line l during period t, namely $Stamp_{fslt}$ and $FStamp_{fslt}$, into variables called $FPack_{ilmct}$ and $SPack_{ilmct}$, representing packed SKU i s on stamping line l and would continue to bundler m and case packer c from fresh and stocked bases respectively during the same period t. Note that these SKU I s are the elements of $I_{(f,s)}$, which is the set of end products having flavor f and bar size s. Moreover, due to the technical incapability of machines to process some products there are allowed routes for each product. The $AllowedRoute_{ilmc}$ parameter has a value of 1 for each SKU i, which is possible to be processed on stamping line l, bundler m and case packer c. It takes a value of 0 otherwise. The goods flow can only take place on the allowed routes. This is ensured by the following constraint (23),

$FPack_{ilmct} + SPack_{ilmct} \leq AllowedRoute_{ilmc} * \text{inf}$ (Where "inf" is a very large number)

Constraint (24) restricts the total capacity used of a line during a period for stamping and changeovers. The capacity used for processing of the bars from stocked and fresh bases and flavor changeovers cannot be larger than the available capacity minus the size changeover time required when multiple sizes of bars are produced on the same line.

Constraint (25) is the capacity constraint for a certain bundler during the period t. Similarly, Constraint (26) restricts the capacity usage of a certain case packer with the available capacity for that period. Note that the same processing time is used for each stage as explained before. Also the same flow amounts are summed up, but only over different indices, to calculate the total amounts stamped, bundled and case packed because all of the stamped bars should be sent to bundlers or case packers and bundled products should be sent to the case packers since there is no storage option in between.

Constraint (27) is the end product inventory balance equality for the first period, taking into account the initial inventory at the beginning of the planning horizon and constraint (28) is the ending inventory balance constraint for all periods till the end of the planning horizon. The end product inventory is equal to the sum of inventory at the end of previous period t-1 and production during the period t minus the amount satisfied from stock, which is calculated as $(DF_{it} - Lostsale_{it})$. The amount of demand which cannot be satisfied at the end of the demand period is lost. Also, delivering more than the demanded amount is not possible since lost sale variables are set nonnegative. Note that there is a delivery of SKU i during the period t if and only if there is demand for that SKU during that period since the customer lead time has been assumed to be one week. Constraint (29) is the safety stock constraint, stating that stock level of SKU i should always be greater than or equal to safety stock level determined by the company for that SKU at the end of each period t.

Constraints (30)-(33) declare the variable types. The number of batches of a certain base produced in a reactor during a period has to have integer values as stated in (30) whereas setup variables of the reactors and stamping lines are binary variables, taking a value of 1 is a certain product is produced on a certain machine during that period and 0 otherwise, as can be seen in (31)-(32).Finally, constraint (33) assigns non-negative real values to all of the other variables used in the model.

Additionally there are constraints fixing the certain flow and production variables to 0, due to the technical capabilities of the equipments in each stage. For example reactors 1 and 2 con not produce base type TALLOW, so $W_{1TALLOWt} = 0 \text{ and } W_{2TALLOWt} = 0$ for all periods.

7 DATA REQUIREMENTS

In this chapter the input parameters and additional information required to use the mathematical model for production planning of the system under investigation are discussed in detail.

7.1 Planning Horizon

The planning horizon has been set to 14 months by the company supervisors. The production plans are made yearly to be able to capture any kind of seasonality effects in demand if exists and possible capacity restrictions in ahead of time, enough to apply the required modifications. The company wants to see the planning for even 2 months more than a year to be on the safe side.

7.2 Product Types and Properties

Types of intermediate bases to be produced, flavors of bars to be stamped, types of bases used to stamp that specific flavor and sizes of bars to be cut should be given to the model as input. Each flavor has a specific base requirement so type of base is not required to be mentioned explicitly for the definition of SKU after the production stage.

As mentioned before each SKU consists of a specific flavor, bar size, bundle size and pack size combination. This specific combination of an end product automatically restricts the equipments to be used during the packaging stage based on the capabilities of the lines. Since the change over requirements and line capabilities depend on the flavor and size combination to be stamped on the stamping line, the flavor and size of each SKU should be provided.

7.3 Equipments and Capabilities

The number of equipments and their capabilities are required to make a realistic and effective planning. In the production stage HEBE and GEAR can be produced on all reactors where as TALLOW can only be produced by one reactor. Some sizes of bars can only be stamped on certain stamping lines and changing between sizes requires changeover time and cost depending on the line properties. Similarly, some bundlers can do only certain sizes of bundles, some case sizes can be packed only by certain case packers. The processing times of a single bar also depends on the equipment used during packaging of that specific product.

7.4 Batch sizes and minimum production amount

Intermediate soap flakes, i.e. DEFI bases, are produced in reactors using a batch production system as seen very often in processing industry. The production starts after the batch is closed and cannot be interrupted until the end of the production process since a chemical reaction is taking place with certain raw material ratios and temperatures. For sake of chemical requirements and economies of scale there are fixed batch sizes and minimum number of batches to be produced of the same base once the required set up is done. Batch size is basically the maximum capacity of the reactor for that base because the production is started only when the reactor is full.

7.5 Capacities

Capacity available per period of each reactor, stamping line, bundler and case packer is given as input to the model. This available capacity basically depends on the number of operating days, days per period and shift per day. The reactors operate 7 days a week and 24 hours per day for all year.

There are also planned maintenance activities, which can block the reactor for 1 week. These planned maintenance hours are deducted from the available capacity as well.

The packaging stage including the stamping lines, bundlers and case packers operate 5 days a week and 24 hours per day all year long. The numbers of shifts are fixed. There are planned maintenances on stamping lines 1 shift in each 2 weeks for Total Productive Maintenance (TPM) and larger maintenance operations 1 or 2 times per year taking longer time. These maintenance hours are deducted from the available capacity per period.

7.6 Production Times

Production rates of the equipments differ based on the process they are involved in. Also equipments doing the same process have different rates based on the technical specifications. The production rates of each stamping line, bundler and case packer is different for each flavor-size-bundle and case pack combination of the end product. Also, there is 5% of difference between time required to process stocked base (received from storage) and fresh base (received from reactor). The equipments have been assumed to be stable and the production rates do not fluctuate over time, hence the production time for each combination has been assumed to be fixed in time (do not change per period). On the other hand, the production time required for a single batch of each base is different but do not depend on the reactor.

7.7 Efficiency Loss Cost

There are some discussions on whether the properties of the stored bases are different than the properties of the flakes directly go to the stamping lines. At this moment there is no restriction on storage time. However, there is an additional cost incurred for the bases sent to stamping lines from storage due to the decreased temperature during storage. The efficiency loss on the stamping lines is assumed to be 5%.

7.8 Change over times and costs

Changing between types of bases involves changeover times and costs. In reactors while changing from GEAR to HEBE or from TALLOW to HEBE, part of the reactor should be cleaned, which requires a certain set up time and material loss costs.

There is a complex setup structure in stamping lines which involves sequence dependent set up times and costs. Several hours of setup time is required to change between base types used in the bar production, between sizes of the bars to be stamped and also between colors and fragrance depending on the strength. Changeover times also depend on the stamping lines. Each of these set up operation cause material losses and is highly labor-dependent so additional costs are involved in addition to the opportunity cost of the capacity loss on the lines.

7.9 Storage Capacity

The capacity of each storage location for intermediate inventory is different. The capacities of internal storage spaces and one externally hires warehouse (external storage space I) are fixed. Since it is always possible to hire external storage space at a certain cost, the capacity of the external storage II is set very high. It has been assumed that there is no storage limit for end product storage.

7.10 Overtime and External Hiring Capacities and Costs

Overtime is only possible for Big Bag Handling Personnel working in the intermediate storage of the bases, handling of the bases into the storage location and out of the storage location. Handling capacity is used whenever DEFI bases are taken into storage locations from reactors, transported to stamping lines from storage locations or sent to satisfy export demand. Handling capacity is based on the number of current Big Bag Handling personnel and tons of DEFI base can be handled by one personnel per shift. 20 tons of DEFI base is handled per shift per person on average. Each regular personnel can make 2 overtime shifts per week at maximum and external labor can be hired at certain cost if maximum overtime is not enough. There is no restriction on the number of external personnel to be hired as long as the hiring costs are paid. These external workers are hired only per week and cannot work overtime. An overtime shift costs 50% more than a regular shift and hiring external personnel costs even more due to the administrative costs involved. The cost differences between overtime cost of regular workers during the weekdays and weekends, as well as the differences between cost of hiring additional personnel during the weekdays and weekends have not been taken into account since the planning has not been done in daily basis.

7.11 Handling and Transportation Costs

Apart from the labor costs, additional handling costs occur because DEFI bases are stored in Big Bags and on pallets. These costs do not differ between storage locations. In addition to the Big Bag and pallet costs there are also costs related to the transportation of these bags into and out of the storage locations. The transportation of the goods within the plant and in the warehouse is done by forklift. The transportation of the intermediates to the offsite storage point is done by trucks which is more costly. Transportation costs depend on the storage location.

7.12 Holding Costs

There are two different types of inventory holding costs: Intermediate inventory holding costs and end product inventory holding costs. Holding cost per ton of DEFI base does not depend on the base type but differs among storage locations and periods. Holding cost per SKU depends only on the period. Both holding costs include the Inflation Charge on Working Capital (IWC) cost, which is calculated at the end of the 4^{th} week of each month. So, inventory holding costs are larger for 4^{th} week of each month compared to the first 3 weeks of the month.

7.13 Initial Inventory

The actual inventory amounts in the intermediate and end product storage locations at the beginning of the first planning period should be taken into account. Since the planning is made for an already running production system and the first planning period is not the first production period, the initial state of the system should be incorporated to the model.

7.14 Safety Stock Requirements

The system operates make to stock and demand cannot be known for sure before production takes place, so a certain amount of product should be kept in stock in case of unanticipated high demand occurrences. There are safety stock restrictions for intermediate storage and end product storage. However safety stock levels are negligible for packaged goods because stock levels are controlled with a vendor managed system using SAP systems of the related parties. Safety stock amounts depend on the base and SKU type but not on time period, because the seasonality in demand is negligible and the demand pattern is assumed to stay constant over time.

7.15 Demand Volumes

Demand stochasticity is not considered and the planning is made based on the forecasts. These forecasts have been used as input to the planning model. The demanded amount for both exported bases and end products are delivered at the end of each period.

7.16 Lost Sales

It may not be possible to satisfy all of the period demand for all intermediate and end products. In that case lost sales occurs. Backordering is not allowed so whenever part of the period demand cannot be satisfied, it is not possible to satisfy them during the later periods. The penalty costs related to lost sales are not easy to estimate since they include loss of goodwill costs in addition to the selling price and contracted penalty costs. Penalty costs depend on the product type based on the price and importance of that product within the product range. Although lost sales have been included to the model for the sake of feasibility and reality, the penalty costs have been set really high because they are highly undesirable for the company. Especially for the end product demand, responsiveness should be very high because customer service level is set to 99.6% for distribution centers.

8 SOFTWARE IMPLEMENTATION

For the implementation of the planning tool, different software packages have been utilized. First of all, the main part of the tool, the MIP model, needs to be coded in a solvable format using an optimization and modeling software. Then the mathematical model should be solved using a powerful and reliable solver. Finally the inputs of the model and output of the solution should be displayed in an understandable format, which is easy to analyze in a spreadsheet. In this chapter the reasoning behind utilization of the software and the outcomes are discussed.

8.1 Modeling Software

AIMMS, acronym of Advanced Integrated Multidimensional Modeling Software, is used as the modeling software. It is a very useful friendly tool to model complex mathematical problems in an organized way under different sections, supported with extensive tutorials and help menu, easy to learn and practical to use for industrial applications compared to the other well-known modeling software such as GAMS, LINDO and Excel Solver. The modeling language is very high level and the low level coding of the constraints are automatically done by AIMMS. Some common programming functions can also be used like if, while, for loops to write the constraints more efficiently. The academic version of the software has no limitations for number of variables, constraints and integers so large and complex models can be constructed and solved. Another motivation to use AIMMS was its capability to be linked to Excel spreadsheets. The employees in Unilever and Mannheim Plant are both familiar with Excel spreadsheet operations and use it frequently for planning purposes, they find it convenient to work with Excel and have the modeling and optimization tool operate in the background. Furthermore, Unilever has already some experience with using this software and have conducted some projects using it successfully in the past. Hence the company supervisors also prefer to utilize AIMMS. The model has been re-written in AIMMS language as displayed in Appendix II. Some additional set and parameters have been defined and used in addition to the mathematical formulation in order to write some of the constraints more easily. The importing of the input data from Excel files and exporting of the output to Excel has been done using Excel Procedures. The sets, parameters, variables, constraints, objective function elements and Excel Procedures can be found under separate model sections.

8.2 Optimization Solver

The model is solved using ILOG CPLEX 12.1. The AIMMS uses XA 14 and 15 as the default solver for MIP and MILP. Attempts to use these default and free solvers to solve the MIP model showed that XA 14 is not capable of solving Mixed Integer Problems of large sizes so it was eliminated after few trials. Attempts with XA 15 showed that it has no limitations in terms of number of variables, constraints and integers. However after several trials to solve the whole model and smaller versions, it has been concluded that the solver was not efficient in terms of branching strategy and powerful enough to solve the even small sizes of the model in reasonable time. Reasonable time has been defined as less than 2 hours for small model sizes used for validation and sensitivity analysis and 12 hours for large sizes of the model to be used in mid-term planning. ILOG CPLEX 12.1 is a very powerful, fast and efficient solver for MIPs, with built in heuristics and Branch & Bound strategies. Academic Initiative of IBM provides the license for that solver to the academicians and the license can be linked to AIMMS. All model runs have been performed on a PC with Intel® Core™ 2 CPU 1.83 GHz and 2 GB RAM. Example optimization windows in AIMMS can be seen in Appendix III.

8.3 Spread Sheet Operations

Inputs are imported to AIMMS from Excel spreadsheet and outputs are displayed in another Excel spreadsheet.

The input sheets have been constructed using data ranges so that when the numbers of equipments, lines, reactor or periods are changed the ranges are updated automatically so there is no need to re-code the Excel procedures in AIMMS. When the values of the parameters are modified, the main initialization in AIMMS should be re-run to import the new data set to the model in AIMMS. The model is solved and the outputs are exported to the Output Excel sheet after each run of the Main Execution in AIMMS. It should be noted that only the variables having non-zero values are printed in flow and production amount tables where as all values, together with the zeros, can be seen in cost, time and changeover tables. The data in Excel can easily be used to make additional calculations, analysis and comparisons.

9 VERIFICATION AND VALIDATION

This chapter discusses how the mathematical model built and explained in the previous chapter has been verified and validated.

As stated in Babuska and Oden (2004), models are an abstraction and representation of the reality, so they can never fully mimic the reality under all conditions. On the other hand, a model should be reliable and usable enough to be utilized for decision making. Tedeschi (2006) emphasizes that Verification and Validation of a model plays a crucial role in determining its usability. However, there are not universally accepted definitions of these terms and their meanings in this research study should be explained explicitly.

Kleijnen (1995) defines Verification as being mainly about debugging the computer program in order to ensure that there are no programming errors left. Harrison (1991) differentiates *verification* from *validation* as follows; *verification* is designed to ensure that a mathematical model performs as intended, while *validation* examines the broader question of whether the intended structure is appropriate, whether it is an accurate representation of the system under study.

There is neither a standard theory nor a set of tools and methods agreed upon to be used for verification and validation purposes. Hamilton (1991) proposes that *validation* is used to assess the extent to which a model is rational and fulfills its purposes. It is comprised of three tasks: (1) verification (design, programming, and checking processes of the computer program), (2) sensitivity analysis (behavior of each component of the model), and (3) evaluation (comparison of model outcomes with real data).

