

## MASTER

### A decision supportive profit maximization model for production-to-facility allocation a case study at DSM coating resins

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Eindhoven, 14 November 2014

A decision supportive profit  
maximization model for  
production-to-facility allocation:  
A case study at DSM Coating  
Resins.

by  
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in partial fulfilment of the requirement for the degree of

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in Operations Management and Logistics**

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## Abstract

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During the last decades a large body of literature has developed relating to facility location and allocation models. However, only few of them discuss the model objective of profit maximization. Aiming to extend the current body of literature, this thesis proposes dynamic, multi commodity profit maximization model. The model is subsequently applied to a case study at DSM Coating Resins. A simple, yet extensive model is developed that decides upon the allocation of production to production facilities while simultaneously considering investment decisions. The model is formulated as an MIP (Mixed Integer Programming) model, and is implemented with the usage of a commercial solver. Finally a sensitivity analysis is performed. It is concluded that the optimal solution is mainly affected by the production cost. Furthermore, the study shows that enhancing the capabilities of a production facility improves the overall profitability.

***There's a clown on your back, we're you going?***

(Daniel Norgren, 2010)

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## Preface

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A desk, a chair, fingers on the keyboard. Natural habitat. Nothing that reminds me of the immeasurable amount of freedom that I enjoyed during my time as a bachelor student, my exchange or while travelling. I think I did a pretty decent job rambling about, developing myself in various ways, none of them having anything to do with a professional career. At a certain point I succumbed under the pressure of “expectations”, but I also wanted to show myself that I was capable of something more challenging without taking a huge leap into business. I think by fulfilling my Master’s degree at Eindhoven, I lived up to expectations. Besides, I have learned a lot and I believe that now more than ever, I am ready to pick up some real corporate projects.

Of course all of the previously mentioned rambling could not have been realized without the support of my parents. Thank you very much for giving me the opportunity to take it slow. I could take my steps when I felt like it, and I know that this is a big privilege which you granted me. Thanks very much for your blind confidence and for never pushing me to do anything without being ready for it.

I am satisfied with my decision to fulfill my Master’s at TU/e. The informal atmosphere and the small scale of most courses constitute a pleasant environment to study and learn. However, education is as good as its teachers and to that regard I would like to give a big shout-out to my first supervisor Zümbül Atan. Not just for your knowledge, but even more for all of your time and patience. I know that I struggled in the beginning and that I am a horrible planner, but you always had some time to talk to me, even in between grading 125 exams. In our meetings you made me regain confidence while decreasing my overall stress level. I am really happy that I got you as a mentor. Also, I would like to thank my second supervisor Joachim Arts for providing me with useful feedback on my model.

Furthermore, I would like to thank my company supervisor Simon van Dingstee. I am sorry for bothering you with a few dozen of questions practically every day. Thank you for involving me in everything I wanted to be involved in, often even exceeding the boundaries of my thesis project. I really like your pragmatic way of thinking and working, often making my life a lot easier. Moreover, thanks very much for pushing me and giving me the freedom to orientate myself on the next steps in my career. I would also like to thank everybody else at DSM that helped me with my project in whatever form or shape.

Further, I want to thank my friends from university, especially Bas, Peter, Camiel en Kevin. I don't think that we had a lot of discussions on the content of our thesis, but multiple in distress make sorrow less. For the same reason, I want to thank my little Mexican love Marianita. You had stress for other reasons, but brought me virtual love and laughs when working outside of the office hours. I also would like to thank Dispuut P.I.O.T.. I know have not been there very much after I left Tilburg, but you showed that it was out of sight, but never out of the hart. When I was there I was welcomed with open arms.

Last of all, I want to thank our John, for always helping me out during my time as a student. He lived on my couch in my freshman year, because there was something wrong with his bed (as they failed to set the stands right). He was the last one to read this work before handing in my final version, and he will most likely be the first one to congratulate into becoming an office clerk by means of some ambiguous speech on my graduation party. Thank you very much for this.

One love,  
Bram

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## Executive Summary

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### Problem Description

This study was performed in order to support decision making at DSM Coating Resins with regard to the production of the Waterborne Urethanes products. The main objective of this research was to come up with a mathematical model that proposes the optimal way to distribute production over the current resources in the European supply chain network. In the initial state, three issues were identified and were subsequently addressed by the model;

- High pressure on the supply chain network (total capacity insufficient to cope with the expected demand)
- Unbalanced workload over the production facilities
- No logical allocation of customer demand to production facilities

The aforementioned issues have two root causes. First, the capabilities of the individual production lines are only limited to certain products. Secondly, the initial allocation of production, or the initial aggregate production plan, is created by outdated and faulty system parameters instead of dynamically, with consideration of all relevant factors that affect the profitability. To this extent, two opportunities were identified to increase the overall performance of the supply chain network. First, investments could be made in order to further exploit the potential of the supply chain network through increasing the capabilities of production lines. Second, the allocation of demand and production to the production facilities was reconsidered.

### Research assignment

In order to guide the research, the following research question was formulated:

*What is the optimal product-to-plant allocation strategy for DCR in order to maximize the profit regarding the waterborne urethane product family, such that the utilization objective is not violated?*

The research was guided by the Operations Research Process methodology proposed by Sagasti and Mitroff (1973). This framework and our application of the framework, are best described in four steps;

- **Conceptualization**, from reality to conceptual model.
  - Identified what to include in the model, and how to include it (i.e. main (cost) drivers, the constraints and scope).
- **Modelling**, from a conceptual model to a scientific model.
  - Formal, mathematical description of the conceptual model.
- **Model solving**, from a scientific model to a solution.
  - Solving the scientific model with DCR case input variables, including a sensitivity analysis to determine model behavior under different circumstances.
- **Implementation**, from a solution towards reality.
  - Recommendations and conclusion deduced from the model solution and sensitivity analysis.



### Model description

The model objective is to maximize the profit, including all relevant cost drivers of the current supply chain network. Table 1 gives a short overview of the most important profit parameters and the accompanying decision variables.

Profit Parameter	Decision variable
Revenue per unit volume of a product sold to a customer	Total volume of each product shipped from a production facility to a customer
Transportation cost per unit volume	Idem
Production capability investment cost	Decision to invest in increasing the capability of a production facility
Raw material cost, production cost	Total volume of each product that is produced at a production facility

Table 1: Profit parameters with the corresponding decision variables.

To allocate the demand and determine the throughput rate, the model focusses solely on the bottleneck of the production process. The model is dynamic, determining the allocating on a monthly basis and allows for both building up stock and delivery from backorder. Only the make-to-stock products were considered. Finally, all three production lines are included by the model as independent facilities.

### Model solution

The model solution proposes investments in the product B-3, B-4, B-8 and B-9. The distribution of production according to the model is displayed in Figure 1, where the colors indicate the different facilities.

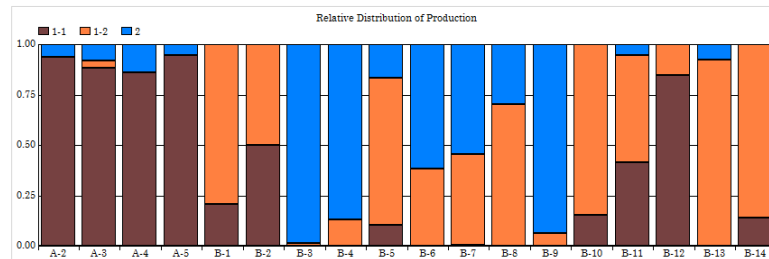


Figure 1: Model solution for the relative distribution of production to the production facilities for each product

The proposed solution is expected to increase the total output with around 3.3 percent without violating the utilization constraints. Furthermore, it is expected to increase the total profit of the supply chain network. After obtaining the model solution, a model extension was designed that included, for each product, penalty idle times for allocating large volumes to the same facility.

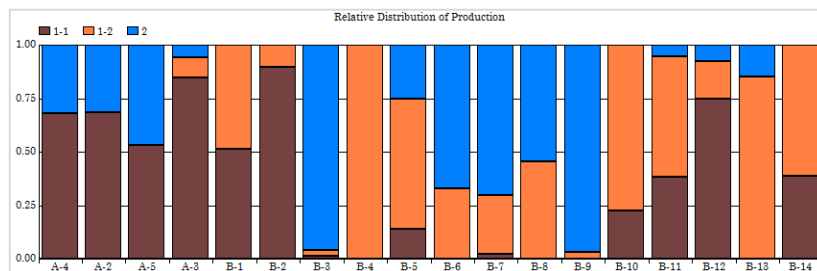


Figure 2: Extended model solution for the relative distribution of production to the production facilities for each product

This solution differs as there was not invested in enabling the production of B-4 at facility 2, because more capacity is allocated to produce A-2, A-4 and A-5 in facility 2. This leads to a decreased service level and a decreased overall profit.

## Conclusion

The model performs well and shows that the profit can be increased by making the proposed investment decisions, combined with suggested allocation of production to the facilities. Subsequently, the customer demand is allocated to the facilities according to a local-for-local strategy. Doing so will increase the overall production efficiency of the network. Furthermore, the right investment decisions (i.e. B-3, B-4, B-8 and B-9) have a big impact on the total profit that can be obtained by the supply chain network. Also, these investments enable the network to increase the output of the network, leading to increased flexibility and service levels. The optimal solution is mainly affected by the investments that are able to release the full potential of the supply network (i.e. enable production at different facilities with accompanying lower throughput or cost rates). In addition, it is affected by the cost of production and raw materials at the different production locations. Freight, backorder, and inventory cost are not expected to affect the optimal solution.