These steps require an experimental design with adequate model size and input data. Section 9.1 explains the data set used during the analysis. In the following section 9.2, verification is discussed. In section 9.3, the model is tested for basic sanity with extreme zero demand and zero cost cases. After that, sensitivity analysis conducted with extreme values for certain model parameters, cost coefficients and some of their combinations are given in section 9.4. Finally, in section 9.5 the evaluation of the model is made comparing the outcomes of the model and actual production amounts for a small data set.

9.1 Experimental Design

In order to test the general usability of the constructed mathematical model, current input parameters of the case study object, Mannheim Dove Soap Bar Production Plant, have been used. The appropriateness of the model to this production environment has been discussed in the previous chapters.

For the sake of practicality the whole data set has not been used. When the model is solved for 52 SKU families and 23 planning periods, no solution within an acceptable optimality gap is obtained in a reasonable time (less than 2 hours). The relative optimality gap is the difference between the best integer solution found by the solver and the best solution of LP relaxation in that node of the branch and bound tree divided by the best integer solution. The formulation used by AIMMS is as follows:

Abs (Best Integer Solution - Value LP Relaxation) / (eps + Abs (Value LP Relaxation)) where eps is a very small positive constant, e.g. 1e-6.

For moderate sizes of the model a feasible integer solution with a gap of 5% can be found in minutes but it takes longer time to make the gap closer, it drops to 3% after several hours. For smaller sizes of the model the solution with a gap of 3% can be found in seconds, drops to 0.1% after minutes but takes hours to drop below 0.01%.

The model size has been preferred to be relatively small considering the time restrictions because many optimization runs for several different values of parameters will be used for the analysis. The experiment set designed for the validation purposes has 8 SKUs. The SKUs have been selected such that the product types having the most percentage in the yearly cumulative demand are represented. The total demand has been allocated to the SKUs according to their cumulative demand percentages to keep the total demand per period same as given by the company. Number of planning periods has been set to 4. The relative optimality gap has been set to 0.01%. The solver finds optimal solution within 3 minutes within the relative optimality gap tolerance. The data validity has been checked by the company supervisors.

9.2 Verification

The model has been coded in AIMMS. AIMMS has its own internal debugger which checks the consistency of the program, in terms of variable and constraint definitions, set indices, the consistency of the units and set elements in addition to the basic coding errors. These checks are repeated each time the model is modified and saved. The debugger of AIMMS has already verified the model in order to be able to run the code to find the optimal solution. The input data used by AIMMS is checked after the input data is taken from the Excel sheet, to see whether they are correct or not. Also a very small size model with 2 SKUs and 2 periods has been solved and the output data in Excel has been checked with recalculating the capacities used and related costs with the decision parameters found in a separate Excel sheet. Also after each run the math program inspector in AIMMS has been used to check whether the constraints are violated or not. Total capacities of the resources used and the total production amounts have been checked and it has been seen that the constraints and the objective function are coded correctly and operates as intended.

9.3 Extreme value check

Before moving to the sensitivity analysis the model has been checked for the most basic situations with zero costs, zero demand. These are the most fundamental and primitive checks helping to see whether there are obvious vital mistakes in the model or not, whether the model is sane. If a model cannot pass these checks there is no point to do sensitivity analysis before remodeling.

9.3.1 Zero Cost

When all costs are set to zero, the model finds the optimal solution in a second with total cost of zero. Nothing is produced, all demand is lost sale and the initial inventory is kept in stock. Actually there are no costs related to delivering the end products from inventory but the model starts branching from the lost sale case. Since there are no lost sale costs, all demand can be lost and no deliveries or production required. When the optimal solution is found the model stops searching. The solution where the initial inventory is used to satisfy part of the demand is an alternate solution and can be found if the branching priorities are changed.

9.3.2 Zero Demand

When the demand for SKUs and exported soap bases are set to zero for the whole planning horizon, but the cost coefficients are left as original, the solver finds the optimal solution in a second with a objective value equal to the total holding cost of the initial inventory in stock during the whole planning horizon. No production or delivery is made as expected.

9.3.3 Extremely High Demand Values

Another basic check has been done with extreme demand values. The demand amounts are set to 10 times larger than the original input data. It is expected that the model should produce as much as the capacities of the lines and the remaining of the demand is lost. The utilizations are close to 100% depending on the technical capabilities and change over times. All capacity hours on the stamping lines are used. The total cost value is much larger than the value found using the original input data. When only end product demand is increased it is seen that reactor utilizations do not change much since the bottleneck becomes the capacities of the stamping lines.

When a single demand value of a single SKU in period 4, which can be produced only by a single resource combination (stamping line 5-bundler 0), was set to 10 times larger, it has been seen that this equipment combination is reserved by this product mostly during 4 periods, inventory is built starting from the 1st period. Only during the 1st period the remaining capacity is used for another SKU, ensuring all the necessary inventory amount is produced for the demand of 4th period. When the single demand has been moved to week 3, although the equipments required for that product used almost fully, capacity during 3 weeks is not enough to produce all the demand and there has been lost sales. It is also realized that the extra production taking place in the specific line for the other product is transferred to another available line in case of insufficient capacity for production of Pacifica-48x75g-gear. The model behaved as expected in case of explained extreme demand scenarios.

9.4 Sensitivity Analysis

After the sanity checks with the most basic cases have been completed and passed successfully, the model has been tested whether it is behaving as expected in case of input parameter changes. The sensitivity analysis has been conducted to see the impact of differences in single input parameters and some of their combinations on the decision variables and objective function value found by the solver. Furthermore, besides helping to validate the reliability of the model, these analyses also have provided insight about the importance of precision and value of these parameters examined. Based on the sensitivity of the model to an input parameter, the company may decide to tune some of the values to achieve cost improvements. The robustness of the production plan found using the model in case of slight differences in the parameter values is investigated in sensitivity analysis. The expected change in the plan when the values of some input parameters are slightly different than the estimated values shows the robustness of the model as well as the relative attention to be paid during estimation of these parameters.

Sensitivity analysis for LP models is provided automatically by most of the commercial solvers available. However for MIP problems either sensitivity values are not provided at all or are meaningless and analysis should be done separately by the modeler himself. Detailed analysis for each parameter cannot be done for a model of this size but overall conclusions can be made after examining the solution of few trials with restricted number of different values. Since this analysis has been done to validate the general usability of the model, test cases with predictable outcomes and rather extreme values have been preferred.

9.4.1 Lost Sale Penalty Cost

When lost sale costs were set to zero, no production took place and most of the demand was lost. Only the initial inventory in excess of the safety stock requirements was used to satisfy the demand in order to avoid the inventory holding costs. When the lost sale penalty costs are high no lost sale occurs as long as there is available capacity for production. There is no production cost coefficient in the objective function but there are still changeover costs to start processing of a product, both in the production and packaging area introducing a tradeoff between producing and having lost sales in the existence of moderate lost sale penalty costs. The capacity is enough to satisfy the demand and lost sale costs are very high, so lost sales only occur when the cost is lowered considerably. So, in order to see the impact of this tradeoff the lost sale penalty cost was set to 10% of its original value. In this case, lost sales of exported bases occurred. Since the batch times are longer and changeover costs are higher for the bases, the model prefers having lost sales for export orders rather than end products. It can be said that due to the high penalty costs the solution is quite robust in case of differences in lost sale penalty costs. The relation between the total cost and lost sale costs can be seen in Figure 9 below.

Since this analysis has been conducted as indicated in the experimental design, the absolute cost values do not represent the actual costs so they are not found very relevant. The main objective of the analysis is examining the relative changes in the values in case of parameter value increases or decreases. Therefore, percentage differences have been displayed for the sake of visibility in the figures provided in this chapter.

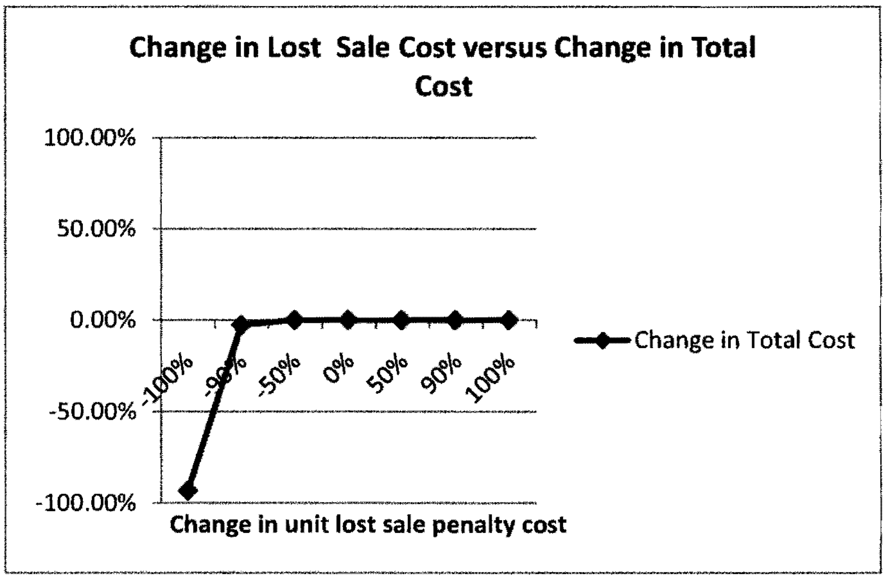

Figure 9: % Change in total cost per % change in unit lost sale penalty cost

When lost sale costs for exported bases were kept as in the original data but the lost sale penalty costs for end products were set to 1% of its original value still no lost sale occurs because lost sale costs for end products are still high. When lost sale cost for export base was the same and lost sale costs for end products were set to zero, all of the end product demand larger than the initial inventory was lost but still production took place in the reactors to satisfy the export demand as expected. It can be concluded that the solution is robust in case of small differences in unit lost sale cost due to the high value of these costs.

9.4.2 Changeover Cost

Changeover costs play an important role in the total cost and solution found by the model since there are quite high costs related to each changeover. These are the only costs directly related to the production decision.

First, in order to see whether the model is behaving as expected in extreme cases, change over costs have been multiplied by 10. It was seen that still no lost sales occurred and all demand was satisfied. However more inventory was kept in stock and handling costs increased as well, to have longer production runs once a changeover had been done and to decrease the number of total changeovers. Having lost sales is still more expensive than making changeovers. Then, even a more extreme case has been examined and the changeover costs were multiplied by 100 while lost sale costs were kept the same. In that case handling and holding costs increased even more. The model decreased the number of changeover by using the stocked bases more often despite the OEE loss costs and transportation costs involved instead of having lost sales.

When changeover cost was set to 0, total cost value and the solution found did not change dramatically due to the existence of handling, holding and lost sale penalty costs. Increasing the unit changeover costs did not change the solution till extreme values (higher than 1000%) because of limited capacity and high lost sale costs.

When changeover cost was 100 times larger and lost sale cost was set to 10% of the original cost, still no change was observed in the solution compared to the case with original lost sale costs. Then more extreme case with 1% of the lost sale penalty cost costs was examined to check whether the model is behaving as expected. In that case it was seen that most of the demand is lost. Stamping lines were used only for a single flavor-size combination and once a setup had been done, whole capacity was used since the holding costs are smaller compared to the changeover and lost sale costs. The analysis showed that increasing or decreasing the changeover costs dramatically do not only change total cost but they are also related to the holding and handling costs. The relation between the change in changeover costs and change in total cost can be seen in Figure 10.

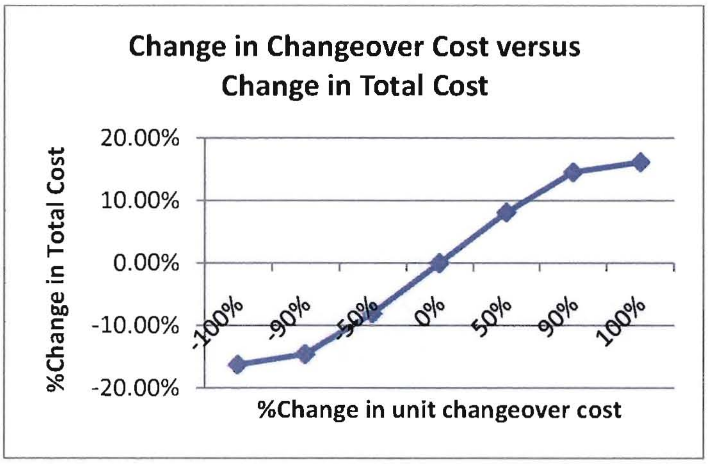

Figure 10: % Change in total cost per % change in unit changeover cost

The changes in holding costs, changeover costs, handling costs and total cost per change in unit changeover costs can be seen in the Figure 11 below.

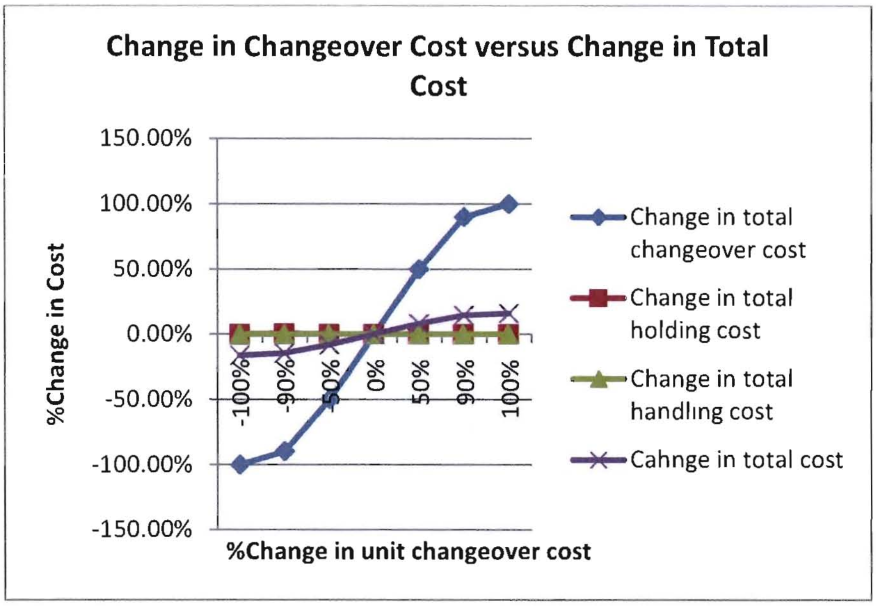

Figure 11: % Change in cost terms per % change in unit changeover cost

It can be seen from the figure that the small to moderate changes in changeover costs do not impact the other cost terms. Holding and handling costs almost stays the same for the +/- 100% range of the changeover costs. It can be concluded that other costs and solution are robust to small differences in unit changeover costs.

9.4.3 Inventory Holding Cost

Inventory costs play an important role in the cost structure with costs depending on both location and period. On the other hand their effect is somewhat limited due to the other handling costs, transportation costs, OEE loss cost and safety stock restrictions related to the stock keeping decisions. When inventory costs are increased the line utilizations are decreasing in order to prevent more than necessary production per period and stock levels are decreased. This impact may be more observable when extreme values are tried. When inventory costs were increased 1000 times, they became larger than penalty lot sales. The model is expected to prefer having lost sales to keep stock. As expected, in that case lost sales for end products were observed especially during the later periods because inventory was not built up from the previous weeks when weekly capacity was not enough to produce all of the weekly demand. In order to decrease the inventory levels and prevent lost sales, stocked bases were also used despite the OEE loss costs involved. Decreasing the inventory costs has led to an increase in utilizations and stock levels. Changeover costs decreased slightly as well due to this increase. When inventory costs were decreased to zero, production took place mostly during the earlier weeks and production runs were longer to decrease the changeover costs. There were fewer changeovers and once the line was set up for a product, its whole capacity was used especially for the earlier periods. Hence change over costs also got lower in addition to the decrease in the holding costs as expected. This output has supported that model gives solutions in line with expectations.

Impact of inventory holding costs may be more visible when modified in combination with other costs. When changeover costs and inventory costs were increased 100 times at the same time, the model preferred having lost sales instead of building up stock and having the same changeover in two consecutive periods. When holding costs were decreased and changeover costs were increased, the amount of inventory kept increased even more and there were less changeovers compared to the situation where only changeover costs were increased due to the decreased stock keeping costs as can be predicted.

Also, the change in the total cost versus changes in unit holding costs is investigated for 100%, 50%, 0% and -50% and -100%. The sensitivity of the total cost in case of holding cost deviations can be seen in Figure 12. The correlation between the unit inventory holding costs and handling costs, changeover costs and total cost can also be seen.

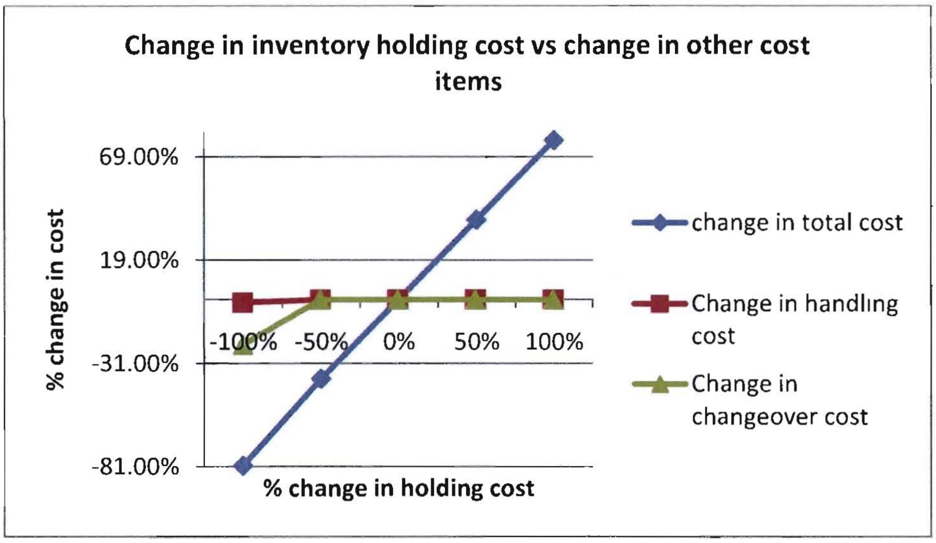

Figure 12: % Change in cost terms per % change in unit inventory holding cost

This analysis shows that the small differences in unit holding cost would not affect the solution significantly. The total cost responds almost linearly to the holding cost modifications and the solution is robust to these changes. Note that these costs are smaller than 0.1 €/per product and even an increase of 0.1 is a large modification hence precision is important.

9.4.4 Handling Costs

The impact of handling costs is expected to similar to the impact of inventory holding costs. Handling costs consist of transportation costs to and from storage locations, pallet costs and big bag costs used to store intermediate soap bases. Examining these cost items one by one is not preferred because this would require much time besides would not provide a different insight because they are all related to each other and effect the solution in the same direction. A decrease in handling cost would lead to increase in inventory levels and increase in handling costs would lead to decreasing inventory levels. It should be kept in mind that only handling of intermediate storage is considered in the model so the impact is mostly on the production and stock decisions of intermediate bases.

When all handling costs were set to zero there was a slight increase in the total inventory kept in the intermediate storage and a small decrease in the total changeover costs, but due to the existence of inventory and OEE loss costs the impact was not as obvious. As handling costs were set to 100 times larger lost sales occurred for export demand of bases. Instead of paying the pallet and big bag costs the model preferred having lost sales. Less production took place in the reactors to decrease the transportation costs to the storage and changeover costs. However, lost sale penalty costs were still higher for end product demand and some stocked bases had to be used in the packaging stage in order to prevent lost sales in that stage despite the handling and OEE loss costs involved.

When inventory and handling costs were decreased at the same time the impact was expected to be more evident. But again although a slight increase was realized in intermediate storage amounts the solution did not changed much compared to the case where only inventory costs were zero. And when they are modified in the opposite directions, the impact should be dampened and inventory levels are not expected to deviate much. As expected, increase in the total cost, increase in the lost sale amounts and decrease in the inventory levels were less, compared to the case when only handling costs were increased. On the contrary, when inventory holding costs were decreased, instead of using stocked bases, products were packaged in the earlier periods and kept in stock to prevent lost sales. Still, lost sales occurred for exported bases due to the increase in the handling costs and fewer changeovers were made. It can be concluded that the solution would not be very sensitive to the deviations in the handling costs as long as the production capacities in the reactors are sufficient to satisfy demand. But, total cost changes significantly with change in handling costs since they constitute a considerable part of the total costs.

Also, the change in the total cost versus changes in unit handling costs has been investigated for 100%, 50%, 0% and -50% and -100%. The sensitivity of the total cost in case of handling cost deviations can be seen in Figure 13. The correlation between the unit handling cost and inventory costs, changeover costs and total cost can also be seen.

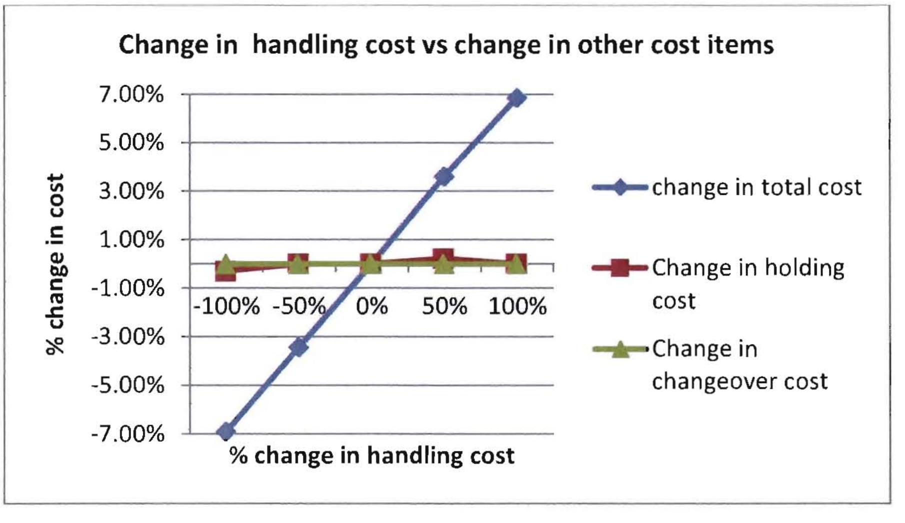

Figure 13: % Change in cost terms per % change in unit handling costs

It can be seen from the figure that the impact of the differences in the unit handling cost is smaller compared to the holding cost. This is because holding cost constitute larger portion of the total cost. The impact of the handling costs are only on the production stage, which is not the bottleneck. So, it can be concluded that the solution is robust to small handling cost modifications.

9.4.5 OEE Loss Costs

As mentioned before OEE loss costs arise due to the efficiency losses occurring when stocked bases are used in stamping lines instead of fresh bases directly received from reactors. These costs are quiet high and their impact on the total costs and optimal solution should be analyzed. OEE loss costs restrict the usage of bases in stock, causing slow turnover in intermediate storage and more changeover requirements to satisfy demand for soap bases from packaging lines in each period. OEE loss costs together with transportation, handling and inventory holding costs dampen the impact of high changeover costs in reactors. If there were no additional costs other than the opportunity cost of higher processing times related to the stocked bases, then OEE loss costs would be zero. In that case, it was seen that usage of stocked base increased, the total cost decreased slightly, but the change in the solution and the costs was not very significant because processing times for stocked bases were still higher than the fresh bases so model prefers using fresh bases mostly in case of high stamping line utilizations. The slight decrease in the total cost was due to the decrease in holding and handling costs which is saved as a result of a decrease in production amount in the reactors. But in case of strict capacity restrictions for reactors rather than packaging lines, decreasing the OEE loss costs would have larger impact on the solution.

9.4.6 Demand Levels

The solution and the total cost is very sensitive to the demand differences of packaged items, i.e. end products, due to the high utilization of the stamping lines. The impact of the demand for exported intermediates is not that pronounced since the demand levels are lower, batch sizes are larger and the utilizations of the reactors are low. For example, when the demand for all end products was increased by 10%, the total cost increased by 260%. When the individual cost terms were examined, it was seen that the difference is mostly due to the 4 times increase in the total inventory holding cost. The other cost terms almost stayed the same but the inventory cost increased dramatically. Since the utilizations are already high, the demand increase can be satisfied by producing for future demand whenever there is excess capacity and keeping stock for several periods.

Next, the end product demand was decreased by 10%, and it was seen that the total cost decreased by 35%. The difference is again largely due to the 50% decrease in the inventory holding cost compared to the other cost items. The changeover and handling costs decrease as well but the difference is not that significant. The decrease in demand eliminates the requirement to keep stock for long time, so the holding costs decrease immediately. The changeover cost is affected less, because while the number of changeovers is increasing not to keep stock and produce whenever a product is demanded, they also decrease since more available capacity enables more effective allocation of the lots to the lines. OEE loss costs, handling costs and OEE costs are more related to the intermediates and since the capacity in the make are is not the bottleneck, these costs are not impacted that much. The comparison of the costs for base case, 10% demand decrease case and 10% demand decrease case can be seen in Table 1 below.

Cost Terms	Base case	90% demand	110% demand
Holding Cost	0.00%	-47.64%	391.62%
Handling Cost	0.00%	-10.14%	-0.37%
ChangeOver Cost	0.00%	-5.71%	-2.54%
BBH Cost	0.00%	0.00%	0.00%
Lost Sale Cost	0.00%	0.00%	0.00%
OEE Loss Cost	0.00%	-100.00%	-83.19%
Total Cost	0.00%	-35.52%	268.07%

Table 1: Comparison of the cost values in demand scenarios

On the other hand export demand has less impact on the total cost due to the lower utilization of the reactors and smaller lost sale penalty costs. When the demand amounts for exported intermediates were increased by 50%, the increase in total cost was only as much as 7% of the total cost. Changeover costs, lost sale costs and handling costs were increased. The values of the variables related to end products stayed the same. The analysis revealed that 3 reactors can handle export demand increases up to 50% but after that point lost sales would occur.

9.4.7 Analysis for Other Parameters

Sensitivity analysis for processing times has not been conducted because they depend on product type, machine type and the combination of other equipments used during packaging and this makes the sensitivity analysis complex and the impact would be difficult to observe. Since there are many different processing times their individual impacts are difficult to predict and test. Furthermore, processing times are technical properties and difficult to be modified by the company. Similarly batch cycle times and changeover times are also fixed by the current equipment and product portfolio.

On the other hand minimum number of batch requirements is determined by the company in order to increase the efficiency of the production and decrease the number of changeovers which means they can be modified if cost reduction opportunities are anticipated. While decreasing the number of changeovers, this constraint also increases the inventory levels of bases which are not used often in the packaging stage due to the OEE loss costs and longer processing times involved. When minimum number of batches requirement was released, i.e. the parameter value was set to zero, the total cost and the solution stayed the same but this was only for this specific small test case. For many other cases its consequences would be more significant.

Then the minimum number of batches was set to 15 times larger to see whether the model responds as expected. In order to produce that much of batches per setup, more than half of the available capacity per reactor per period was used up for a single base type. In that case number of changeovers had to decrease and stock levels in intermediate storage were expected to increase in order to prevent lost sales. The total cost increased due to OEE loss costs involved when stocked bases were used in packaging despite the decrease in the changeover costs. The packaging utilizations increased as well, due to the longer processing times of stocked bases. Minimum number of batch restriction would have a large impact on the solution, total cost, run times and feasibility of the problem in case of tight capacity restrictions for reactors, larger exported base demand and less available capacity.

Batch size decisions are also made by the company in order to increase efficiency and decrease the changeover requirements. As seen frequently in processing industry once a bath is closed the batch cycle time is fixed and the process cannot be interrupted after it is started. Mostly it is preferred to start production after the reactor is full so batch size is equal to the maximum capacity of the reactor.

Safety stock amount is another strategic decision which should be made by the management before a production plan is made. It is more dependent on the demand structure, ordering policy and product portfolio of the company and it has been kept out of the scope of this research so this parameter was not analyzed.

Available capacity per planning period is fixed with the number of equipment available in each stage and number of working days. These decisions are more strategic and have been studied further in scenario analysis.

9.5 Evaluation Compared to Real Data

Finally, the model is validated comparing the outcomes of the model and actual production amounts realized in the factory for a short term. The production data for only previous 4 weeks was used since comparing the values of thousands of variables would be time consuming and useless. For the same reason, the selected 4 weeks is one of the lowest demand periods with less number of SKUs in order to decrease the number of non-zero variables to be compared. Since stock and demand information was not available, the production amounts during each shift in tons were converted to weekly demand parameters to be used as input by the model to get comparable outputs, for both intermediates and SKUs.

The total weekly real production amounts and the proposed production amounts by the model were the same for end products and very similar for intermediates. Since the capacity was enough no end products was kept in stock as in the real case. The stock levels showed differences in intermediate storage. In order to prevent additional changeovers, the model kept more stock of intermediates in the first weeks. In some weeks, the line allocations were different in the packaging stage. The model achieved to allocate more production lots to the faster resources.

The model showed no unexpected stock or production level. The production amounts, lot sizes and number of changeovers proposed by the model were in the expected range. The output proposed matches the reality except for a few small differences. The production amounts are not expected to be exactly the same since some of the required information was missing such as stock levels and assumptions were made. The analysis validates that the model performs as intended and the intended structure is appropriate representation of the system under study.

10 SCENARIO ANALYSIS

The analysis performed for verification and validation showed that the model is reliable and usable to make least cost production plans in multi-echelon, batch production-packaging systems with changeover times and costs. Besides, the model can also be used to investigate the possible impacts of strategic decisions like increasing or decreasing the number of equipments, number of handling personnel in the storage locations, number of storage options as well as values of the input parameters and costs. Possible demand scenarios can also be investigated to forecast the budget for following years and worst/best case total costs can be determined. These pre-investigations with what-if analysis would provide valuable insights, flexibility and safety to the company in case of uncertainties.

The current cost allocation of the cost terms within the total cost for the whole planning horizon of 14 months with the given input data can be seen in Figure 14 below in terms of percentages.

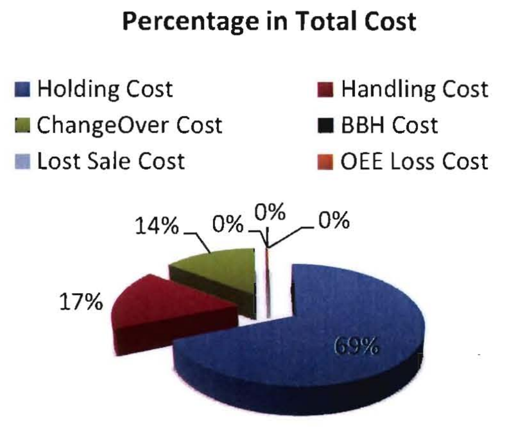

Figure 14: Distribution of the Cost Terms in Total Cost

The main components of the total cost are inventory holding costs, handling costs (including the transportation to and from intermediate storage locations, big bag and pallet costs) and changeover costs. This is the base scenario, with which the following scenarios will be compared.