## Recommendations

In order to guide DCR with the implementation of the recommendations, a summary of the proposed actions is described in order of execution.

1. Make investments on transitions of B-3, B-8 and B-9 to facility 2 as these investments are suggested by the model the base-case, the extended model case, and virtually all other considered scenarios.
2. Reconsider the current aggregate production plan, redistributing the production over the different facilities, thereby creating a feasible production plan for 2015. Change the corresponding system parameters that trigger the initial production plan accordingly.
3. Recalculate the current stock levels based on the model outcome. This includes elaborating on the calculations or estimations of holding and the backorder cost parameters.
4. Build up stock to cope with the demand peak in January 2015
5. For products A2, A-3 and A-5 at facility 1-1, investigate the exact production levels for which the bottleneck shifts towards a different production stage. Estimate the costs for debottlenecking and compare this to the extra profit that can be obtained by the optimal model solution. Hereafter decide whether these investments are preferred.
6. Reevaluate the raw material costs and estimate possible economies of scale for procurement of raw materials in the new situation.
7. Quantify the future demand increase for products B-3 and B-4, based upon this decide to increase the total availability for the products under consideration.

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## Research Introduction

This chapter is introductory to the master thesis project. First, Section 1.1 and Section 1.2 give some background information on the company where the research was conducted. Hereafter, Section 1.3 briefly describes the problem situation at the commencement of the project. After that, Section 1.4 gives an overview of previous research relevant to the problem under consideration. Subsequently, Section 1.5 summarizes the research assignment that guided the research. The methodology used in order to perform the research is described in Section 1.6, and finally the outline of the report is given in Section 1.7. For a more extensive introduction of the research, there is referred to Jacobs (2014a).

### 1.1. Royal DSM N.V.

DSM was established as “De Nederlandse Staatsmijnen” (English: Dutch State Mines) in 1902, a company that exploited the Dutch coal mines located in the south of Holland. Over the years focus of the company shifted towards *Life Sciences and Materials Sciences*, encompassing a wide range of products within the health, nutrition and materials industries. For 2013 the company achieved a total revenue of around 10 billion dollars, employing 24.500 people worldwide. DSM aims for continuous and steady growth in a responsible way, translating into a strategy that creates innovative and sustainable products. Simultaneously they intent to grow within the emerging markets. The company is currently listed at the Euronext Amsterdam Stock Exchange. In terms of sales, three important clusters can be distinguished; Nutrition, Performance materials and Polymer Intermediates. Figure 2 shows the 2013 sales per cluster and region.

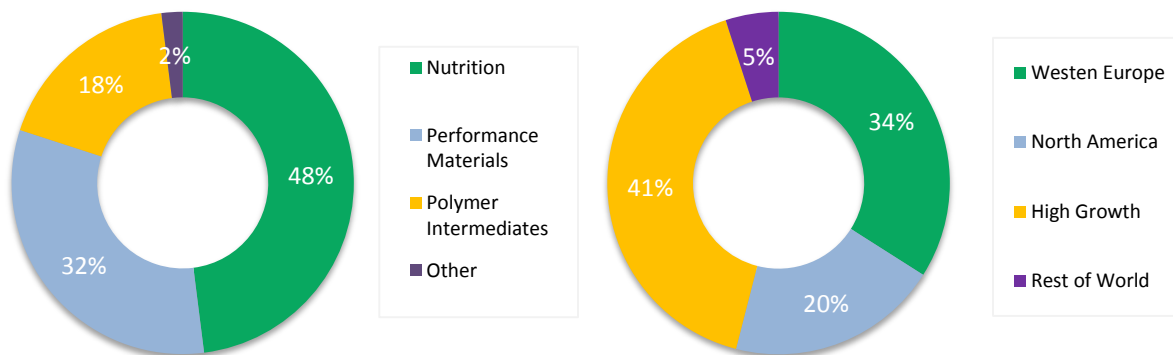


Figure 3: 2013 net sales per cluster and per region (% of total)

### 1.2. DSM Coating Resins

This research takes place within the business cluster of performance materials, of which the business group DSM Coating Resins (DCR) is part. DCR develops, manufactures and markets high-end resins and coatings. A resin is an intermediate product towards the development of paints and coatings and largely determines the properties of the end-product. Currently DSMs resins are used in different end markets, including automotive, aviation, electronics, marine, sports and leisure, paint, coating and construction.

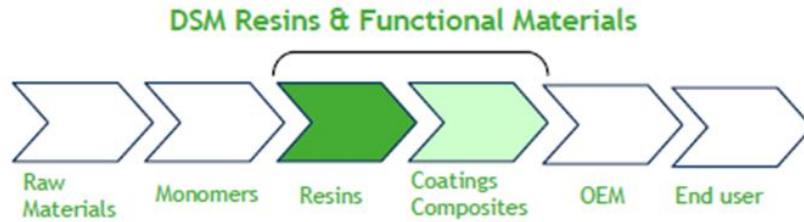


Figure 4: DSM R&FM's position within the value chain

Within the coating industry, DCR plays a leading role in the realization of the current market shift towards sustainability by developing and continuously improving multiple different types of sustainable coatings.

### 1.2.1. Waterborne Urethanes

This project considers only a specific product family produced by DCR, i.e. the waterborne urethane (WBU). WBUs are high quality, sustainable and eco-friendly resins. They are characterized by their strong chemical compounds, that translate to robust, hard and durable resins, insusceptible to undesirable reacting behaviors. The WBUs serve as a fundamental raw material for a wide range of coatings used in industrial-, architectural-, varnish-, graphical arts- and adhesives industries. Accordingly, its applications are broad with examples that range from high-end varnishes to currency printing ink to mobile phone coatings. In spite of their costliness, their special properties as well as their sustainable character, have made WBU products increasingly popular over the last years. The resins are developed to serve all kinds of purposes. They can differ with regard to their flexibility, toughness, adhesion or feeling. DCR aims to provide and develop *specialty resins* to the exact needs of the market as well as individual customers, giving them a strong competitive edge.

### 1.2.2. Supply Network

The research project focusses on the EMEA region (short for Europe Middle East & Africa, though in the case DCR it also includes several countries in Southern America). A simplified version of the supply chain network for WBUs is depicted in Figure 5. It shows two different DCR manufacturing sites, both supplied by (multiple) regional suppliers. Inventory is stored at the production facilities and the customers are served directly from the production facilities. Both production facilities serve customers within the same region, i.e. EMEA, however, both factories only produce part of the total product portfolio (i.e. some products are produced only in Waalwijk (NL), others only in Parets (ES), and others in both factories). In the current state, production lines are incapable of producing all products. At additional costs, it is possible to enable production of a specific product for a specific production line.

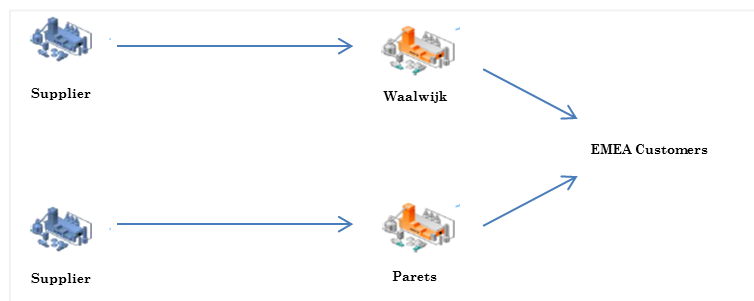


Figure 5: Supply chain network for WBU product family

### 1.3. Current Situation

This section gives a short summary of the problem situation at the start of the project. Figure 6 displays the main problem as perceived by DCR's management initially and the initial problem causes. The main assumption was that the supply network for the WBU products (i.e. the whole network that includes procurement of raw materials, the production and distribution of goods towards customers) was not used efficiently. This problem was two-folded: I. the pressure on the supply network was too high, and II. the supply network was operating at excess costs.

#### 1.3.1. High Pressure on Supply Network

When referring to high pressure on the supply network, this means that the supply network has difficulties to cope with the total demand. First, this was caused by inefficient use of resources in the supply network; The Aggregate Production Plan (APP) allocated the production over the available production facilities, where the initial production plan was created by the Enterprise Resource Planning (ERP) system. However, the ERP used faulty and outdated parameters to allocate customer demand to production facilities. Adjustments to the APP were made, but only on the lowest hierarchical planning level. As such, critical factors to effectively constitute the APP remained ignored. Simultaneously, DCR recognized that investments were to be made in order to utilize the current resources in a more efficient way. The investments that were expected to be most cost-effective and feasible in terms of available budget, were investments that increase the production portfolio for one of the production facilities.

#### 1.3.2. Excess Cost of Operating the Supply Network

The second assumption made by DCR's management, was that the supply network was operated at excess cost. First, part of the distribution costs were believed to be redundant as for the majority of the customers there did not exist any consistency with regard to the production facility that fulfilled their orders. Furthermore, a large and unnecessary flow of goods was observed between production facilities. Finally, excess costs arose since both the cost of raw materials and production were not considered for determination of the production location.

#### 1.3.3. Root Causes of Current Problem

Figure 6 shows that the majority of the causes can be directed back to inefficient planning and more specifically to the *faulty and outdated system parameters* that created the initial production plan. These parameters did not only trigger the initial APP, also did they determine the location from which a product was shipped to a customer. Now, structurally, a high proportion of the APP was adjusted, leading to a situation where production and distribution became desynchronized. To illustrate this, consider the following example; product **x** is ordered by customer **z**. According to the system parameters, product **x** will be produced in factory **A**. Factory **A** has capacity issues, so finally the product is rescheduled to factory **B**. Finally, according to the system, product **x** still needs to be delivered from production facility **A**. This results in a product transfer of **x** from **B** facility **A**, before being sent to the customer. The capacity issues at either of the facilities were caused by increased demand together with the lack of investments to increase the total network capacity. Investments could both increase the effective usage of resources in the network, as well as the total capacity of the network.