10.1 Number of Reactors

When the production plan proposed by the planning tool using the current input parameter and demand data has been investigated, it was seen that the bottle-neck stage is mostly the stamping lines. The utilizations of the reactors are relatively low compared to the stamping lines. The average utilizations of the 3 reactors are 59%, 39% and 85% respectively. Therefore, it has been investigated what would be the impact of removing one of the reactors from the production area. The number of the reactors was decreased to two by removing reactor-2, which has the same technical characteristics as reactor-1, and the model was run with the same input data parameters. The results showed that, it is possible to have a production plan without any lost sales using only 2 reactors. The inventory cost was larger with increased inventory levels in the internal storage areas and further use of external stock areas. Higher inventory levels and higher transportation costs to and from external storage locations also caused an increase in the handling costs. The utilizations of the reactors were close to 100% for many periods, and the average utilization was 95% for reactor-1 and 90% for reactor-3 respectively. The stamped amount from stock was increased leading to an increase in the total OEE loss costs on stamping lines. On the other hand, the production runs were longer and the number of changeovers was decreased. More changeover saving was applied in reactor 3 by producing the TALLOW and GEAR on the same reactor in the same period. The total cost was 12% higher than the total cost of the base case scenario with 3 reactors. The allocation of the cost terms with in the total cost in terms of percentages and comparison with the base case can be seen in Table 2.

Cost Terms	% in Total Cost	% Change Compared to The Base Case
Holding Cost	69.06%	13.33%
Handling Cost	17.68%	18.26%
ChangeOver Cost	12.89%	2.03%
BBH Cost	0.00%	0.00%
Lost Sale Cost	0.00%	0.00%
OEE Loss Cost	0.36%	31.63%
Total Cost	100.00%	12.61%

Table 2: Comparison of 2 reactor scenario to the Base Case

This is an important insight since it has been seen that there is no need to increase the capacity in the production area as long as it is not expected to have a large increase in export demand and/or end product demand. Removing the reactor and using the extra space for storage or any other purpose can be possible if the costs related to removing is less than the salvage value of the reactor plus the added value of the new purpose. It can also be concluded that reactors are not the bottleneck in the system. Furthermore, a new production scheme can be considered dedicating one extra reactor to a single new product and enlarge the product portfolio and continue using the other 2 reactors for production of the current reactor. These decisions should be made comparing the expected costs and benefits of the related modification.

10.2 Stamping Line Dedication

As mentioned before, the utilization of the stamping lines is usually around 85% and there is considerable changeover hours spent related to the current production and demand amounts. Maximum changeover hours spent on a line per period goes up till 26% of the capacity per period with the current input parameter values. The utilization of the lines and percentage of the capacity hours spent for size and flavor changeovers can be seen in Table 3.

Line	Avg Utilization	Changeover Time
stamping line-1	80.36%	4.13%
stamping line-2	56.58%	7.83%
stamping line-3	91.32%	5.38%
stamping line-4	88.95%	4.61%
stamping line-5	84.74%	13.69%

Table 3: Utilization and Changeover percentages of Stamping Lines for Base Case

Considering the current demand amounts and line utilizations, removing one of the lines is not an option for the time being. However the allocation strategy of the lots among the products can be modified in order to increase the efficiency and enable easier planning. Dedication of the lines can be an option for a complex system with many different products to decrease the changeover requirements. An analysis has been conducted in which fixed schedules are used on all of the 5 lines considering the sequence dependent setup times, the capabilities of the lines and the average demand volumes. The line-product allocations with fixed sequences used in this scenario can be seen in Table 4.

Line	Flavor-Size Combination Produced on the Line in Sequence
stamping line-1	Pacifica-100gr, Phuket-100gr, Nightfire-100gr, ProAge-100gr
stamping line-2	Angelic-75gr, Joanna-75gr, Pacifica-75gr, Phuket-75gr, Nightfire-75gr, Braveheart-75gr, Braveheart-100gr
stamping line-3	Angelic-100gr, None-100gr, Joanna-100gr
stamping line-4	Angelic-100gr, None-100gr, Joanna-100gr
stamping line-5	Angelic-135gr, Joanna-135gr,Braveheart-135gr, Pacifica-135gr, Phuket-135gr, Nightfire-135gr, Pink-135gr, Pink-100gr, Cocoon-100gr

Table 4: Line-Product Allocations Used in the Scenario for All Dedicated Lines

The lot sizes can be altered, one or more products in the fixed sequence may not be produced at all but the sequence and the line allocation cannot be changed. This modification was applied in the model in AIMMS using the parameters allowed routes, processing times and changeover times. This scenario gave a solution with several lost sale amounts and consequently far more cost compared to the base case with flexible lines, despite less total changeover time and cost. Having flexibility in line-product allocation is very vital in the system due to the fluctuating demand amounts per product per period. While some flavor-size combinations are produced in similar amounts in each period, some are only demanded once a month in various amounts. When the line allocation was fixed and there were peak demands for more than one product per period on the same line then the capacity of the allocated line was not enough and lost sales occurred. Then the impact of single dedication has been investigated where stamping line 1 was dedicated to lots having flavor Joanna and bar size of 100 gram. When a single line was dedicated to only one products and the rest of the lines were kept as original, the lost sales decreased but total cost stayed higher than the base case. On the other hand, line dedication decreased the solving time significantly. When all the lines had fixed sequences, the model was solved in seconds and even when just a single line was dedicated to a flavor-size combination, the solution with the same optimality gap was found in 1.5 hours compared to 12 hours in the base case scenario with more flexible lines. This is due to the fact that the combinations to be searched for the model decreases considerably with these additional fixations. The comparison between total costs and solving times can be seen in Table 5 below.

	Base Case	Dedicate line 1	Dedicate all
% Change in Total Cost	0.00%	1.11%	675122.40%
Solving Time(sec)	42985	4361	19

Table 5: Comparison of Dedicated line scenarios to the Base Case

Additionally, changing the technical properties of the machines can be considered, comparing the expected cost savings and related cost of the change. When the flexibility of the lines is higher, the feasible region gets larger and more cost saving opportunities are expected. The mathematical model can be used to make feasibility analysis for such strategic decisions.

10.3 Number of Big Bag Handling Personnel

Another important decision is the number of the regular handling personnel in the intermediate storage locations. The labor cost of the regular workers has not been considered in the planning model but it has been assumed as a sunk-cost, which should be paid always. However, changing this number is a strategic decision which would impact the total cost. When the number of regular workers is decreased to a certain level the number of overtimes and external hiring would increase. Hence this certain limit is crucial information. After several trials with different number of BBH personnel it was seen that when the number of BBH personnel is larger than or equal to 3 there was no need to use overtime shifts or to hire external personnel and the regular capacity was enough to handle the big bags coming in and out of the storage locations. When there are 3 less regular personnel there was still no overtime or external hiring but the solution changed slightly and the total cost has increased by 30 € which is insignificant. In order to decrease the additional handling, more inventory was kept in storage and less was sent from storage to packaging. It can be concluded that having 3 less people for handling operations in the intermediate storage location is enough and increasing it further does not change the total cost of the production plan considerably. Rest of the personnel can be relocated to other departments or positions. When the number of BBH personnel was decreased one more, overtime hours were used during most of the periods. However there was still no need to hire external personnel. The total cost is increased by %2 which was mostly due to the increase in the overtime costs. The comparisons of the costs to the base case in percentages can be seen in Table 6 below.

Cost Terms	Current	BBH-3	BBH-4
Holding Cost	0.00%	0.16%	0.46%
Handling Cost	0.00%	-0.17%	-0.25%
ChangeOver Cost	0.00%	-0.05%	-0.94%
BBH Cost	0.00%	0.00%	0.00%
Lost Sale Cost	0.00%	0.00%	0.00%
OEE Loss Cost	0.00%	-23.48%	-65.34%
Total Cost	0.00%	0.00%	1.99%

Table 6: Comparison of Cost Terms in scenarios with different number of BBH personnel

To conclude, the total cost does not change considerably when the BBH personnel number is decreased till by 4. The slight increase can be negligible when the accuracy of the solution is considered. The optimum number of BBH personnel seems to be that in terms of minimizing the overtime costs and labor hours. On the other hand, the overhead cost savings related to the decreasing the number of personnel and the additional costs related to firing personnel should be considered in a more detailed cost-benefit analysis before determining the optimal number.

10.4 External Storage Option

The handling and holding costs are much higher for external storage locations. When the solution of the base case was examined it has been seen that external storage was used only for keeping the initial inventory of GEAR till there was an export demand for GEAR during week 9. The transportation costs related to transporting the initial stock to the packaging area and the related OEE loss costs were higher than the total holding cost for 9 weeks hence the inventory was kept for that time period. However, when that initial stock was removed and the external storage I and II options were out of use for the planning horizon, it has been seen that the total cost was decreased and no lost sales occurred. It can be concluded that at the moment more inventory than necessary is kept in the intermediate storage. Taking into account that, the total percentage of inventory holding costs is 69% of the total cost for the planning horizon, more attention should be paid to decrease the inventory levels. Safety stock level amounts can be re-evaluated based on the uncertainty in the demand. Assuming the average demand levels would stay similar, there is no need to use the external storage options.

10.5 Insights for Mannheim

During the scenario analysis important insights for Mannheim Dove Soap Production and Packaging Plant have been gained in addition to the further understanding of the planning model and the system. After these insights have been combined with the outcomes of runs of a smaller version of the model with different input parameters during the validation analysis, many recommendations can be made for Mannheim Plant.

The sensitivity analysis revealed that the plans provided by the models are robust to the small unit cost modifications. Although the small changes in unit handling cost coefficients do not impact the values of the decision variables such as values of the inventory levels and production amounts till, their effect on the total cost is high. There is a high difference in the total cost due to the relative magnitude of the cost coefficients of unit handling costs. Decreasing handling costs would not increase the efficiency but increase the profitability of the plant considerably. Hence further studies can be done on how to decrease pallet and transportation costs. The same can be said for changeover costs as well. Inventory costs should be calculated with care since they impact the production plan and the total cost as well as distribution of cost among the cost terms even for decimal value differences. OEE loss costs also should be calculated with care in case of high inventory costs, changeover costs and/or tight capacity restrictions in the production area. Lost sale penalty costs are difficult to estimate but they should be set large enough considering the relative magnitude of other cost terms related to production and the importance of customer satisfaction. Low penalty costs would lead to high lost sale amounts especially in case of higher changeover, handling and holding costs. The plans are very sensitive to the demand differences, especially for SKUs, due to the limited capacity and high utilization of the equipments.

Moreover the scenario analysis showed that the number of BBH personnel in the intermediate storage location should be lowered. The labor costs per period, related overtime costs and costs of hiring and firing personnel should be considered. It can also be said that the initial stock of intermediate soap bases should be decreased and the use of external stock locations should be reconsidered since they seem to be unnecessary under current circumstances.

Based on the scenario in which each line was dedicated for a certain combination of product, it has been seen that line dedication and fixed sequences should not be used since they decrease the feasibility of the system which is risky in a system with large product assortment with fluctuating demands between planning periods. According to the analysis conducted with different number of reactors, it has been concluded that the bottleneck in the system is not the production area but can be the packaging area especially the stamping lines. Capacity extension for reactors would not be profitable unless demand volumes are increased or product portfolio is enlarged.

11 FURTHER EXTENSION OF THE MODEL

As seen from the solution of the base scenario with current input values, changeover costs and times on stamping lines are important since stamping lines seem to be the main bottle-neck in the system. As discussed in section 3.3, the model has been built to be used for medium-term planning with longer planning horizon so detailed scheduling has not been included in the study. To deal with the setup carryovers and sequence dependent setups, some assumptions and simplifications have been used. It was assumed that setup carryovers are not allowed hence at the beginning of the each period there is a changeover regardless of the production during the last period.

There is at most one changeover saving possible per stamping line per period. In the best case, the setup carryover can be one of the largest two changeover hours on that line for each of the 23 periods. Based on the maximum changeover time requirements on stamping lines, the upper bounds on the mistake on changeover time per period is 4.5 hours on stamping lines 1, 2 and 5.1 hours on stamping lines 3, 4, 5. The upper bound of the mistake in total cost has been calculated by adding these maximum changeover time errors to the line capacities per period for each line and re-running the model. The overestimation in the cost has been found to be 14% of the total cost. When the current solution of the Base Case Scenario was investigated in detail, the lots produced on each line was examined for each period and possible setup carryovers were counted, it has been seen that average changeover time error due to setup carryover is 2.5 hrs per line per period. Multiplying the number of possible setup carryovers by the setup cost, the related mistake in the total cost has been calculated as 7% of the total cost.

Similarly, there is at most one changeover saving possible per reactor per period. The upper bound for the deviation of changeover hours is 6 hours per reactor per period. However, the total mistake due to missing carryover consideration in reactors is expected to be less. The only missing setup carryover is for GEAR because it has been assumed that there is a default setup carryover of HEBE for each reactor and the changeover saving when GEAR and TALLOW are produced on the same reactor is already taken into account. Considering the demand ratios, producing GEAR on all reactors during all periods does not make sense because the available capacity of a single reactor for two months is enough to produce almost half of the yearly demand for GEAR. The upper bound of the error in the total cost due to the overestimation in total changeover time on reactors has been calculated in the same fashion as the stamping lines and found to be 2%. When the current solution of the Base Case Scenario was investigated in detail and the setup carryovers which had been possible but not taken into account by the model were counted based on the cots produced per reactor per period, it has been seen that the average changeover mistake due to setup carryover is 2 hrs per reactor per period. Once the number of probable setup carryover is multiplied by the setup cost, the related mistake in the total changeover cost found is 0.5% of the total cost.

11.1 Setup Carryover Extension

Including the setup carryovers to the model in a simple way is possible with additional constraints and many binary variables. A binary variable COF_{flst}^{save} has been defined which takes a value of 1 if there is a setup carryover from the previous period for the lot with combination of flavor f and size s on stamping line l during period t, and takes a value of 0 otherwise.

$COF_{flst}^{save} \in \{1,0\}$ $\forall f, \forall s, \forall l, \forall t$[7]

If the same lot with the same flavor-size combination is produced during two successive planning periods on the same stamping line then there is a possibility of changeover saving for that flavor in the second period. In order to have changeover savings, this lot is the last one produced in the former period and fist one produced in the later period. The implicit assumption has been that if a lot will be produced on the same line in two successive periods, it will be produced as the last lot in the previous period and will be the first lot in the later period. This restriction has been formulated into the flowing constraints:

$$COF_{flst+1}^{save} \leq Z_{flst} \qquad \forall f, \forall s, \forall l, \forall t | t \neq T$$

$$COF_{flst+1}^{save} \leq Z_{flst+1} \qquad \forall f, \forall s, \forall l, \forall t | t \neq T$$

These constraints ensure that COF_{flst+1}^{save} can have positive value if and only if the lot having the flavor f and size s is produced on stamping line l both during planning period t and t+1, in which situation both Z_{flst} and Z_{flst+1} have a value of 1. The only positive value possible for COF_{flst+1}^{save} is 1.

The sign of the inequality has been chosen to be less than equal instead of greater than equal with a purpose. There can be more than one common product type produced in two successive periods. In that case, only one changeover can be saved by setup carryover so the total of setup savings per period cannot be larger than 1. Hence, even if the same product is produced in 2 successive periods; it is not carried over to the next period necessarily. There can be only one last lot and one first lot on a line during a period. The model has to choose which setup to carryover and produce as the last lot in period t and first lot in period t+1. Only one binary variable COF_{flst}^{save} can be 1 for each line l and period t. This constraint has been represented as:

$$\sum_{f}\sum_{s} COF_{flst}^{save} \leq 1 \qquad \forall l, \forall t | t \neq 1$$

Also it has been assumed that it is not possible to have the setup carryover for the same flavor-size combination for two consecutive periods since it has been assumed that a lot cannot be the first lot and the last lot on the same line during a period. This assumption was made based on the observation that usually there is more than one lot produced on a stamping line during a period. Furthermore, the number of flavor-size combinations demanded per period is larger than number of stamping lines and none of the combinations constitute the 20% of the total demand, in on average, in which case dedicating whole capacity of a line per period would be reasonable. This condition has been represented in the model with the following constraint:

$$COF_{flst+2}^{save} + COF_{flst+1}^{save} \leq 1 \qquad \forall f, \forall s, \forall l, \forall t | t \neq T-1, T$$

For example, assume that two flavor-size combinations f-s and f'-s' are stamped on line 1 in 3 consecutive periods, t, t+1 and t+2. If f-s is the last lot in t and first lot in t+1 on line l, then f'-s' can be the last lot in t+1 and first lot in t+2 on line l, (or vice versa) because f-s cannot be both the first and last lot on line l during period t+1. In that case, there is a changeover saving of f-s in period t+1 and of f'-s' in period t+2.

[7] t ϵ P= {1,2, ..., T-1, T}

Changeover savings are deducted from the total changeover time used in the total capacity constraint as follows:

$$\sum_{i}\sum_{m}\sum_{c}\left(FPack_{ilmct} * t_{ilmc}^{fresh} + SPack_{ilmct} * t_{ilmc}^{stocked}\right) + \sum_{f}\sum_{s}\left(\left(Z_{fslt} - COF_{flst}^{save}\right) * ct_{fl}\right)$$
$$\leq CL_{lt} - CO_{lt}^{size} * ct_{l}^{size} \ \forall l, \forall t$$

When there is a changeover saving, the related changeover cost is saved as well. This saving is deducted from the total changeover cost calculation in the objective function as follows:

$$\sum_{l}\left(\sum_{f}\left(\sum_{s} Z_{fslt} - COF_{flst}^{save}\right) * cost^{Fchange} + CO_{lt}^{size} * cost^{Schange}\right)$$

All these assumptions have been made to be able to integrate setup carryover into a mid-term planning model (with a minimum period length of a week) to decrease the number of constraints and variables while preventing unrealistic amounts of changeover hour requirements.

The same approach has been applied to the reactors as well, using the binary changeover saving variableCOR_{rbt}^{save}, adding the same kinds of constraints and including the related terms into capacity constraint and objective function. The extended mathematical model with setup carry-overs both on reactors and stamping lines can be seen in Appendix IV.

Note that when the setup carryover extension is added to the reactors, there is no need to use the changeover saving variable and constraints in the previous version of the model. These were used to include the saved changeovers into the model, but in less detail, using continuous variables instead of binaries, based on some simplifying assumptions, as discussed in detail in Chapter 6. The assumption about default setup of HEBE in reactors was used in the previous version of the model already to decrease the impact of setup carryovers to some degree. Moreover, the available capacity in production area is enough to satisfy the current demand and most of the time there is excess capacity. In the scenario analysis, it was seen that capacity restrictions in the production stage does not create a bottleneck in the system. So, the increase in available capacity may not be as crucial as for stamping lines when the setup carryovers are added into the model. In that case, these new binary variables for reactors can be prevented by not considering the setup carryover and keeping the previous constraints as they are.

11.2 Software Implementation

In the model used in the analysis so far, there are 391438 variables, 3864 of which are integer variables and 38899 constraints. When the full model with 23 periods (12 weekly and 11 monthly) for a planning horizon of 14 months has been solved in AIMMS with CPLEX12.1, there has been a relative optimality gap of % 14.3 after 12 hours which was determined as the maximum reasonable time for the solving the model (assuming the model can be run during the whole night). Including the setup carryover constraints and variables for production and packaging stages, the extended model has 395026 variables, 7521 of which are integer variables and 48893 constraints. This model is expected to require even longer solving time compared to the previous version not only because of the increased number of constraints but also due to the exponentially increasing complexity of the MIP model with additional binary variables. The number of decisions to be made by the model has also increased since now it also has to decide which setup to carryover on each line in each period and there more feasible production plans to explore.

The extended version has been re-written in the same version of AIMMS and tried to be solved using the same solver, to see whether the solving performance is better than expected. It has been seen that after 12 hours the gap is still 99.99%, the best integer solution found by the solver till then has very high total cost caused by many lost sales of end product demand and export demand. It cannot be solved within a reasonable amount of time by the solver, as expected. The LP bound is lower than the LP bound of the previous version of the model after 12 hours but it is not certain whether a solution converging to that LP bound can be found or not and how long would it take.

11.3 Heuristic Approach

Another option is to use a heuristic or a combination of heuristics rather than trying to solve the complete problem at once to optimality. There are many studies using different kinds of heuristics to solve similar problems. A detailed review of MIP models and heuristics approaches proposed to solve these MIP models for such problems available in literature has been conducted during Master Preparation I. The heuristics to be used in this study should be easy to understand and easy to implement for the users in the company. Commonsense heuristics using relaxation and decomposition have been preferred rather than mathematics based heuristics or reformulations for that reason. Relaxing the constraints one by one did not lead to significant performance improvements and the main problem has been determined as the number of integer variables. In order to decrease the number of integer variables to be decided per each run of the model, there are several alternatives used in literature:

1) Decomposing the production stage and packaging stage and dividing the problem into two parts is investigated in the study by Ferreira et al. (2008). First aggregate calculation would be made based on demand for intermediate bases and it would be decided whether each base is produced or not and have some upper/lower limits. Then changeover variables would be fixed, make amount variables would be relaxed as nonnegative or fixed to upper limits and model solved for the packaging. In the following stage the solution of packaging would be fixed and re-solved for the first stage until there is no improvement.
2) Item by item decomposition is proposed by Kirca et al. (1994). It can be applied to the system in this thesis as keeping the planning horizon and unit planning period but decreasing the number of products considered in each run. Start with first K items based on the cumulative demand percentages. In the next run fix the decision variables related to these first K items and solve for the next K items until all products are allocated.
3) A similar method is period by period decomposition, applied by keeping the product assortment as it is but decreasing the number of planning periods for each run. Optimize the production plan for first M planning periods. In the next run use the values of these variables as input and solve for the next M periods. Repeat till end of the planning horizon.
4) Lot Sizing Window method is proposed in the article by Stadtler (2003). The procedure is applied by deciding on setup (integer) variables only in the lot sizing window whereas deciding for other (continuous) decision variables for the later periods as well. The setup decisions in the previous lot sizing windows are fixed.

First heuristics approach has not been found applicable in the presence of intermediate storage. It violates the one of the motivations of the study as integrated planning so it was not preferred. The second approach has been found to be risky since the importance of setup decisions increases as the number of product type increases but this is not reflected fully when only limited number of products is considered and there is extra capacity available on the lines for the first runs. The third approach can be problematic when there are already known peak demand periods or seasonality effects because there is no facility to detect future bottlenecks. When M is small, these anticipations are not incorporated in the optimization for the first M periods and may lead to lost sales and inefficiencies in the plans. In that sense fourth approach with lot sizing windows is more promising since these impacts are taken into account but in limited detail using nonnegative changeover and number of batch variables.

Stadtler (2003) first proposed this approach in his study about multilevel lot sizing with setup times and multiple constrained resources. The approach can be summarized as making lot sizing decisions sequentially within internally rolling planning intervals, i.e. lot sizing windows, while considering the capacity over the entire horizon. This approach can be applied to the Planning Model for Mannheim Soap Production Packaging Plant as:

- Keep changeover and make amount variables as integers just for the first M periods and relax them to be nonnegative for the rest of the planning horizon. Set the lot sizing window as [1, M] and relax the binary integers to nonnegative for the time interval [M+1, T] where T is the last period in the planning horizon. Run the model.
- In the next run fix the values of changeover and make amount variables for first [1, M] periods to the values found in the previous run. Set the lot sizing window as [M+1, 2M], keep integer variables for time interval [M+1, 2M] and relax them to nonnegative for [2M+1, T]. Run the model again.
- Repeat until all integer variables are fixed.

Value of M should be determined considering the tradeoff between the solving time of the model using the heuristics and the optimality gap of the solution at the end. When M is set larger, the solution would be more reliable but the solving time of a single run gets longer exponentially. When M is smaller a solution with a larger optimality gap would be obtained in shorter time. For the extended model the value of M has been proposed to be 2 due to the increasing number of integer variables with number of planning periods. When M is set 4, after 3 hours the optimality gap is larger than 15% for the first run. When M is set 3 the gap decreases to 4% in 3 hours. Due to the time restrictions, the extended model with setup carryovers and the heuristic solution approach proposed could not be tested in this study. But it may be interesting to investigate this topic in a future study.

Being understandable and simple is the first prerequisite for using heuristics because heuristics means making exceptions and assumptions in the general processing of the model and the users in the company should be able to interfere with these since they are in the best position to decide whether these assumptions/relaxations are realistic or not. It should be always kept in mind that models are only mathematical abstractions of the real system and hard constraints are not that strict in reality, many exceptions may be possible. These opportunities should be considered and the plans provided by the mathematical model should be modified accordingly.

12 CONCLUSIONS

The main research assignment motivating this master thesis project was determined together with academic and company supervisors as: "Design a planning tool for integral planning and control of production and packaging in Dove soap supply chain, where production and packaging take place at different physical locations with different intermediate storage options and restrictions, different capacities in the two facilities, sequence dependent setup times and costs, parallel non-identical packaging lines, minimum batch sizes, minimum safety stock requirements and overtime possibilities in packaging lines". The designed tool should be effective, easy to use for periodic planning and scenario analysis and generally applicable, which can be applied in similar production environments.

The outcome of this research is a production planning tool, which consists of an MIP model to find the production plan with minimum total cost in AIMMS, an input file in Excel which can be easily modified by the Excel-users and an output file in Excel having all the production amounts, number of batches, inventory levels, delivered demand and lost sale amounts as well as related costs of the proposed plan, which can be easily checked or used for further analysis.

After the software implementation, verification and validation analysis, it has been concluded that the tool is applicable for the system used for case study and similar production environments. It was seen that the model has been coded correctly in the software, runs as intended, gives expected results and behaves as expected when input parameters and unit costs are modified. Furthermore, it has been seen that the model easily finds optimal solutions in seconds for small size problems with less product types and planning periods (8 product types and 4 planning periods) whereas the solution time increases exponentially with increased number of product types and planning horizons. When 70% of the demand is used a solution with an optimality gap of 5% can be found less than 10 hours. The largest reasonable solving time is determined as 12 hours assuming the model can be run whole night. For the model with 52 product types and 23 planning periods an integer solution with 14.3% gap was found in 12 hours, which is seen as promising by the company. On the other hand, another observation about the model is that, the solving time depends on the values of the input parameters. When there are capacity shortages so that lost sales are inevitable or when the demand is so low that the optimum line-lot allocation is obvious the solution times are rather low. These observations provided insight about the behavior of the model under different parameter combinations.

The proposed planning tool was also aimed to be usable for conducting scenario analysis with different input parameters, in order to see the impact of modifications in system design on system performance. All the required modifications can be done simply by changing the values in the related cells in input excel sheets and the results can be compared in output excel sheet. The designed tool can be used by production, inventory and demand planners for what if analysis with different demand scenarios and feasibility analysis so that it can assist the management while making mid-term decisions. The users should be able to use Excel for data modifications and analysis, have basic AIMMS knowledge for starting and ending the execution of the model and have basic modeling experience in order to make certain modifications in the model when required.

Another outcome of these analyses was the importance of changeover costs and changeover times on the proposed plan and total cost. Changeover times are quite large and unit changeover costs are one of the highest unit costs. Hence small differences in these parameters can make a large difference on the optimal solution and total cost. Including setup carryovers with some simplifying assumptions and additional binary variables and constraints would enable more realistic changeover time and cost calculations. The upper bound on the possible mistake due to missing setup carryover considerations has been found 14% of the total cost, which is substantial enough to make further investigation on the issue. So an extended MIP model which allows setup carryovers has been constructed. However the increased reality comes with increased complexity in the model with more constraints and more binary decision variables. The extended model is implemented in AIMMS and it is seen that after 12 hours the integer solution still has a relative optimality gap of 99.9%. Since the model cannot be solved by the commercial optimization tool in a reasonable time, a heuristic approach is proposed with "lot sizing windows" which is simple, easy to understand and use. Unfortunately, due to the time restrictions, the extended model with setup carryovers and the heuristic solution approach proposed cannot be tested in this study. But it may be interesting to investigate this topic in a future study. Analyzing the setup carryover extension and heuristics constitutes a promising future research topic.

Uncertainty in demand is not included in this study because it is already a very large and complicated model taking into account multiple considerations. On the other hand a linear model cannot give optimal production plans because it underestimates the uncertainty. When the plan is rolled for the next period, if the demand amounts has turned out to be considerably different than expected for the previous periods, the plan can be changed significantly which decreases the reliability of the plan for longer planning horizons. The lot sizes will be smaller in the first weeks in order to deal with the difference between the forecasted and actual inventory and demand amounts in the previous periods. The lot sizes gets larger in the later periods as the model takes the forecasts for the 14 months as deterministic data. However the lot sizes for these later periods are very prone to change and they can get smaller after rolling the model for several periods. Including the uncertainty considerations into the planning stage, provides safety and robustness in the plans for this situation. Including the impact of uncertainty in demand would be a very interesting and valuable study for future researchers since this may provide a more reliable and robust production plans.

There are not many researches available in the lot sizing literature studying the multi-product, multi-echelon batch production systems with intermediate storage options. Especially the systems, in which overtime options, non-identical parallel lines and special setup structures are existent, are not modeled in a medium level problem, using weekly and monthly planning periods and a planning horizon larger than a year. Most of the time, these systems are handled with scheduling models with small buckets and short planning horizons of at most several weeks (Ferreira et al. 2008, Doganis and Sarimveis 2008 and Gunther et al. 2007). The few studies, in which simultaneous lot sizing and scheduling is done with complex setup structures and parallel non-identical lines, consider only single level (Meyr 2002, Bude 208 and Lukac et al. 2008). Integrating two levels while considering the intermediate storage options in between, has been possible by using both production and flow variables with different dimensions, i.e. number of indices. The MIP model proposed in this research is a medium level planning model which allocates the production batches to the resources and determines the lot sizes but does not schedule these lots on a given line. On the other hand, setup costs and times are too large to ignore in the plan. Hence setups have been included into the model with certain assumptions about allocating certain types to the same equipments. These assumption about changeover structure and the related estimation of the (actually sequence dependent) times and costs were other differences of the study from the available literature. Also implementing the model on a real life case study with different problem sizes and for several scenarios is another contribution to the literature.

The tool proposed has been designed as a generally applicable tool for similar production and packaging environments but it has been only tested and analyzed on a single case study, Dove Soap Production and Packaging Plant. In further study it can be applied in a different soap facility or another make-and-pack process environment to test its generality. Also the tool has been designed based on rolling horizon approach but it could not be rolled with actual data. The performance of the tool after applied in real life and rolled for several periods can be studied in the future.

13 RECOMMENDATIONS

The sensitivity and scenario analysis provided valuable insights for the Mannheim Soap Production Plant. Based on the analysis conducted with current input parameter values provided by the company, the recommendations to the Mannheim Plant can be summarized as follows:

- Although the small changes in unit handling cost coefficients do not impact the values of the decision variables such as values of the inventory levels and production amounts till, their effect on the total cost is high. There is a high difference in the total cost due to the relative magnitude of the cost coefficients of unit handling costs. Decreasing handling costs would not increase the efficiency of the system but increase the profitability of the plant considerably. Hence further studies can be done on how to decrease pallet and transportation costs.
- Inventory holding costs should be calculated with care since they impact the production plan and the total cost as well as distribution of cost among the cost terms. Inventory holding costs used in this study are calculated by distributing the cost of 3rd and 4th week to all weeks. This assumption should be re-checked.
- Lost sale penalty costs are difficult to estimate but they should be set large enough considering the relative magnitude of other cost terms related to production and the importance of customer satisfaction.
- OEE loss costs also should be calculated with care in case of high inventory costs, changeover costs and/or tight capacity restrictions in the production area.
- The number of BBH personnel in the intermediate storage location should be lowered. The labor costs per period, related overtime costs and costs of hiring and firing personnel should be considered to decide on the correct number.
- Line Dedication and fixed sequences should not be used since they decrease the flexibility of the system which is risky in a system with large product assortment, with fluctuating demands between planning periods and parallel non-identical lines.
- The initial stock of intermediate soap bases should be decreased and the use of external stock locations should be reconsidered since they seem to be unnecessary under current circumstances. The safety stock amounts should also be re-considered as they increase both changeover requirements and inventory levels.
- The bottleneck in the system is not the production area but the packaging area especially the stamping lines. Capacity extension for reactors is not found to be profitable unless demand volumes are increased or product portfolio is enlarged.
- The company can increase the stamping line capacity by allowing packaging during weekends. The additional labor costs would not be high since the packaging stage is mostly automated. The model may be extended to decide which line(s) to be used during the weekend.