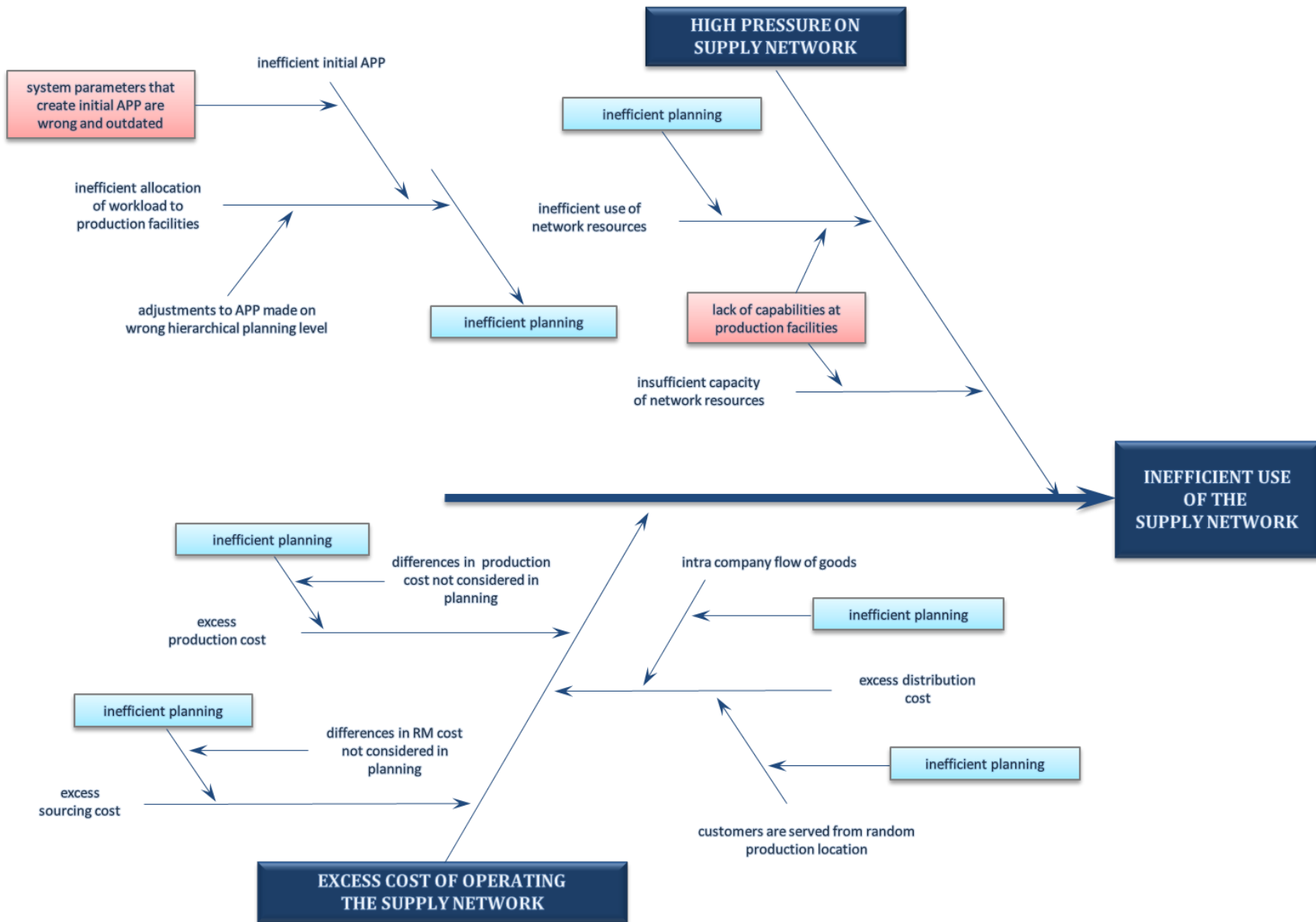


Figure 6: Cause-and-Effect Fishbone Diagram of the current problem situation (Ishikawa, 1990)



## 1.4. Literature Review

This section gives a brief overview of the literature available that relates to the problem under consideration. It supports the development of the mathematical optimization model and it identifies possible gaps in the current literature. This section summarizes the parts of the work of Jacobs (2014b), for a more extensive review of related literature there is referred to his original work.

### 1.4.1. Facility Location Problem

The science of facility location has developed into a popular field of research over the last decades. Farahani and Hekmatfar (2009) define the facility location problem as: *the problem to locate a set of facilities such that costs are minimized while satisfying some set of demand points and taking into account a number of constraints*. Typical questions to answer are: (i) which facilities should be opened or used? (ii) Which demand points are served from which facility? Scientists have explored the field of location theory for both private as well as public sectors, leading to a vast amount of publications, algorithms and mathematical formulations, all of it in service of supporting decision making with regard to locating facilities (for a recent overview of the literature see e.g. Owen and Daskin, 1998; Klose and Drexler, 2005; Snyder, 2006; Shen and Qi, 2007; Melo, Nickel and Saldanha-da-Gama, 2009).

### 1.4.2. Multi-Facility Loading Problem

In multiple cases, locations of production or distribution facilities are already in place, emphasizing on the optimal way to utilize the facilities. Especially for companies with large product portfolios, decisions regarding the production location comprise an important part of determination of the production strategy. As the facility locations are already fixed, they strictly do not qualify as facility location problems, but rather as a generalization of the facility location problem with multiple commodities. The location is already determined, but the problem to decide where to produce what products, and what quantities remains. Cohen and Moon (1991) present a model that determines the allocation of products to a number of capacitated plants in order to minimize total cost. A similar model formulation proposed by Mazzola and Schantz (1997). The literature directly addressing the multi-facility loading problem however, is limited.

### 1.4.3. Modelling Characteristics

The previous research on facility location models can be divided into sequential and integrated models. The former only considers strategic decisions on facility locations, while the latter also includes tactical decisions with regard to routing and inventory levels. Shen and Qi (2007) prove that integrated models perform better than sequential models. More specifically, they postulate that the lower the proportion of location cost in the total cost, the higher the potential benefits of using integrated models. This suggests that if the operational and/or tactical costs are relatively high in relation to the fixed cost of opening a facility, then it is beneficial to include both to make decisions related to facility locations.

For both sequential and integration, the most important modelling characteristics are considered the following:

- When cost structures and demand patterns display high fluctuations over time, and the cost of reallocation is relatively low, dynamic modelling characteristics can be considered. Dynamic models can consider opening as well closing down facilities over time (Klose and Drexler, 2005).
- Provided that the future state of the supply chain, in terms of e.g. demand or cost to serve, is very uncertain, a model needs to include uncertainties. Ignoring possible uncertainties in the data can lead to highly sub-optimal solutions. Models can include

multiple scenarios that occur with a certain probability, such that the optimal *expected* objective values are attained. (Farahani & Hekmatfar, 2009).

- If possible, a benefit should be made from decisions making on multiple echelons simultaneously instead of considering decisions and factors for each individual echelon. Ghiani et al., 2013; Pirkul and Jayaraman, 1998).
- Different objective functions are found in the literature. Besides cost minimization, models can be formulated with objective functions such that e.g. profit is maximized, customer responsiveness is maximized, product lateness is minimized, environmental impact is minimized or workload balance is maximized. Also, depending on the purpose of the model, multiple objective functions can be included. In such cases, the weight attributed to the different objectives, determines the solution that is chosen (Melo et al., 2009).
- When production or transportation costs are expected to be non-linear, a model can account for economies of scale (or scope) by including non-linear, concave cost functions (Shen, 2005).
- Where profit maximization is considered, there cannot be assumed that all customer demand is fulfilled. Shen (2006), includes an option for demand rejection into his model, in order to reject demand for which the marginal revenues are higher than the marginal cost to serve the customer.

#### 1.4.4. Identified Gaps

The facility location problem has been an important research topic over the last decade, as facility location decisions are recognized as critical elements in strategic planning for both public- and private organizations. Still many directions remain uncovered. In relation to supply chain management, the following gaps are found in the literature under consideration;

- The models found in the literature largely relate to cost minimization (Melo et al., 2009). Research should be directed more towards other objective functions, such as profit maximization, workload balancing, production efficiency, customer responsiveness or the environmental impact.
- Studies towards multiple objectives are still limited, especially when solely considering the sequential models that exist within the literature (Melo et al., 2009).
- Regarding the multi facility loading problem models, only few studies address this specific problem. Extending the body of literature for those specific models is expected to lead to more insights on ditto problems. Moreover, it will aid practitioners from different industries with their decisions upon production locations.
- For multi facility loading problem, no integrated models exist. Such models should be developed to see if the (economic) impact of integration is similar to the impact of integration on facility location problem.

In order to contribute to the common scientific knowledge, this research aims to gain more insight into the multi facility loading problem. In order to further extent the current body of literature of the facility location problem, the research will be directed towards profit maximization, as this topic is still only marginally covered in contemporary literature.

## 1.5. Research Assignment

### 1.5.1. Objective

In an attempt to eliminate the root causes of the current problem, the goal is to develop a mathematical optimization model that simultaneously considers all important aspects of the supply network. The model should be able to guide in decisions making related to mid-long term investments, the allocation of production (for each product) to plants, and the allocation of the (forecasted) demand to the production facilities. The research is conducted within the dynamics of an real, existing supply chain. Therefore the model outcome should be tested given multiple (realistic) scenarios, thereby providing insights in the most important variables that affect the optimal solution, as well the way that they affect the optimal solution. Altogether, this should result into insights on how to decrease the high pressure on supply network, while simultaneously decreasing the total operational cost.

### 1.5.2. Research Questions

In order to guide the research, the following questions are formulated. The main research question for the project under consideration is:

*What is the optimal product-to-plant allocation strategy for DCR in order to maximize the profit regarding the waterborne urethane product family, such that the utilization objective is not violated?*

The following sub-questions are formulated to guide in answering the main research question;

1. *What are the relevant cost and revenue drivers of the supply network?*
2. *What are the constraints with regard to product-to-plant allocation?*
3. *How does reallocation of products to plants affect the production efficiency and what is the impact on the utilization rates for the different production facilities?*
4. *How is the optimal strategy affected by investment decisions?*
5. *What variables influence to the optimal product-to-plant allocation strategy and how do those variables affect the optimal strategy?*

## 1.6. Methodology

The research is conducted in accordance with the methodology proposed by Sagasti and Mitroff (1973) and later adapted by Mitroff, Betz, Pondy, and Sagasti (1974). They consider Operations Research (OR) from a general systems theory, postulating that the OR process should be considered as a system with several component subsystems. The researcher should be concerned with both the subsystems and the relation between them. Each subsystem corresponds to a particular phase within the OR process. Furthermore, they state that the subsystems only exists in relation to each other, i.e. analyzing a subsystem in itself is meaningless. This section will briefly describe the systems view of problem solving as proposed by Sagasti and Mitroff (1973), a schematic representation of the methodology is given in Figure 7.

The first subsystem is named *reality*. It consists of all the aspects of the real world that concern the problem situation. It includes all the unorganized perceptions of the researcher that relate to the problem situation. Sagasti and Mitroff (1973) propose that when facing a problem, or reality, the operations researcher needs to construct a “mental image” that corresponds to reality. This “mental image” is called the *conceptual model* of the problem situation. The mental image should function as a framework that has the ability to translate reality to concepts that allow the reality to be modelled. The focus should be on those characteristics that are relevant to the problem under investigation. The conceptual model is ought represent reality to a high degree of abstractness, allowing the researcher to successively construct a scientific model. Through conceptualization, a rigorous definition of the scope and the problem

under investigation are proposed. The conceptual model specifies *what* variables are used in order to describe the problem, as well as *how* those variables are included in the model (e.g. the degree of aggregation, the time horizon and so on, Mitroff et al. 1974).

The *scientific model* is achieved through formalization of the conceptual model. Critical to the scientific model is its genuine correspondence to reality. A scientific model can be developed at a high level of abstractness, it should still relate to the real world in order for it to be useful and valid. By manipulating the model in this phase, the researcher is able to test the model for its internal consistency, validity and degree of correspondence with regard to the reality.

Ultimately, solving the scientific model should lead to a feasible *solution*. The solution is often looked at as the output of the OR process and should lead to recommendations or implementations that affect reality. In some cases, the solution phase is linked back to the conceptual model by another feedback loop. Sagasti and Mitroff (1973) refer to this as feedback in the narrow sense, for it allows the operations researcher to test the relevance and coherence of the solution by contrasting it with the original, conceptualized model of the problem situation.

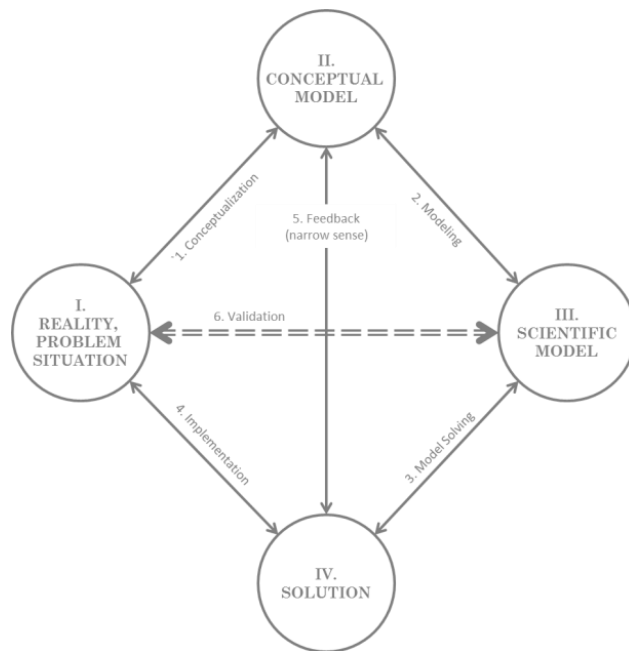


Figure 7: A systems view of problem solving (adopted from Sagasti & Mitroff (1973))

## 1.7. Report Structure

The report is structured in line with the research methodology. First, Chapter 2 describes the reality by performing an in depth analysis of the relevant supply chain characteristics. It aims to accurately describe and validate the problem under consideration. Second, Chapter 3 is used for the conceptualization of the current problem, where after the conceptual model is presented. In Chapter 4 there is explained how the model is formalized from a conceptual to a scientific-, or mathematical model. Subsequently, Chapter 5 is used for model solving, explaining the choices for and configuration of the selected software. Furthermore this chapter validates the model and its assumptions and elaborates on the chosen input for the model. Hereafter, a sensitivity analysis is performed in Chapter 6 and a model extension is presented in Chapter 7. Finally, in Chapter 8, the conclusions are presented together with the recommendations that follow from them. This final chapter is concluded with model feedback and directions for future research.

## Supply Chain Network Analysis

According to Mitroff & Sagasti (1973), the first subsystem of OR research should contain all aspects that concern the problem situation or “reality”. This part of the research should include all the data and initial input to the operational researcher that relates to the current problem. Therefore, in Section 2.1, the supply chain network characteristics related to demand, production and sourcing, as well as the accompanying cost drivers are discussed. A summary of this chapter is provided in Section 2.2.

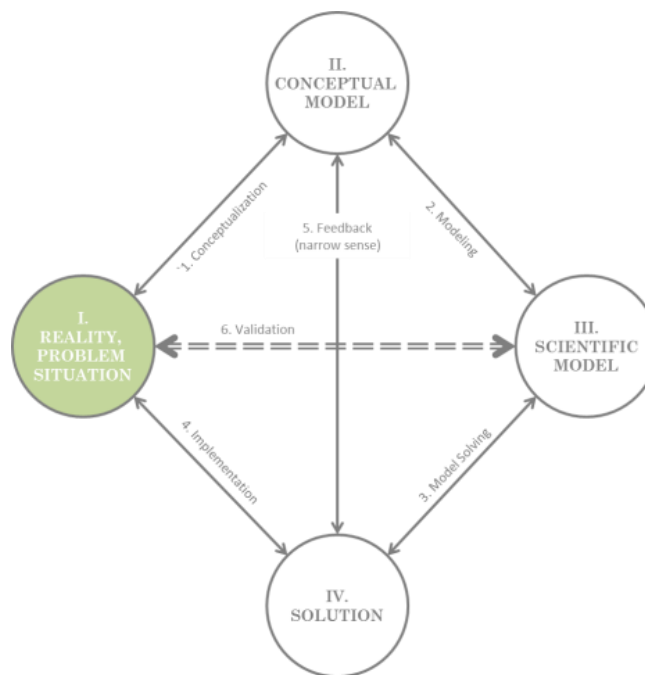


Figure 8: A systems view of problem solving, I. Reality (adopted from Sagasti and Mitroff, 1973)

### 2.1. Supply Chain Network Characteristics

This part elaborates on supply chain characteristics relevant to the current research. In order to perform analysis on the right level of aggregation and by means of consistency, there is decided to include the full year of 2013 in the analysis phase. If deemed necessary, the forecasted data of 2014 and 2015 are considered as well.

#### 2.1.1. Demand

Demand, or the demand patterns, are fundamental in the to the design of a supply chain. (Langevin and Riopel, 2005). The characteristics of demand in terms of its center of gravity concerning the products and customers, as well as the development of the demand, are discussed in this section.

## Products

Within the WBU and WBU/A product family there are 80 different product types that have been sold over the last year. These products are subdivided into 155 Stock Keeping Units (SKU)s. All SKUs are a unique combination of a product type (onwards referred to as product) and packaging type.

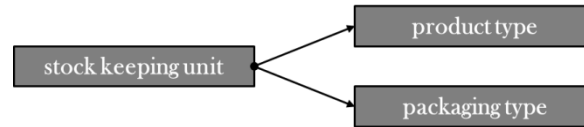


Figure 9: Product SKU characteristics

## Historical and Future Demand

For the aggregated (both realized and expected) demand volume up to the end of 2015, 18 products account for over 80 percent of the total demand volume. The remaining 20 percent of the products have a yearly demand volume that is relatively low. The former 18 products are all made to stock, whereas the latter are only made on request of the customer. From here onwards, there is assumed that increasing the capabilities of production lines, can only be beneficial for the make-to-stock products. For this reason, the remainder of the case study at DCR will focus on these products. The distribution of the (forecasted) sales volume of these products is depicted in Figure 10.