The model has been extended to include the setup carryover consideration, which would enable more realistic changeover time and cost calculations. After some preliminary runs with the model with setup carryovers, it has been proposed to use a heuristic to solve the model and set the lot sizing window length to 2 in this study. The further investigation on the model with set up carryovers is strongly suggested because it would lead to a reduction up to 14% of the total cost in the current situation. It also gives a more detailed plan, including some information on the sequence of the production lots, i.e. the last and first production lot on the lines for each planning period.

Another recommendation would be considering the reliability of the forecasts. The total cost is very sensitive to the differences in demand amounts and the higher the certainty in demand values, the higher the robustness of the plans. If uncertainty is large and forecasts are only reliable for short term, further investigation to include the stochasticity in the planning stage can improve the reliability.

The tool is recommended to be used by medium level planners, production and inventory planning managers for making mid-term production plans and what if analysis with different parameters, tactical rules and system designs. The users should be able to use Excel for data modifications and analysis, have basic AIMMS knowledge for starting and ending the execution of the model and have basic modeling experience in order to make certain modifications in the model when required. The users are recommended to gain at least intermediate modeling and coding skills in AIMMS to be able to change the constraints, add or remove decision variables, making fixations while analyzing the impact of some radical system designs and production strategies. This report would be the starting point for the basic training to use the tool. However, further training on AIMMS and MIP modeling can be obtained by detailed examination of the model code in AIMMS, some external documents and seminars.

All in all, the planning tool proposed is an easy to use analytical tool which would help the planners in the company during the production planning process in such a complex system. The tool should be used by the production and/or inventory planners. It enables making medium level production plans, cost estimations, capacity analysis and scenario analysis for a planning horizon of 14 months which is very difficult and erratic using the current planning methods.

14 REFLECTIONS

Production planning in a supply chain involves many variables and decisions. Considering them all at once is impractical due to the complexity and size of the problems with different planning horizons. Hence the modeler should choose the level of the planning activity with care and make realistic assumptions to leave out the unnecessary or too detailed parts of the system out of the model. However planning levels are generally overlapping and it is difficult to distinguish with clear lines. The MIP model proposed in this research is a medium level planning tool which allocates the production batches to the resources, determines the inventory levels and lot sizes but does not schedule the lots on a given line. On the other hand, setup costs and times are too large to ignore in the plan. Hence setups have been included into the model with certain assumptions about allocating certain types to the same equipments. These assumption about changeover structure and the related estimation of the (actually sequence dependent) times and costs were one of the most difficult and intriguing points of the study.

Additionally multi-level make and pack systems with intermediate storage options are not frequently studied in lotsizing studies with overtime options and special setup structures in a medium term level using weekly and monthly planning periods. The few studies, in which simultaneous lot sizing and scheduling is done with complex setup structures and parallel non-identical lines, consider only single level. Integrating two levels while considering the intermediate storage options in between was achieved by using both production and flow variables with different dimensions, i.e. number of indices. This was another complicating point in the construction of the planning model.

Moreover, after constructing a mathematical model, there are still many steps to be taken to attain a reliable and usable planning tool. Implementing the model using software requires through knowledge and expertise in the related software besides modeling skills. Also the modeling tool should be linked to the appropriate software that can easily be modified and used by the users in the company. The tool should be understandable and easy to use in order to allow the users to get more involved and make modifications when required. The technical problems faced, such as the problems during coding, software implementation, solver incompatibilities etc., can be time consuming and can decrease the motivation when struggled with for a long time. But, asking for help from more experienced people on the subject as soon as possible would make life a lot easier and save plenty of time and effort.

Working on a real life case study has many additional complications compared to being solely theoretical. Getting the required information, modifying it to the usable format, calculating and most of the time converting the available information to the input parameter values involve many assumptions, discussions with the data provider and company supervisors since most of the time the available data has not been in the exactly usable format. This task is prone to many errors and the parameters should be checked frequently to make the tool up-to date, reliable and usable. The time required to collect the data in the correct form can be the longest period in the project plan, so it should not be underestimated. The information required should be explained clearly and exactly for efficiency of information sharing and the time needed for this should not be underestimated. Also, being flexible is important to be able to satisfy different expectations of academicians and practitioners or make some differences in the direction of the study which were not planned at the beginning of the project.

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LIST OF ABBREVIATIONS AND DEFINITIONS

Abs: Absolute value

AIMMS: Advanced Integrated Multidimensional Modeling Software

APS: Advanced Planning System

BBH: Big Bag Handling

BPS: Business Problem Solving

CLSP: Capacitated Lot Sizing Problem

CPLEX: A high performance solver for Linear Programming (LP), Mixed Integer Programming (MIP) and Quadratic Programming (QP/QCP/MIQP/MIQCP)

eps: very small real constant

DEFI base: Intermediate chemical products used to produce soap, used interchangeably with soap flake and soap noodles in this study.

GAMS: The General Algebraic Modeling System is a high-level modeling system for mathematical programming and optimization

IBM: International Business Machines is a multinational computer, technology and IT consulting corporation

ILOG: A C++ library that uses constraint programming to find solutions to optimization problems (Intelligence and Logiciel)

inf: infinity

INFOR: Supply chain management software, which can be used to create constraint-based production schedules[8]

IWC: Charge on Working Capital

LINDO: Optimization Software for Integer Programming, Linear Programming, Nonlinear Programming and Global Optimization

LP: Linear Problem

MILP: Mixed Integer Linear Problem

MINLP: Mixed Integer Non-Linear Problems

MIP: Mixed Integer Problem

MRP: Material Requirements Planning

MLCLSP: Multi-Level Capacitated Lot Sizing Problem

MTS: Make to Stock

NP: Non-linear Problem

OEE: Operational Equipment Efficiency

R&D: Research and Development

SKU: Stock Keeping Unit

TPM: Total Productive Maintenance

USCC: Unilever Supply Chain Company

XA: A Linear Programming (LP) and Mixed Integer Programming (MIP) solver, default solver used in AIMMS

[8] http://www.infor.com/solutions/

APPENDIX I: Preliminary model with monthly planning periods

For the definition of the sets, indices, parameters and variables see section 6.4.1, pages 22-25.

- Objective Function

$$
\begin{aligned}
Min\ TotalCost = \sum_t \Bigg\{ & \sum_r \left[\left(\sum_b W_{rbt} \right) - CO_{rt}^{save} \right] * cost^{Bchange} \\
& + \sum_k \left(\sum_b \sum_r MS_{rbkt} \right) * \left(cost_k^{transTo} + cost^{pallet} \right) \\
& + \left(\sum_r \sum_b ME_{rbt} * cost^{pallet} \right) + \sum_k \left[\sum_b \left(\sum_l SP_{bklt} \right) + SE_{bkt} \right] * cost_k^{transFrom} \\
& + \sum_k \left[\left(\sum_b IS_{bkt} \right) * h_{kt} \right] + \left(BBO_t * cost^{overtime} + BBH_t * cost^{hire} \right) \\
& + \sum_l \left(\sum_b \sum_k SP_{bklt} \right) * Loss_l \\
& + + \sum_l \left(\sum_f \left[\left(\sum_s Z_{fslt} \right) - CO_{flt}^{save} \right] * cost^{Fchange} + CO_{flt}^{save} * cost^{Schange} \right) \\
& + \sum_f \sum_s \sum_e \sum_p IF_{fsept} * hf_t \Bigg\}
\end{aligned} \quad (1)
$$

- Make Constraints

$$\sum_k MS_{rbkt} + \sum_l MP_{rblt} + ME_{rbt} = Make_{rbt} * batch_b \qquad \forall b, \forall r, \forall t \quad (2)$$

$$Make_{rbt} * batch_b \geq MinBatch_b * W_{rbt} \qquad \forall b, \forall r, \forall t \quad (3)$$

$$Make_{rbt} * t_b \leq CM_{rt} * W_{rbt} \qquad \forall b, \forall r, \forall t \quad (4)$$

$$\sum_b (Make_{rbt} * t_b + W_{rbt} * ct_b) \leq CM_{rt} + CO_{rt}^{save} * tr^{save} \qquad \forall r, \forall t \quad (5)$$

$$CO_{rt}^{save} \geq W_{rbt} + W_{rb't} - 1 \qquad b = GEAR, b' = TALLOW, \forall r, \forall t \quad (6)$$

$$CO_{rt}^{save} \leq W_{rbt} \qquad b = GEAR, \forall r, \forall t \quad (7)$$

$$CO_{rt}^{save} \leq W_{rb't} \qquad b' = TALLOW, \forall r, \forall t \quad (8)$$

- Intermediate Storage

$$IS_{bkt} = IS_{bk0} + \sum_r MS_{rbkt} - \sum_l SP_{bklt} - SE_{bkt} \qquad \forall b, \forall k, t = 1 \quad (9)$$

$$IS_{bkt} = IS_{bkt-1} + \sum_r MS_{rbkt} - \sum_l SP_{bklt} - SE_{bkt} \qquad \forall b, \forall k, \forall t > 1 \quad (10)$$

$$IS_{bkt-1} + \sum_r MS_{rbkt} \leq CS_k \qquad \forall k, \forall t \ (11)$$

$$\sum_k IS_{bkt} \geq SS_b \qquad \forall b, \forall t \ (12)$$

- Big Bag Handling

$$\sum_r \sum_b \sum_k MS_{rbkt} + \sum_b \sum_k \sum_l SP_{bklt} + \sum_r \sum_b ME_{rbt} + \sum_k \sum_b SE_{kbt} \leq BB_t + BBO_t + BBH_t \quad \forall t \ (13)$$

- Export Demand

$$\sum_r ME_{rbt} + \sum_k SE_{kbt} \geq DE_{bt} \qquad \forall b, \forall t \ (14)$$

- Stamping Lines

$$\sum_k SP_{bklt} + \sum_r MP_{rblt} = \sum_{f \in F_b} \sum_s Stamp_{fslt} * ton_s \qquad \forall b, \forall l, \forall t \ (15)$$

$$Stamp_{fslt} * t_{fsl} \leq CL_{lt} * Z_{flst} \qquad \forall f, \forall s, \forall l, \forall t \ (16)$$

$$\sum_s \sum_f (Stamp_{fslt} * t_{fsl} + Z_{fslt} * ct_{fl}) \leq CL_{lt} - CO_{lt}^{size} * ct_l^{size} \qquad \forall l, \forall t \ (17)$$

$$CO_{lt}^{size} \geq Z_{flst} \qquad \forall f, s = 100, l \in \{2,5\}, \forall t \ (18)$$

$$CO_{lt}^{size} \leq 1 \qquad \forall l, \forall t \ (19)$$

$$Stamp_{fslt} = \sum_m PB_{fslmt} + \sum_c PC_{fs1lct} \qquad \forall f, \forall s, \forall l, \forall t \ (20)$$

- Bundlers

$$\sum_l PB_{fslmt} = \sum_e Bundle_{fsemt} \qquad \forall f, \forall s, \forall m, \forall t \ (21)$$

$$\sum_f \sum_s \sum_e Bundle_{fsemt} * t_{sem} \leq CB_{mt} \qquad \forall m, \forall t \ (23)$$

$$Bundle_{fsemt} = \sum_c BC_{fsemct} \qquad \forall f, \forall s, \forall e, \forall m, \forall t \ (24)$$

- Case Packers

$$\sum_l PC_{fs1lct} + \sum_m BC_{fsemct} = \sum_p Casepack_{fsepct} \qquad \forall f, \forall s, \forall e, \forall c, \forall t \ (25)$$

$$\sum_f \sum_s \sum_e \sum_p Casepack_{fsepct} * t_{sepc} \leq CP_{ct} \qquad \forall p, \forall t \ (26)$$

- Final Product Demand

$$IF_{fsept} = IF_{fsep0} + \sum_{c} Casepack_{fsepct} - DF_{fsept} \qquad \forall f, \forall s, \forall e, \forall p, \forall t = 1 \; (27)$$

$$IF_{fsept} = IF_{fsept-1} + \sum_{c} Casepack_{fsepct} - DF_{fsept} \qquad \forall f, \forall s, \forall e, \forall p, \forall t > 1 \; (28)$$

- Variable Types

$$Make_{rbt} \in N \qquad (29)$$

$$W_{rbt} \in \{1,0\} \qquad (30)$$

$$Z_{fslt} \in \{1,0\} \qquad (31)$$

$$BBO_t \in [0, MaxOvertime_t] \qquad (32)$$

$$MS_{rbkt}, MP_{rblt}, ME_{rbt}, CO_{rt}^{save}, IS_{bkt}, SP_{bklt}, SE_{bkt}, BBH_t, BBO_t, Stamp_{fslt}, CO_{flt}^{save}, PB_{fslmt}, PC_{fs1lct},$$
$$Bundle_{fsemt}, BC_{fsemct}, Casepack_{fsepct}, IF_{fsept} \geq 0 \qquad (33)$$