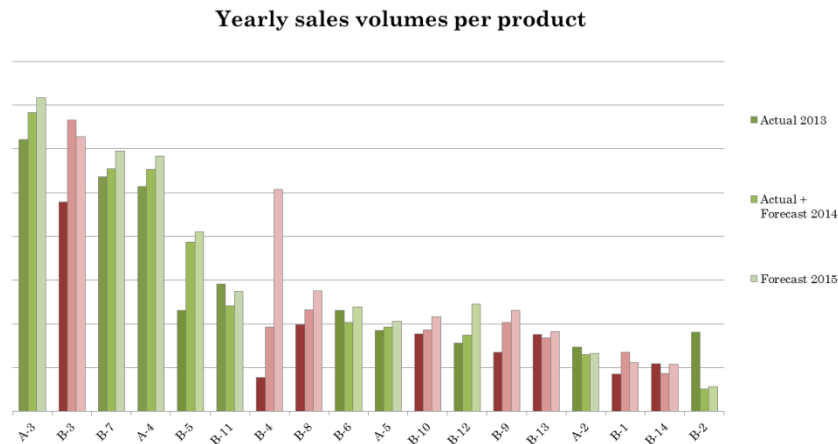


Figure 10: Total yearly sales volume per product

The graph shows, for each product, from left to right; the actual sales for 2013, the latest view on sales for 2014 (i.e. actual demand plus the forecasted demand for the remaining months), and the forecasted sales for 2015. The green columns indicate products that can be produced both in the PA and WW (i.e. current state, considering no additional investments), the red columns display the demand volume for products that can solely be produced in WW. Products B-3, B-4 and B-8 stick out, as their (expected) demand volumes are relatively high, but only one out of the two production facilities possesses the capability to produce them. The demand for the EMEA zone further consists of the intra company flow of goods towards DCR factories located on different continents, i.e. one in Asia, the other in Northern America. For simplicity, they are treated as normal customers.

## Dispersion of Customers

The customers of the PA and WW factories are dispersed all over the world, though the center of gravity of demand is Europe. Figure 11 displays the dispersion of the demand from European based customers graphically. Every blue circle represents demand from a specific customer, the

size of the circle reflects the total demand volume for 2013. The aggregated sales for all countries outside of Europe is represented by the blue spot in the Atlantic. All circles are scaled continuously (i.e. their diameter is equal to the scaled sales volume).

The demand volume for customers outside of Europe is aggregated because of the relatively low demand volume per country. Also, the customer demand for these countries is satisfied similarly from both the PA and WW locations, i.e. the differences in terms of transportation cost and lead time to serve customers, are negligible. From the graph, there can be deduced that demand was highest in Germany. Other important regions are The Netherlands, Italy, Belgium, Sweden, UK, Spain and France.

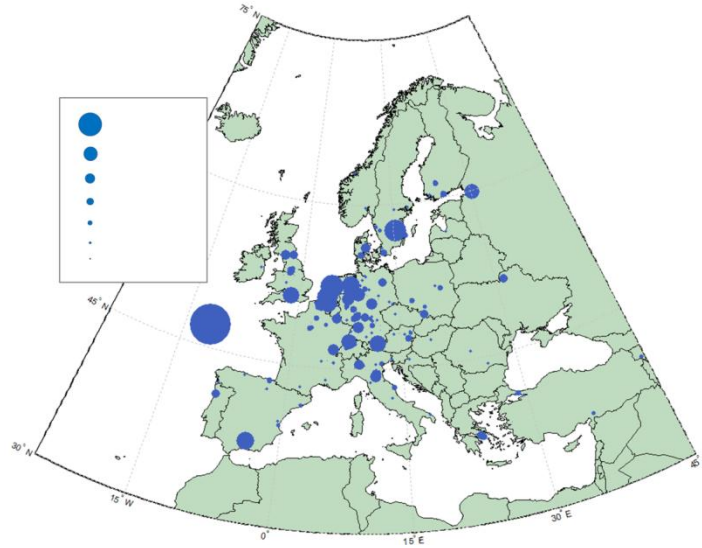


Figure 11: Dispersion of the historical demand for European customers, 2013

### Dispersion per Product

On a product level, the demand volume differs widely among the countries. The differences between countries are attributed to the relatively low number of total customers per country. The data under consideration counts 273 unique customers, spread over 46 countries. Since customers generally procure between 1 to 5 different products, this explains the disparity between regions in terms of product sales. The total number of orders per month (for 2013) ranges from 300 up to 400. Considering the number of orders per month, the total amount of different products, and the spatial dispersion of customers, the monthly demand per country per product is very dynamic. As an example, Figure 12 illustrates the monthly sales volume for a high volume product (A-3) in a high volume country (Germany). From this example it shows that the demand of January is around 45 times the demand of December.

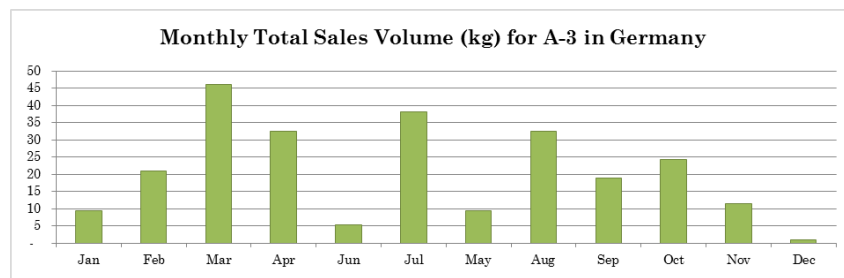


Figure 12: Example of monthly total sales volumes for the A-3 in Germany, 2013 (scaled)

### 2.1.2. Supply

#### Production process

All production facilities consist of sequenced reactors where the chemical processes take place. For some products two, and for other products three different reactors are used in succession. The order in which the process takes place, is fixed. Furthermore, independent of the product and the production facility, the first reactor in the process was identified as the bottleneck reactor. The routing times per reactor, as well as the batch size differ per product and per production facility. The cost of production is linear, i.e. no economies of scale can be obtained. Batch sizes are fixed for each product-production facility combination, and the routing times are independent sequence in which batches are produced.

#### Unbalanced Workload

Part of the problem related to the allocation of the demand to the different production facilities. The workload was structurally imbalanced, such that the WW facilities were overloaded, while the PA factory was under loaded. This part of the problem is verified by means of Figure 13, which shows, for both factories, the sales plan (2013) along with the actual produced volumes. The sales plan includes both the customer- and intra company demand that was initially allocated to each of the production plants, i.e. it created the initial production plan.

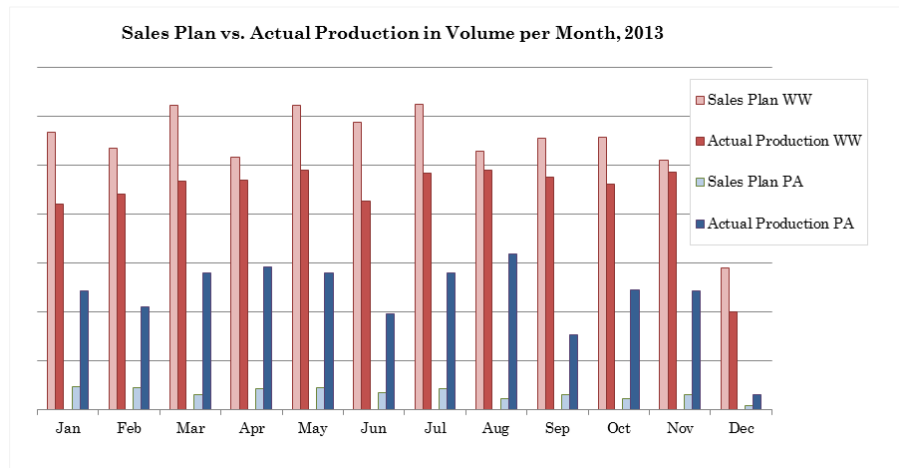


Figure 13: Sales plan vs. actual production volumes for WW and PA factories, 2013

Considering Figure 13, notice that the sales plan for WW in every month of 2013 was higher than the actual production, while the sales plan for PA in every month of 2013 was structurally lower than actual production. A structural imbalance in the supply network is not necessarily bad, e.g. think of two factories with low fixed costs and set-up costs. Factory A has a low variable cost to produce and serve customers, while B has a high variable cost. In this case, factory B could be used only to back up factory A. However in practice, this is usually not the case; workload balancing is an important consideration for the design of the supply network (Klose & Drexl, 2005). In the case of DCR, the imbalance meant that the initial production plan for the mid-long term was infeasible. It was corrected every month by the operational schedulers, leading to excess work and a poor performance of the aggregate production plan.

#### Fulfillment of Demand

The absence of a structural plan to allocate customer demand (or demand regions) to production locations, is also expected to have caused excess distribution cost. The dispersion of the customers and the accompanying yearly sales volumes, *only for those products that were produced in both PA and WW*, are depicted in Figure 14a and Figure 14b. The red circles suggest that the production took place in WW, whereas the blue circles signal PA production.



Multiple red and the blue circles originate from the same point, implying that a customer was served from both production locations. This was the case for over 48 percent of all European-based customers. The demand of each customer was not structurally fulfilled by a specific production plant, rather the demand was fulfilled in a random fashion. This could be justified if the benefits obtained by the indirect delivery via a fixed location (i.e. through consolidation of stock) are higher than the total cost increase (e.g. (un)loading of trucks, excess transport costs and other additional handling costs). However, inventory is not considered to be a main cost driver (more about this subject in Section 2.1.5). Therefore, direct delivery should be preferred by DCR.

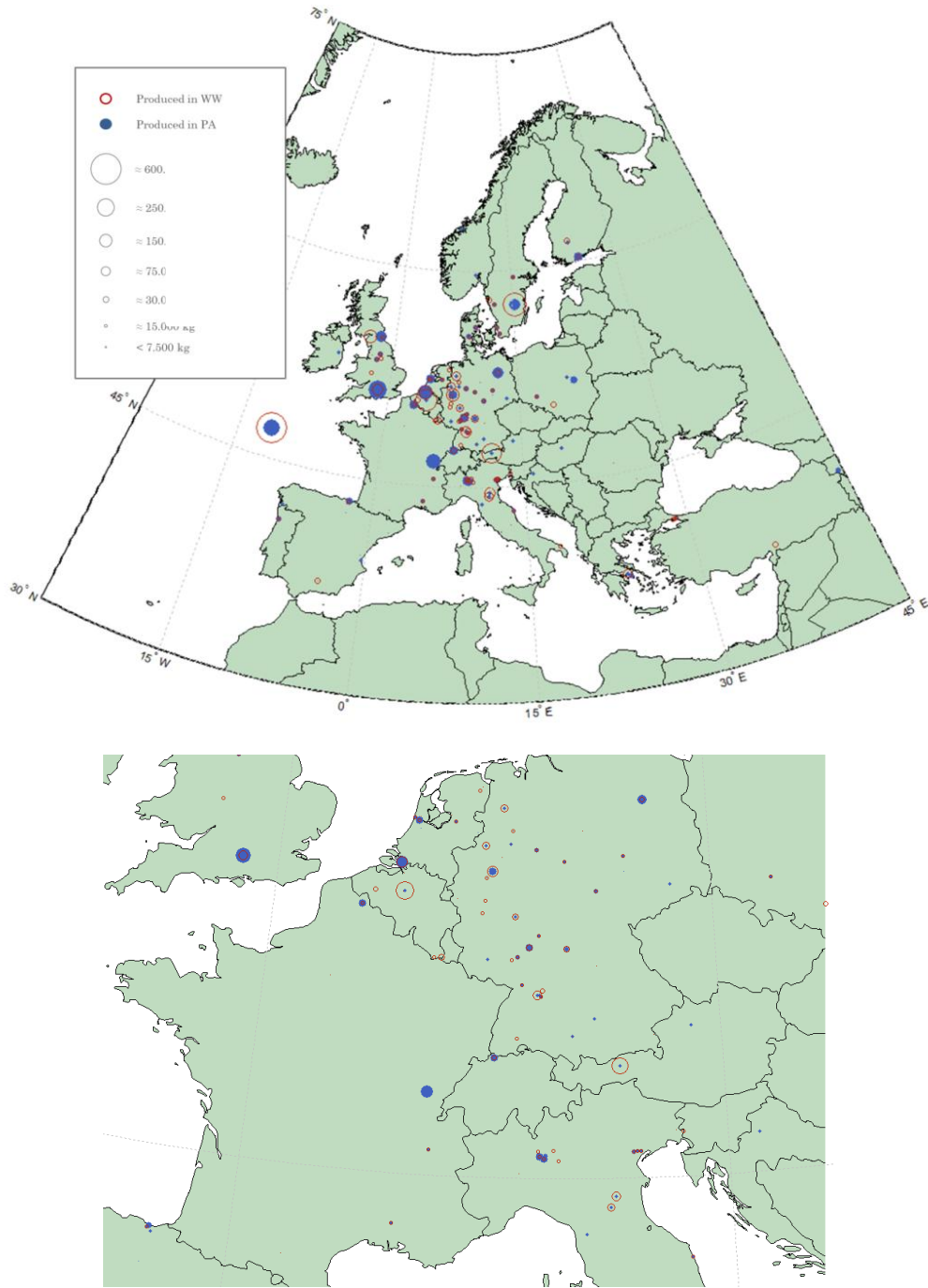


Figure 14a (above): Sales volume dispersion, 2013; Figure 14b (below): Magnification of clustered area.

### Service level

The realized service levels of both the PA and WW plant are depicted in Figure 15. Both the WW and the PA site had difficulties to reach the service level target of 95 percent. Again, not that only the MTS products are considered.

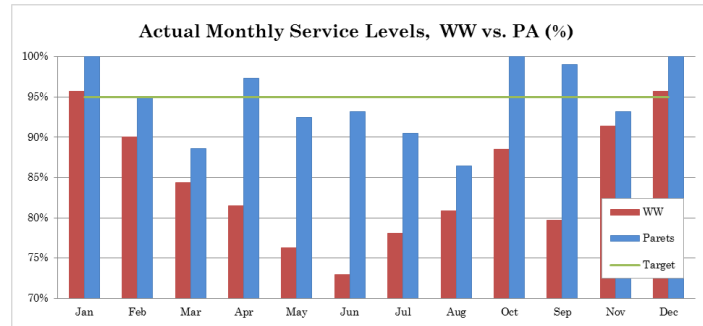


Figure 15: Actual monthly service levels for the WW and PA factories, 2013.

Poor customer service levels negatively impact the company in various ways. It decreases customer satisfaction and could cause undesirable extra costs to serve a customer, a loss of sales and eventually the loss of customers. Also it could negatively impact the company’s reputation (Gupta & Zeithaml, 2006). In the case of MTS products, the service levels depend on the choice of appropriate inventory levels. The inventory levels are driven by the desired customer service levels, the lead time to the customer, and the expected magnitude of future demand (Langevin and Riopel, 2005). The preceding assumes sufficient and adequate supply of raw materials and production capacity. For the supply of raw materials, this assumption is reasonable (more about this in Section 2.1.3), yet the production capacity of the supply network was insufficient, hereby explaining the low service levels.

### (Expected) Asset Utilization

The DCR facilities are facing high (expected) asset utilization rates. To illustrate this see Figure 16. It shows both the actual utilization rates from the start of 2013 up to July 2014, as well as the expected asset utilization rates, given the forecasted demand and current production capacity.

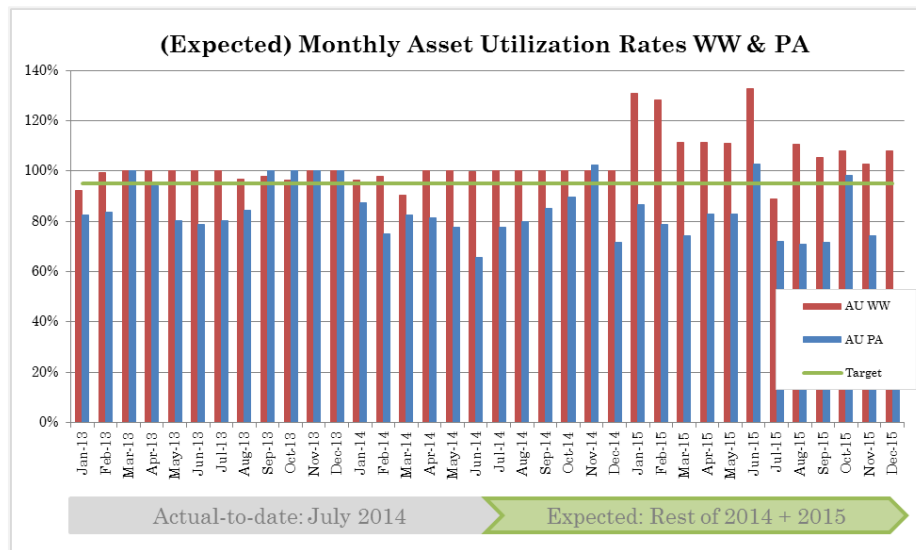


Figure 16: Actual and expected asset utilization rates for WW and PA factories

First, the figure shows that from the start of 2013 until July 2014, both factories struggled to stay below the upper bound target on the utilization rate of 95 percent. A high utilization

(especially when it approaches 100 percent), is expected to have a negative effect on the overall service level (Hopp and Spearman, 2000; Felberbauer, Altendorfer, & Jodlbauer, 2013). This is because the production facility loses its flexibility and is unable to cope with variability. As service levels are negatively impacted by a high utilization rate, this could be one of the reasons that the PA factory performed better than the WW factory. Second, the figure illustrates that the production plan (from July 2014 onwards) was infeasible. The WW factory structurally exceeded an expected asset utilization of a hundred percent, and in some instances, this is the case for both factories. From January 2015 onwards, part of the WW production plan could still be reallocated to PA, but this possibility would not suffice in order to create a feasible production plan.

### Resources

The production for the WBU and WBU/A products takes place on three different production lines. Two of those are located in WW (from here on referred to facilities 1-1 and 1-2), the third is located in PA (facility 2). Two performance measures are considered relevant for the current research. The first is the Manned Running Time Available (MRTA), which indicates the total hours in each month that a production line can be utilized to generate output. From this point onwards, there will be referred to MRTA as the availability of a production facility, or simply availability. It does not consider the planned (e.g. planned maintenance) and unplanned time losses. What it does consider is the downtime that occurs because there is no demand. The second is the Capacity Requirement Factor (CRF). It displays the required *availability* at the bottleneck reactor, in order to produce one ton of output (i.e. 1 divided by the throughput rate). It is calculated through historical data, and implicitly includes information on the product recipe, reactor size, reactor design, setup, raw material dosing and the heating/cooling processes. The CRFs are calculated on different levels of aggregation, i.e. for each product-production line combination, production line and production plant. As such, they can be used for different purposes. The two measures mentioned above (CRF and availability), combined with the total calendar time (i.e. in principle, a production facility is opened every day of the year, 24 hours a day), constitute the total production capacity in terms of output volume. A very small percentage of the total output cannot be sold to the market directly due to quality issues with the end product. Quality issues are related to the production line, and not to the product-production line combination.