APPENDIX II: AIMMS Code of the Model

```
SECTION TheModel
SECTION SetDeclerations
DECLARATION SECTION ProductionSetDeclerations
SET:
identifier    :  BaseType
index         :  b
order by      :  USER
definition    :  !{'HEBE','GEAR','TALLOW'} ;
SET:
identifier    :  FlavorType
index         :  f
order by      :  USER ;
STRING PARAMETER:
identifier    :  InputExcel
initial data : "C:\\Users\\MannheimModel\\senemInputDataCluster_base.xls";
STRING PARAMETER:
identifier    :  OutputExcel
definition    : "C:\\Users \\Mannheim Model\\ OutputDataCluster_base.xls" ;
STRING PARAMETER:
identifier    :  SizeOfSKU
index domain :  i ;
STRING PARAMETER:
identifier    :  FlavorOfSKU
index domain :  (i) ;
STRING PARAMETER:
identifier    :  BaseOfFlavor
index domain :  f ;
SET:
identifier    :  CasePackers
index         :  c ;
SET:
identifier    :  IntermediateStorageLocation
index         :  k ;
SET:
identifier    :  StampingLines
index         :  l
definition    :  ElementRange(1,5,Prefix:'stamping line-') ;
SET:
identifier    :  SKUType
index         :  i
order by      :  USER ;
SET:
identifier    :  Bundlers
index         :  m ;
SET:
identifier    :  Reactors
index         :  r
order by      :  r
definition    :  {'reactor-1','reactor-2','reactor-3'} ;
SET:
identifier    :  SizeOfBar
index         :  s
definition    :  {'75','100','135'} ;
SET:
identifier    :  Periods
index         :  t;
ENDSECTION  ;
ENDSECTION SetDeclerations ;
SECTION ParameterDeclerations
DECLARATION SECTION ProductionParameterDeclarations
PARAMETER:
identifier    :  BatchSize
index domain :  (b) ;
PARAMETER:
identifier    :  ReactorCapacity
index domain :  (r,t) ;
```

```
PARAMETER:
identifier   :  MinimumNumberOfBatchesofBase
index domain :  (b) ;
PARAMETER:
identifier   :  SafetyStockOfBase
index domain :  (b) ;
PARAMETER:
identifier   :  TimePerBatch
index domain :  (b) ;
PARAMETER:
identifier   :  ChangeOverTimeInReactor
index domain :  (b) ;
PARAMETER:
identifier   :  ChangeOverSavingTimeInReactor ;
PARAMETER:
identifier   :  BBHRegularCapacity
index domain :  t ;
PARAMETER:
identifier   :  MaximumOvertimeBBH
index domain :  (t) ;
PARAMETER:
identifier   :  IntermediateStorageCapacity
index domain :  (k) ;
PARAMETER:
identifier   :  ConversionToTon
index domain :  (s) ;
PARAMETER:
identifier   :  FlavorSizeOfSKU
index domain :  (f,s,i)
definition   :if FlavorOfSKU(i)=f and SizeOfSKU(i)=s then 1 Else 0 endif ;
PARAMETER:
identifier   :  FlavorOfBase
index domain :  (f,b)
definition   :  if BaseOfFlavor(f)=b then 1 else 0 endif ;
PARAMETER:
identifier   :  StampingLineCapacity
index domain :  (l,t) ;
PARAMETER:
identifier   :  ChangeOverTimeForFlavorOnLine
index domain :  (f,l) ;
PARAMETER:
identifier   :  ChangeOverTimeForSize
index domain :  (l) ;
PARAMETER:
identifier   :  AverageStampingTime ;
PARAMETER:
identifier   :  AllowedRoute
index domain :  (l,m,c,i)
definition   :if ProcessingTimeFresh(l,m,c,i)>=10000 then 0 else 1 endif ;
PARAMETER:
identifier   :  ProcessingTimeFresh
index domain :  (l,m,c,i) ;
PARAMETER:
identifier   :  ProcessingTimeStocked
index domain :  (l,m,c,i)
definition   :  ProcessingTimeFresh(l,m,c,i)*1.05 ;
PARAMETER:
identifier   :  BundlerCapacity
index domain :  (m,t) ;
PARAMETER:
identifier   :  CasePackerCapacity
index domain :  (c,t) ;
PARAMETER:
identifier   :  ExportDemand
index domain :  (b,t) ;
PARAMETER:
identifier   :  InitialStockLevelIntermediate
index domain :  (b,k) ;
```

```
PARAMETER:
identifier    :  EndProductDemand
index domain :  (i,t) ;
PARAMETER:
identifier    :  InitialStockLevelEndProduct
index domain :  (i) ;
PARAMETER:
identifier    :  SafetyStockOfSKU
index domain :  (i) ;
ENDSECTION  ;
DECLARATION SECTION CostParameterDeclerations
PARAMETER:
identifier    :  OEELossCostDuringStamping
index domain :  (l) ;
PARAMETER:
identifier    :  BaseChangeOverCost
index domain :  (b) ;
PARAMETER:
identifier    :  SavingChangeOverCostOnReactor ;
PARAMETER:
identifier    :  FlavorChangeOverCost ;
PARAMETER:
identifier    :  SizeChangeOverCost ;
PARAMETER:
identifier    :  HiringCostBBH ;
PARAMETER:
identifier    :  OvertimeCostBBH ;
PARAMETER:
identifier    :  PalletCost ;
PARAMETER:
identifier    :  TransportationFromStorageCost
index domain :  (k) ;
PARAMETER:
identifier    :  TransportationToStorageCost
index domain :  (k) ;
PARAMETER:
identifier    :  EndProductLostsalePenaltyCost
index domain :  (i) ;
PARAMETER:
identifier    :  ExporLostsalePenaltyCost
index domain :  (b) ;
PARAMETER:
identifier    :  HoldingCostIntermediateStorage
index domain :  (k,t) ;
PARAMETER:
identifier    :  HoldingCostEndProductStorage
index domain :  t ;
ENDSECTION  ;
ENDSECTION ParameterDeclerations ;
SECTION VariableDeclerations
DECLARATION SECTION ModelVariables
VARIABLE:
identifier    :  StockLevelIntermediate
index domain :  (b,k,t)
range         :  nonnegative
VARIABLE:
identifier    :  StockLevelEndProduct
index domain :  (i,t)
range         :  [SafetyStockOfSKU(i), inf)
VARIABLE:
identifier    :  LostSaleExport
index domain :  (b,t)
range         :  nonnegative
VARIABLE:
identifier    :  LostSaleEndProduct
index domain :  (i,t)
range         :  nonnegative
VARIABLE:
```

```
identifier   :  MakeAmount
index domain :  (r,b,t)
range        :  integer
VARIABLE:
identifier   :  StampedAmountFromFresh
index domain :  (f,s,l,t)
range        :  nonnegative
VARIABLE:
identifier   :  StampedAmountFromStocked
index domain :  (f,s,l,t)
range        :  nonnegative
VARIABLE:
identifier   :  bundledamount
index domain :  (m,i,t)
definition   :  sum[(l,c),FreshPack(l,m,c,i,t)+StockedPack(l,m,c,i,t)] ;
VARIABLE:
identifier   :  casepackedamount
index domain :  (c,i,t)
definition   :  sum[(l,m),FreshPack(l,m,c,i,t)+StockedPack(l,m,c,i,t)] ;
VARIABLE:
identifier   :  totalstampingused
index domain :  (l,t)
definition   :
(sum[(m,c,i),FreshPack(l,m,c,i,t)*(ProcessingTimeFresh(l,m,c,i)/6000)+StockedPack(l
,m,c,i,t)*(ProcessingTimeStocked(l,m,c,i)/6000)]
+sum[(f,s),ChangeOverStamper(f,s,l,t)*ChangeOverTimeForFlavorOnLine(f,l)]+ChangeOve
rTimeForSize(l)*SizeChangeOverOnStamping(l,t)) ;
VARIABLE:
identifier   :  totalreactorused
index domain :  (r,t)
definition   :  sum[b,
MakeAmount(r,b,t)*TimePerBatch(b)+ChangeOverReactor(r,b,t)*ChangeOverTimeInReactor(
b)]-SavingChangeOverOnReactor(r,t)*ChangeOverSavingTimeInReactor  ;
VARIABLE:
identifier   :  totalcasepackused
index domain :  (c,t)
definition   :
sum[(l,m,i),FreshPack(l,m,c,i,t)*(ProcessingTimeFresh(l,m,c,i)/6000)+StockedPack(l,
m,c,i,t)*(ProcessingTimeStocked(l,m,c,i)/6000)] ;
VARIABLE:
identifier   :  totalbundlerused
index domain :  (m,t)
definition   :
sum[(l,c,i),FreshPack(l,m,c,i,t)*(ProcessingTimeFresh(l,m,c,i)/6000)+StockedPack(l,
m,c,i,t)*(ProcessingTimeStocked(l,m,c,i)/6000)] ;
VARIABLE:
identifier   :  totalflavorchangeovertime
index domain :  (l,t)
definition   :
sum[f,sum(s,ChangeOverStamper(f,s,l,t))*ChangeOverTimeForFlavorOnLine(f,l)] ;
VARIABLE:
identifier   :  totalsizechangeovertime
index domain :  (l,t)
definition   :  ChangeOverTimeForSize(l)*SizeChangeOverOnStamping(l,t) ;
ENDSECTION  ;
DECLARATION SECTION DecisionVariables
VARIABLE:
identifier   :  OvertimeBBHPersonnel
index domain :  (t)
range        :  [0, MaximumOvertimeBBH(t)] ;
VARIABLE:
identifier   :  HiredExternallyBBHPersonnel
index domain :  (t)
range        :  nonnegative ;
VARIABLE:
identifier   :  ChangeOverReactor
index domain :  (r,b,t)
range        :  binary ;
```

```
VARIABLE:
identifier   :  ChangeOverStamper
index domain :  (f,s,l,t)
range        :  binary ;
VARIABLE:
identifier   :  SizeChangeOverOnStamping
index domain :  (l,t)
range        :  nonnegative ;
VARIABLE:
identifier   :  SavingChangeOverOnReactor
index domain :  (r,t)
range        :  nonnegative ;
VARIABLE:
identifier   :  FromEndStorageToDemand
index domain :  (i,t)
range        :  nonnegative ;
VARIABLE:
identifier   :  FromMakeToExport
index domain :  (r,b,t)
range        :  nonnegative ;
VARIABLE:
identifier   :  FromMakeToStamper
index domain :  (r,b,l,t)
range        :  nonnegative ;
VARIABLE:
identifier   :  FromMakeToStorage
index domain :  (r,b,k,t)
range        :  nonnegative ;
VARIABLE:
identifier   :  FromStorageToExport
index domain :  (b,k,t)
range        :  nonnegative ;
VARIABLE:
identifier   :  FromStorageToStamper
index domain :  (b,k,l,t)
range        :  nonnegative ;
VARIABLE:
identifier   :  FreshPack
index domain :  (l,m,c,i,t)
range        :  nonnegative ;
VARIABLE:
identifier   :  StockedPack
index domain :  (l,m,c,i,t)
range        :  nonnegative ;
ENDSECTION  ;
ENDSECTION VariableDeclerations ;
SECTION ConstraintDeclerations
DECLARATION SECTION MakeConstraints
CONSTRAINT:
identifier   :  TotalMake
index domain :  (r,b,t)
definition   :
MakeAmount(r,b,t)*BatchSize(b)=sum[k,FromMakeToStorage(r,b,k,t)]+sum[l,FromMakeToSt
amper(r,b,l,t)]+FromMakeToExport(r,b,t) ;
CONSTRAINT:
identifier   :  MinBatchSize
index domain :  (r,b,t)
definition   :
MakeAmount(r,b,t)>=MinimumNumberOfBatchesofBase(b)*ChangeOverReactor(r,b,t) ;
CONSTRAINT:
identifier   :  ChangeOver
index domain :  (r,b,t)
definition   :
MakeAmount(r,b,t)*TimePerBatch(b)<=ChangeOverReactor(r,b,t)*ReactorCapacity(r,t) ;
CONSTRAINT:
identifier   :  Capacity
index domain :  (r,t)
definition:
```

```
sum[b,
MakeAmount(r,b,t)*TimePerBatch(b)+ChangeOverReactor(r,b,t)*ChangeOverTimeInReactor(
b)]<=ReactorCapacity(r,t)
+SavingChangeOverOnReactor(r,t)*ChangeOverSavingTimeInReactor ;
CONSTRAINT:
identifier   :  ChangeOverSaving1
index domain :  (r,t)
definition   :  SavingChangeOverOnReactor(r,t)>=ChangeOverReactor(r,'GEAR',t)+
ChangeOverReactor(r,'TALLOW',t)-1  ;
CONSTRAINT:
identifier   :  ChangeOverSaving2
index domain :  (r,t)
definition   :  SavingChangeOverOnReactor(r,t)<=ChangeOverReactor(r,'GEAR',t);
CONSTRAINT:
identifier   :  ChangeOverSaving3
index domain :  (r,t)
definition   :  SavingChangeOverOnReactor(r,t)<=ChangeOverReactor(r,'TALLOW',t) ;
ENDSECTION  ;
DECLARATION SECTION IntermediateStorageConstraints
CONSTRAINT:
identifier   :  StockeLevelInt
index domain :  (b,k,t)
definition   :if t= 'week01' then
StockLevelIntermediate(b,k,t)=InitialStockLevelIntermediate(b,k)+sum[r,FromMakeToSt
orage(r,b,k,t)]-sum[l,FromStorageToStamper(b,k,l,t)]-FromStorageToExport(b,k,t)
else
StockLevelIntermediate(b,k,t)= StockLevelIntermediate(b,k,t-
1)+sum[r,FromMakeToStorage(r,b,k,t)]-sum[l,FromStorageToStamper(b,k,l,t)]-
FromStorageToExport(b,k,t)endif   ;
CONSTRAINT:
identifier   :  StorageCapacity
index domain :  (k,t)
definition   :
sum[(r,b),FromMakeToStorage(r,b,k,t)]+sum[b,StockLevelIntermediate(b,k,t-
1)]<=IntermediateStorageCapacity(k) ;
CONSTRAINT:
identifier   :  SafetyStock
index domain :  (b,t)
definition   :  sum[k,StockLevelIntermediate(b,k,t)]>= SafetyStockOfBase(b) ;
CONSTRAINT:
identifier   :  ExportLostSale
index domain :  (b,t)
definition   :  LostSaleExport(b,t)=ExportDemand(b,t)-
sum[r,FromMakeToExport(r,b,t)]-sum[k,FromStorageToExport(b,k,t)] ;
ENDSECTION  ;
DECLARATION SECTION BigBagHandlingConstraints
CONSTRAINT:
identifier   :  BBHCapacity
index domain :  t
definition   :
sum[(r,b,k),FromMakeToStorage(r,b,k,t)]+sum[(b,k,l),FromStorageToStamper(b,k,l,t)]+
sum[(r,b),FromMakeToExport(r,b,t)]+
sum[(b,k),FromStorageToExport(b,k,t)]<=BBHRegularCapacity(t)+OvertimeBBHPersonnel(t
)+HiredExternallyBBHPersonnel(t) ;
ENDSECTION  ;
DECLARATION SECTION StampingConstraints
CONSTRAINT:
identifier   :  Stampfromfresh
index domain :  (f,s,l,t)
definition   : StampedAmountFromFresh(f,s,l,t)=
sum[i,(FlavorSizeOfSKU(f,s,i)*sum[(m,c),FreshPack(l,m,c,i,t)])] ;
CONSTRAINT:
identifier   :  stampfromstock
index domain :  (f,s,l,t)
definition   : StampedAmountFromStocked(f,s,l,t)=
sum[i,(FlavorSizeOfSKU(f,s,i)*sum[(m,c),StockedPack(l,m,c,i,t)])] ;
CONSTRAINT:
identifier   :  FreshStamp
```

```
index domain :  (b,l,t)
definition   :  sum[r,FromMakeToStamper(r,b,l,t)]=sum[f,
FlavorOfBase(f,b)*sum(s,StampedAmountFromFresh(f,s,l,t)*ConversionToTon(s))];
CONSTRAINT:
identifier   :  StockedStamp
index domain :  (b,l,t)
definition   :  sum[k,FromStorageToStamper(b,k,l,t)]=sum[f,
FlavorOfBase(f,b)*sum(s,StampedAmountFromStocked(f,s,l,t)*ConversionToTon(s))];
CONSTRAINT:
identifier   :  ChangeOverStamp
index domain :  (f,s,l,t)
definition   :
(StampedAmountFromFresh(f,s,l,t)+StampedAmountFromStocked(f,s,l,t))*(AverageStampin
gTime/6000)<= StampingLineCapacity(l,t)*ChangeOverStamper(f,s,l,t) ;
CONSTRAINT:
identifier   :  ChangeOverSizeStamp1
index domain :  (f,l,t)
definition   :  if l="stamping line-2" then
SizeChangeOverOnStamping(l,t)>= ChangeOverStamper(f,'100',l,t)
else if l="stamping line-5" then
SizeChangeOverOnStamping(l,t)>= ChangeOverStamper(f,'100',l,t)
else
SizeChangeOverOnStamping(l,t)>=0
endif
endif ;
CONSTRAINT:
identifier   :  ChangeOverSizeStamp2
index domain :  (l,t)
definition   :  if l="stamping line-2" then
SizeChangeOverOnStamping(l,t)<= 1
else if l="stamping line-5" then
SizeChangeOverOnStamping(l,t)<= 1
else
SizeChangeOverOnStamping(l,t)<=0
endif
endif ;
CONSTRAINT:
identifier   :  CapacityStamp
index domain :  (l,t)
definition   :
sum[(m,c,i),FreshPack(l,m,c,i,t)*(ProcessingTimeFresh(l,m,c,i)/6000)+StockedPack(l,
m,c,i,t)*(ProcessingTimeStocked(l,m,c,i)/6000)]
+sum[f,sum(s,ChangeOverStamper(f,s,l,t))*ChangeOverTimeForFlavorOnLine(f,l)]<=
StampingLineCapacity(l,t)-ChangeOverTimeForSize(l)*SizeChangeOverOnStamping(l,t) ;
ENDSECTION  ;

DECLARATION SECTION BundlingConstraints
CONSTRAINT:
identifier   :  CapacityBundler
index domain :  (m,t)
definition   :
sum[(l,c,i),FreshPack(l,m,c,i,t)*(ProcessingTimeFresh(l,m,c,i)/6000)+StockedPack(l,
m,c,i,t)*(ProcessingTimeStocked(l,m,c,i)/6000)]<= BundlerCapacity(m,t) ;
ENDSECTION  ;

DECLARATION SECTION CasePackingConstraints
CONSTRAINT:
identifier   :  CapacityCasePacker
index domain :  (c,t)
definition   :
sum[(l,m,i),FreshPack(l,m,c,i,t)*(ProcessingTimeFresh(l,m,c,i)/6000)+StockedPack(l,
m,c,i,t)*(ProcessingTimeStocked(l,m,c,i)/6000)]<= CasePackerCapacity(c,t) ;
ENDSECTION  ;
DECLARATION SECTION StockEndProduct
CONSTRAINT:
identifier   :  StockSKU
index domain :  (i,t)
```

```
definition    :  if t='week01' then
StockLevelEndProduct(i,t)=InitialStockLevelEndProduct(i)+sum[(l,m,c),FreshPack(l,m,
c,i,t)+StockedPack(l,m,c,i,t)]-FromEndStorageToDemand(i,t)
else
StockLevelEndProduct(i,t)=StockLevelEndProduct(i,t-
1)+sum[(l,m,c),FreshPack(l,m,c,i,t)+StockedPack(l,m,c,i,t)]-
FromEndStorageToDemand(i,t)
endif  ;
CONSTRAINT:
identifier    :  SafetySKU
index domain :  (i,t)
definition    :  StockLevelEndProduct(i,t)>= SafetyStockOfSKU(i) ;
CONSTRAINT:
identifier    :  SKULostSale
index domain :  (i,t)
definition    :  LostSaleEndProduct(i,t)=EndProductDemand(i,t)-
FromEndStorageToDemand(i,t) ;
ENDSECTION  ;
DECLARATION SECTION fix_variables
CONSTRAINT:
identifier    :  packfix
index domain :  (l,m,c,i)
definition    :
sum(t,FreshPack(l,m,c,i,t)+Stockedpack(l,m,c,i,t))<=AllowedRoute(l,m,c,i)*inf
CONSTRAINT:
identifier    :  reactorcap
index domain :  (r,t)|r<> 'reactor-3'
definition    :  MakeAmount(r,'TALLOW',t)=0 ;
ENDSECTION  ;
ENDSECTION ConstraintDeclerations ;

SECTION ObjectiveFunction
DECLARATION SECTION LeastCost
VARIABLE:
identifier    :  CostPerPeriod
index domain :  t
definition    :  sum[t,ChangeOverCost(t)+ LostSaleCost(t)+ HoldingCost(t)+
HandlingCost(t)+ TotOEELossCost(t)+ BBHCost(t)];
VARIABLE:
identifier    :  ChangeOverCost
index domain :  (t)
definition    :  sum[r,sum[b,ChangeOverReactor(r,b,t)*BaseChangeOverCost(b)]-
SavingChangeOverCostOnReactor*SavingChangeOverOnReactor(r,t)]+
sum[l,(sum[(f,s),ChangeOverStamper(f,s,l,t)]*FlavorChangeOverCost+SizeChangeOverOnS
tamping(l,t)*SizeChangeOverCost)] ;
VARIABLE:
identifier    :  LostSaleCost
index domain :  (t)
definition    :  sum[b,LostSaleExport(b,t)*ExporLostsalePenaltyCost(b)]+
sum[(i),LostSaleEndProduct(i,t)*EndProductLostsalePenaltyCost(i)] ;
VARIABLE:
identifier    :  HoldingCost
index domain :  (t)
definition    :
sum[k,(sum[b,StockLevelIntermediate(b,k,t)]*HoldingCostIntermediateStorage(k,t))]+
sum[(i),StockLevelEndProduct(i,t)]*HoldingCostEndProductStorage(t) ;
VARIABLE:
identifier    :  HandlingCost
index domain :  (t)
definition    :
sum[k,(sum[(r,b),FromMakeToStorage(r,b,k,t)]*(TransportationToStorageCost(k)+Pallet
Cost))]+ sum[(r,b),FromMakeToExport(r,b,t)]*PalletCost+
sum[k,(sum[b,(sum[l,FromStorageToStamper(b,k,l,t)]
+FromStorageToExport(b,k,t))])*TransportationFromStorageCost(k)] ;
VARIABLE:
identifier    :  TotOEELossCost
index domain :  (t)
```

```
definition    :
sum[l,sum[(b,k),FromStorageToStamper(b,k,l,t)]*OEELossCostDuringStamping(l)];
VARIABLE:
identifier    :  BBHCost
index domain :  (t)
definition    :
(OvertimeBBHPersonnel(t)*OvertimeCostBBH+HiredExternallyBBHPersonnel(t)*HiringCostB
BH);
VARIABLE:
identifier    :  TotalCost
definition    :  sum[t,CostPerPeriod(t)]/1000 ;
MATHEMATICAL PROGRAM:
identifier    :  LeastCostPlan
objective     :  TotalCost
direction     :  minimize
constraints   :  AllConstraints
variables     :  AllVariables
type          :  MIP ;
ENDSECTION  ;
ENDSECTION ObjectiveFunction ;
```

Appendix III: Process Window as displayed in AIMMS 3.9

AIMMS	: 4weeksrange.amb	
Executing	: MainExecution	
Line number	: 1 [body]	
Math.Program	: LeastCostPlan	
# Constraints	: 2478	
# Variables	: 11321 (192 integer)	
# Nonzeros	: 110533	
Model Type	: MIP	
Direction	: minimize	
SOLVER	: CPLEX 12.1	
Phase	: Postsolving	
Iterations	: 294263	
Nodes	: 30006	(Left: 13018)
Best LP Bound	:	(Gap: 0.01%)
Best Solution	:	(Post:)
Solving Time	: 57.49 sec	(Peak Mem: 47.7 Mb)
Program Status	: Optimal	
Solver Status	: Normal completion	

Figure 15: The output of the validation run with 8 SKU types and 4 weekly periods

AIMMS	: 4weeksrange.amb	
Executing	: MainExecution	
Line number	: 1 [body]	
Math.Program	: LeastCostPlan	
# Constraints	: 38899	
# Variables	: 391438 (3864 integer)	
# Nonzeros	: 4009561	
Model Type	: MIP	
Direction	: minimize	
SOLVER	: CPLEX 12.1	
Phase	: Postsolving	
Iterations	: 31572607	
Nodes	: 2251	(Left: 1670)
Best LP Bound	:	(Gap: 14.32%)
Best Solution	:	(Post:)
Solving Time	: 43269.33 sec	(Peak Mem: 499.5 Mb)
Program Status	: Integer solution	
Solver Status	: User interrupt	

Figure 16: The output of the base case used in scenario analysis with 52 product families and 23 period

APPENDIX IV: The Model with Setup Carryover Extension

For the definition of majority of the sets, indices, parameters and variables see section 6.4.1, pages 22-25. For the definition of the additional and/or modified variables and detailed explanations on the added and/or modified restrictions see section 11.1, pages 54-56.

Objective Function

$$
\begin{aligned}
Min\ TotalCost = \sum_t \Bigg\{ & \sum_r \left[\left(\sum_b W_{rbt} - COR_{rbt}^{save} \right) * cost_b^{Bchange} \right] \\
& + \sum_k \left(\sum_b \sum_r MS_{rbkt} \right) * (cost_k^{transTo} + cost^{pallet}) + \left(\sum_r \sum_b ME_{rbt} * cost^{pallet} \right) \\
& + \sum_k \left[\sum_b \left(\sum_l SP_{bklt} \right) + SE_{bkt} \right] * cost_k^{transFrom} + \sum_k \left[\left(\sum_b IS_{bkt} \right) * h_{kt} \right] \\
& + (BBO_t * cost^{overtime} + BBH_t * cost^{hire}) + \sum_l \left(\sum_b \sum_k SP_{bklt} \right) * Loss_l \\
& + \sum_l \left(\sum_f \left(\sum_s Z_{fslt} - COF_{flst}^{save} \right) * cost^{Fchange} + CO_{lt}^{size} * cost^{Schange} \right) + \sum_i IF_{it} * hf_t \\
& + \sum_b Lostexport_{bt} * penalty_b^{lostexport} + \sum_i Lostsale_{it} * penalty_i^{lostsale} \Bigg\} \qquad (1)
\end{aligned}
$$

Constraints

- *Production Stage*

$$\sum_k MS_{rbkt} + \sum_l MP_{rblt} + ME_{rbt} = Make_{rbt} * batch_b \qquad \forall b, \forall r, \forall t\ (2)$$

$$Make_{rbt} \geq MinBatch_b * W_{rbt} \qquad \forall b, \forall r, \forall t\ (3)$$

$$Make_{rbt} * t_b \leq CM_{rt} * W_{rbt} \qquad \forall b, \forall r, \forall t\ (4)$$

$$\sum_b [Make_{rbt} * t_b + (W_{rbt} - COR_{rbt}^{save}) * ct_b] \leq CM_{rt} \qquad \forall r, \forall t (5)$$

$$COR_{rbt+1}^{save} \leq W_{rbt} \qquad \forall r, \forall b, \forall t | t \neq T\ (6)$$

$$COR_{rbt+1}^{save} \leq W_{rbt+1} \qquad \forall r, \forall b, \forall t | t \neq T\ (7)$$

$$COR_{rbt+1}^{save} + COR_{rbt+2}^{save} \leq 1 \qquad \forall r, \forall b, \forall t | t \neq T-1, T\ (8)$$

$$\sum_b COR_{rbt}^{save} \leq 1 \qquad \forall r, \forall t | t \neq 1 (9)$$

- *Intermediate Storage*

$$IS_{bkt} = IS_{bk0} + \sum_r MS_{rbkt} - \sum_l SP_{bklt} - SE_{bkt} \qquad \forall b, \forall k, t = 1 (10)$$

$$IS_{bkt} = IS_{bkt-1} + \sum_{r} MS_{rbkt} - \sum_{l} SP_{bklt} - SE_{bkt} \qquad \forall b, \forall k, \forall t > 1 \; (11)$$

$$\sum_{b} (IS_{bkt-1} + \sum_{r} MS_{rbkt}) \leq CS_k \qquad \forall k, \forall t (12)$$

$$\sum_{k} IS_{bkt} \geq SS_b \qquad \forall b, \forall t \; (13)$$

- *Big Bag Handling*

$$\sum_{r}\sum_{b}\sum_{k} MS_{rbkt} + \sum_{b}\sum_{k}\sum_{l} SP_{bklt} + \sum_{r}\sum_{b} ME_{rbt} + \sum_{k}\sum_{b} SE_{kbt} \leq BB_t + BBO_t + BBH_t \qquad \forall t \; (14)$$

$$BBO_t \leq MaxOvertime_t \qquad \forall t \; (15)$$

- *Export Demand*

$$\sum_{r} ME_{rbt} + \sum_{k} SE_{kbt} = DE_{bt} - Lostexport_{bt} \qquad \forall b, \forall t (16)$$

- *Stamping Lines*

$$\sum_{k} SP_{bklt} = \sum_{f \in F_b} \sum_{s} Stamp_{fslt} * ton_s \qquad \forall b, \forall l, \forall t \; (17)$$

$$\sum_{r} MP_{rblt} = \sum_{f \in F_b} \sum_{s} FStamp_{fslt} * ton_s \qquad \forall b, \forall l, \forall t \; (18)$$

$$\left(Stamp_{fslt} + FStamp_{fslt}\right) * ts^{average} \leq CL_{lt} * Z_{flst} \qquad \forall f, \forall s, \forall l, \forall t \; (19)$$

$$CO_{lt}^{size} \geq Z_{flst} \qquad \forall f, s = 100, l \in \{2,5\}, \forall t \; (20)$$

$$CO_{lt}^{size} \leq 1 \qquad \forall l, \forall t \; (21)$$

$$COF_{flst+1}^{save} \leq Z_{flst} \qquad \forall f, \forall s, \forall l, \forall t | t \neq T \; (22)$$

$$COF_{flst+1}^{save} \leq Z_{flst+1} \qquad \forall f, \forall s, \forall l, \forall t | t \neq T (23)$$

$$COF_{flst+2}^{save} + COF_{flst+1}^{save} \leq 1 \qquad \forall f, \forall s, \forall l, \forall t | t \neq T-1, T \; (24)$$

$$\sum_{f}\sum_{s} COF_{flst}^{save} \leq 1 \qquad \forall l, \forall t | t \neq 1 (25)$$

$$FStamp_{fslt} = \sum_{i \in I_{(f,s)}} \sum_{m}\sum_{c} FPack_{ilmct} \qquad \forall f, \forall s, \forall l, \forall t \; (26)$$

$$Stamp_{fslt} = \sum_{i \in I_{(f,s)}} \sum_{m}\sum_{c} SPack_{ilmct} \qquad \forall f, \forall s, \forall l, \forall t \; (27)$$

$$\sum_i \sum_m \sum_c \left(FPack_{ilmct} * t_{ilmc}^{fresh} + SPack_{ilmct} * t_{ilmc}^{stocked}\right) + \sum_f \sum_s ((Z_{fslt} - COF_{flst}^{save}) * ct_{fl}) \leq CL_{lt} - CO_{lt}^{size} * ct_l^{size} \quad \forall l, \forall t (28)$$

- *Bundlers*

$$\sum_i \sum_l \sum_c \left(FPack_{ilmct} * t_{ilmc}^{fresh} + SPack_{ilmct} * t_{ilmc}^{stocked}\right) \leq CB_{mt} \qquad \forall m, \forall t \ (29)$$

- *Case Packers*

$$\sum_i \sum_l \sum_m \left(FPack_{ilmct} * t_{ilmc}^{fresh} + SPack_{ilmct} * t_{ilmc}^{stocked}\right) \leq CP_{ct} \qquad \forall c, \forall t \ (30)$$

- *Final Product Demand*

$$IF_{it} = IF_{i0} + \sum_l \sum_m \sum_c (SPack_{ilmct} + FPack_{ilmct}) - (DF_{it} - Lostsale_{it}) \qquad \forall i, t = 1 \ (31)$$

$$IF_{it} = IF_{it-1} + \sum_l \sum_m \sum_c (SPack_{ilmct} + FPack_{ilmct}) - (DF_{it} - Lostsale_{it}) \qquad \forall i, \forall t > 1 \ (32)$$

$$IF_{it} \geq SS_i \qquad \forall i, \forall t \ (33)$$

- *Variable Types*

$$Make_{rbt} \in N \qquad \forall r, \forall b, \forall t (34)$$

$$W_{rbt} \in \{1,0\} \qquad \forall r, \forall b, \forall t (35)$$

$$Z_{fslt} \in \{1,0\} \qquad \forall f, \forall s, \forall l, \forall t (36)$$

$$COF_{flst}^{save} \in \{1,0\} \qquad \forall f, \forall s, \forall l, \forall t (37)$$

$$COR_{rbt}^{save} \in \{1,0\} \qquad \forall r, \forall b, \forall t (38)$$

$$MS_{rbkt}, MP_{rblt}, ME_{rbt}, IS_{bkt}, SP_{bklt}, SE_{bkt}, Lostexport_{bt}, BBH_t, BBO_t, Stamp_{fslt},$$

$$FStamp_{fslt}, CO_{lt}^{size}, FPack_{ilmct}, SPack_{ilmct}, IF_{it}, Lostsale_{it} \geq 0 \qquad (39)$$