### Resource Capabilities

The current production capabilities are summarized in Table 2: Production capabilities of all production facilities in the current state.. F1-1 and F1-2 represent the production lines in WW, F 2 in PA.

Product	Capabilities		
	F 1-1	F 1-2	F 2
A-2	1	0	1
A-3	1	1	1
A-4	1	0	1
A-5	1	0	1
B-1	1	1	0
B-2	1	1	1
B-3	1	1	0
B-4	0	1	0
B-5	1	1	1
B-6	0	1	1
B-7	1	1	1
B-8	0	1	0
B-9	0	1	0
B-10	1	1	0
B-11	1	1	1
B-12	1	1	1
B-13	0	1	1
B-14	1	1	0

Table 2: Production capabilities of all production facilities in the current state.

For the current state, the CRFs (or the throughput rates) at the bottleneck reactors were analyzed. If a production facility did not have the capability to produce a certain product yet, a CRF was estimated together with the cost to obtain that specific capability. This was done for all product-production facility combinations, and led to the following conclusions;

- (Part of the) production does not always take place at the production facility with the lowest CRF. Also, there exists a big gap between some of the estimated CRFs in PA and current CRFs in WW. An example is B-3, a product that is expected to have a large advantage in terms of throughput times, when it would be produced in PA.
- Changing the production mix by focusing on the production efficiency will lead to an increase of the total production capacity (in terms of total output volume).
- In the current state, it is possible to better the workload balance through an improved allocation of production. There are sufficient opportunities for production in PA, even without investing. This is illustrated by Figure 17, which for each product demonstrates the production at each production location as a percentage of the total production. The figure is based on the actual production in 2013.

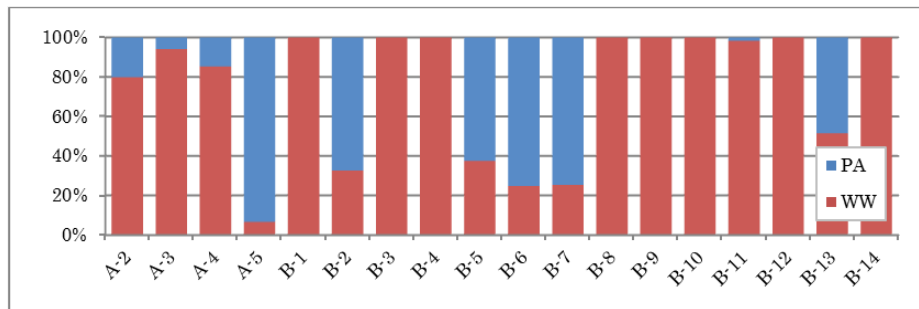


Figure 17: Relative distribution of production, 2013

The additional cost to increase the capability of a production line differs between products and ranges from around two percent of the yearly sales revenue for the high demand volume products (e.g. B-3 and A-3), up to around fifteen percent for products with a lower demand volume (e.g. A-2).

### 2.1.3. Sourcing

DCR works with around 40 “main” raw materials in order to enable production for all products under consideration. A single raw material can be handled to produce different products, therefore the total number of unique raw materials used is limited. For each raw material and for each production facility, multiple suppliers exist. The purchasing department pursues effective and efficient procurement of the materials. For each raw-material and at each site, DCR has multiple sourcing options, hereby mitigating the risk of supply disruptions (Kleindorfer & Saad, 2005). Actual raw material prices are dynamic, but since on average the monthly standard deviation of the price over the preceding year was below one percent of the mean, prices are assumed to be stable. The average prices *do* substantially differ among regions. The differences can range up to 10 percent.

### 2.1.4. Inventory & Distribution

The inventory is kept at warehouses that are located on the same sites as the production facilities. Inventory is controlled following an (s,Q) stock policy as described by Silver, Pyke, and Peterson (1998). The stock levels are continuously reviewed by the MRP system. Stock levels are determined semiannually by historical data of the product volumes shipped from each plant. This is undesirable for two reasons;

- First, the inventory levels should be determined by the magnitude of the future demand (Langevin and Riopel, 2005). Currently, historical data is used to determine the inventory levels, which implicitly assumes that the historical demand data is a good indicator for the expected demand. Some products were recently introduced (e.g. the B-3 and B-4), others are at the end of their product life cycle, hence their future demand is expected to differ substantially from the historical demand.
- Second, the product volume shipped from a specific plant does *not* indicate the demand volume fulfilled by that plant. At present, the largest part of the customer demand is still allocated to- and fulfilled from the WW site. Production takes place in PA, subsequently products are shipped to WW, and finally the products are shipped from WW to the customer, resulting in inventory at both locations.

For the distribution of goods, in principle, two different modes of transport are used. Parties outside of Europe, are supplied intermodal, i.e. combined barge and freight transport. Within Europe, all customers are supplied via road transport. The distribution of goods through road transport is fully outsourced to a Third Party Logistic (3PL) operator. Orders are consolidated internally for different product families and regions (other than WBU and WBU/A), where after a transport request is sent to the 3PL. Vehicle routing and further consolidation decisions are made by the 3PL. Price agreements are made in advance, on a quarterly basis, and the price agreements include the price per unit volume to deliver to predefined regions. The price per kilogram is also influenced by the percentage of the truck's capacity that can be filled with the initial request of transport, or the truck utilization. The average truckload is estimated to be around 85 percent. It is important to note that the customer lead time does not include transport. This means that the service level is not depended on the reliability of the 3PL. It also implies that, from the perspective of DCR, e.g. an Asian customer is handled with the same lead time as a Belgian customer.

### 2.1.5. Main Cost Drivers

The costs for the production and distribution as currently considered by DCR are subdivided into 4 cost components; i.e. raw material cost, production cost, freight cost, and inventory cost. The average production and distribution cost, in percentages of the total cost is given in Figure 18.



Figure 18: Breakdown of the production and distribution cost drivers for the of WBU and WBU/A, as percentage of the total cost, prices considered of July 2014.

The breakdown of the operational costs displays the dominance of the raw material cost, as it accounts for around 71 percent of the total cost. As stated before, the raw material cost are site-dependent. The production cost is the second largest driver, as it comprises around 25 percent of the total cost. It includes the costs of all resources used in order to enable production. The production costs are also site depended. First, because the actual costs of the resources (e.g. personnel cost, energy cost, repair and maintenance cost etc.), differ among sites. Second, because of the distinct production efficiency for each product-production facility combination, i.e. if less production hours are necessary to produce a ton of output volume, the production cost per ton is lower. The third cost driver is related to the transportation of goods towards the customer.

The freight cost is, on average, equal to 4 percent of the total cost price. As the freight cost is a direct derivate of transport distance, it is obvious that, for the individual customers, the freight cost differ per production facility.

Finally, the last two drivers relate to backorder cost and holding cost. For the former, no numerical estimates, or indicators were identified. According to DCR, the extra costs for processing a backorder are solely administrative and are assumed negligible. Furthermore, DCR's products are exclusive and product development often takes place in collaboration with customers. Hence the majority of the customers is, on the short term, inflexible in the choice of their supplier. Therefore direct lost sales from a back order (i.e. stock-out) rarely occur. However, given the low average service levels of the DCR, it is expected that the high amount of back orders in the long term will have a negative impact on the company's revenue. Customers (and potential customers) tend to seek more reliable suppliers as the reputation of DCR decreases. DCR identifies the holding cost as the cost of storage, which is in fact an underestimation as it does neither consider opportunity cost, nor depreciation cost of stock. Estimates of the latter two will be made later on.

## 2.2. Summary of Supply Chain Network Analysis

The following characteristics of the supply chain are considered to be the most relevant;

### Demand

- There are a number of products that have a high demand volume, but at present, can only be produced in one of the two production facilities.
- 48 percent of the customers based within Europe are served from both production facilities.
- Customer demand is dispersed over multiple countries. At the same time, the total number of customers, as well as the total number of products per customer is relatively low. Combined, this leads to a current situation with a diverse demanded product mix per country.
- The monthly demand per product and per country is highly dynamic.

### Supply

- The workload at the production facilities is structurally imbalanced as the customer demand is not allocated to the different plants correctly.
- The production plan is infeasible as the expected monthly utilization rates at both production facilities surpass a hundred percent on average.
- Service levels are poor and far below target, caused by the workload imbalance and high asset utilization rates.
- Opportunities exist to balance the workload and increase capacity of the supply network. This can be achieved by reallocation demand (or production) to plants given the current situation, but also by investing in R&D in order to enhance the production capabilities of the PA production line.

### Inventory & Distribution

- Inventory levels are set using the wrong parameters; i.e. usage of *historical* volume that is *shipped from* a plant, instead of the *forecasted customer demand* allocated to a plant.
- A large intercompany flow of goods exists between PA to WW, instead of directly delivering to the customer

### Sourcing

- Prices of raw materials differ among production locations.
- Sufficient opportunities for procurement of raw materials at both sites.

### Distribution

- Distribution is outsourced, the cost depend on truck utilization and the delivery region. Consolidation with other product families takes place and on average, the truck utilization is equal to 85 percent.

### Cost drivers

- Raw material, production and freight cost are the most important cost drivers, and all differ between sites. Back order costs are expected to be important, but cannot be traced back from company data.

All prior characteristics are addressed by the remainder of the research. If possible, they are included in the scientific model. Otherwise, they will be examined qualitatively.

## Conceptualization and Conceptual Model

Section 1 and 2 analyze the current situation and describe the problem. According to Mitroff et al. (1974), the next step indicates the “first phase” of the problem solving by means of conceptualization, moving towards a conceptual model of the current situation. First Section 3.1 elaborates the objective of the model, then Section 3.2 defines the time horizon and postulates some practical points related to it. Hereafter, Section 3.3 narrows down the scope, while Section 3.4 emphasizes upon the variables that will be included in the model. Section 3.5 summarizes the conceptual model.

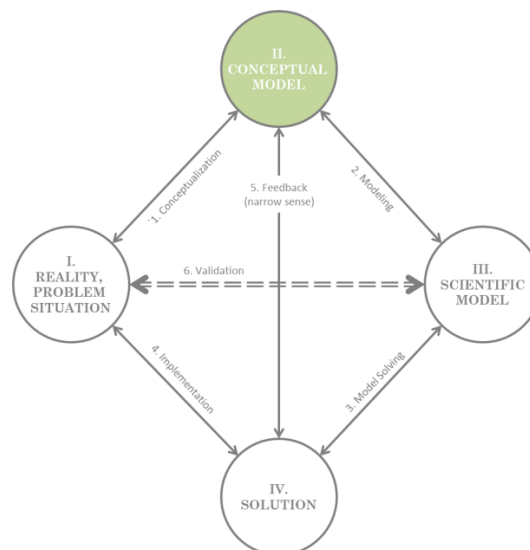


Figure 19: Schematic view of phase II, Conceptual Model. Adapted from Sagasti and Mitroff (1973)

### 3.1. Model Objective

The objective of the model is to maximize the total profit. The model seeks for an optimal configuration of multiple decision variables, such that a maximum profit is obtained. The decision variables concern two different stages in the supply chain. The first affects the production stage; i.e. decisions towards investments in order to increase production capabilities, as well as decisions regarding the aggregate production planning of each production line. The second relates to distribution, i.e. the model decides *if*, and *from which* production facility the demand is fulfilled.

### 3.2. Time Horizon

For the design of the model a full year is considered. In this case, a full operational year is equivalent to 50 weeks of production, 7 days a week, 24 hours a day. The time horizon is chosen in accordance with decision variables. Decisions are to be made on the mid to long-term and are



considered to be in between strategic (high cost, long term for the decisions on development of production line capabilities) and tactical (no additional investment cost, mid-term for aggregate production planning and customer demand fulfillment). Regarding the long term decisions on investments, the model decision variables consider the full time horizon of one year. However, for the mid-term tactical decisions, the model has a dynamic, monthly approach. Therefore, unless stated otherwise, all variables in- and output will be scaled to their monthly equivalent.

### 3.3. Narrowing Down the Scope

As stated before, the problem is considered as a generalization of the facility location problem. The production facilities already exist, so strictly it does not qualify as an FLP, but rather as a generalization of the FLP with multiple commodities. Nonetheless, questions related to e.g. where to produce which products, what production quantities, and the allocation of customer demand to the production locations remain in place. Like most case studies towards facility location problems in supply chain management, the problem under consideration is highly complex. It would be very time consuming and impractical to model all aspects of the problem. Through an adequate model scope, there is attempted to include only the most relevant determinants to the current problem.

#### 3.3.1. Inventory and Lead Times

Decisions on inventory levels are left out of scope. First of all, because the focus of the research is to increase the overall capacity by reconsidering the current production strategy. Secondly, because the holding cost is low relatively to the total operational cost. Furthermore, section 2.1.2 points out that when service level targets are obtained, backorder costs are assumed to be negligible. The decision to refrain the model from decisions on inventory levels complies with the theory from previous research; i.e. integration of decisions on stock levels and production locations are considered, only when the cost related to the former represent a substantial proportion of the total cost (Shen and Qi, 2007).

Lead times are out of scope for related reasons. The production strategy for the considered products is MTS, therefore shorter production and procurement lead times will influence the stock levels of both raw materials and finished goods. As just discussed, stock levels are out of scope because they are not expected to impact the optimal configuration of the decision variables.

That stock levels are out of scope does not mean that they are not considered at all by the model. The determination of stock *levels* is out of scope, however, because of its dynamic nature (more about this in section 3.4.1). The model does account for backorders and/or building up stock, in order to cope with demand fluctuations.

#### 3.3.2. Uncertainty

A deterministic approach is taken for all the model variables. Short term variances are out of scope. Through aggregation of both production and demand, the short term variances are expected to have a low or insignificant impact on the optimal solution. The model does account for expected consequences of variance, e.g. slack in production caused by waiting times, by means of an upper bound on the utilization rate of resources. The research focuses on reconsidering the production strategy, involving mid- to long-term decisions. For that reason, the uncertainty on the short term is considered less relevant.

Another form of uncertainty relates to possible future scenarios, all of which can occur with a given probability. For simplicity, the model assumes only one scenario, for all forecasted parameters (i.e. demand, production efficiency of new production line-product combination etc.). It is important to note that forecasts are predictions and hence the optimal solution based on

the forecasted values is prone to errors in the forecasted values. The optimal model configuration is thus likely to change when the forecasted input values will change. Nonetheless, the insights gained from the model solution are still valuable. Moreover, through sensitivity analysis (Chapter 6), different future scenarios and their impact will be explored, yet a multi-scenario, stochastic approach is out of scope.

### 3.4. Model Variables

In accordance with the model objective and the time horizon, this section describes the model variables that are included, what assumptions are made to include them, and how they are included in the model in terms of e.g. their aggregation level and composition.

#### 3.4.1. Demand

The demand is categorized by three main characteristics, that is; the type of product, the customer and the moment of occurrence in time.

##### Finished Products

With regard to the products, there is decided to aggregate the demand to product-type level (see Figure 9), because the attention should be directed towards the production process and not on the packaging process (SKU level). The finished products that are delivered to the customer are always accepted by the customer. Returns as a consequence of delivery mistakes or quality issues never take place.

**[Assumption: All deliveries are accepted by the customer, i.e. no returns of goods]**

##### Regions

It would be impractical to calculate the transportation cost towards all customers individually and for that reason, it is decided to aggregate customer demand per region in order to make spatial decisions in terms of demand allocation. The model chooses, combined with the available capacity, if all the demand will be fulfilled or if (part of) the demand is backordered. The model will also determine from which facility the demand will be fulfilled. Demand can be served from a single, or from multiple locations. There is assumed that a customer is indifferent of the production location that supplies him with the products. From here onwards, the term customer is used to indicate the aggregated customer demand for a full region and hence the transportation cost to serve a region is equivalent to the cost to serve a customer within that region.

**Assumption: All customers are indifferent of the production facility that supplies their products]**

**[Assumption: For each customer within the same geographical region, the transportation cost is equivalent to the transportation cost to serve center of the geographical region]**

##### Dynamics of Demand

Demand is assumed to be dynamic (see Section 2.1.1). In order to capture the dynamics in the demand, there is decided to include the aggregated monthly demand as input for the model.

#### 3.4.2. Production

In order to fulfill the demand, a limited number of resources is available in the production network. A fixed number of production facilities is included. Production on each production facility is constrained by its unique characteristics related to;

- Capacity (how many hours are available for production)

- Production capability (i.e. what type of products can be produced in each production facility and what the accompanying throughput volumes per unit time)
- Batch size (for each product-production facility combination, there exists only a single batch size that can be produced)
- Throughput rate (again specific to each product-production facility)

The opportunity exists to expand the production capabilities at excess cost. Investment cost are specific to the corresponding production facility-product combinations. The investments cost are “one-off”, which means that once an investment is made, a production facility acquires a new capability, and preserves this capability for the rest of its life time. Another assumption for the model is that the life time of the assets (i.e. the production lines), ranges beyond the life cycle of individual products. Hence to include this one-off, fixed investment cost in the model, it will be depreciated of the remaining product life cycle time and not over the asset life time.

**[Assumption: The total (remaining) life time of the production resources is always longer than the total (remaining) product life cycle of each individual product]**

From a practical point of view, it should be noted that the availability (in hours) for production is converted to output volume. To this extent, the throughput (per unit time) is adopted as a model parameter for each product-production facility combination. The total production volume depends on the planned product-mix for each of the available production facilities. In order to create a feasible production plan, a parameter is introduced that sets an upper bound to the utilization level of each production line. By choosing an adequate utilization level, the model protects itself against the influence of short term variability. The part of the available time that is not utilized, serves as a buffer for the slack (i.e. waiting and idle time) that is created by the stochastic nature of the actual production tasks.

### 3.4.3. Sourcing

The sourcing is modeled one to one to with the demand, i.e. it is assumed that every product type requires one specific raw material. Furthermore, it is assumed that there is ample supply available for all raw materials at both production facilities.

**[Assumption: There exists an ample supply of raw materials for both production facilities]**

**[Assumption: Production for every product type requires only one raw material]**

### 3.4.4. Distribution

The cost of distribution per unit of volume is predetermined for all possible combinations of customer regions and production facilities. In this model, there is assumed that products flow directly from production facility to customer, i.e. without the interference of a distribution center. Moreover, deliveries are direct, meaning no vehicle routing is considered. Finally, fixed truckloads are assumed.

**[Assumption: The distribution of goods takes place directly from production facility to customer, truckloads are fixed and deliveries are direct.]**

### 3.4.5. Financial Drivers

The objective of the model is profit maximization, hence the model is driven by the cost and revenue parameters that are included in the model. The revenue component is fairly straightforward, as every fulfilled order equals a certain amount of revenue. The prices are stable throughout the execution period of the model. The costs are divided into four sub categories, i.e.; inbound cost, outbound cost, production cost, and investment cost.

The first is equal to the procurement cost of raw materials, including the inbound transportation cost. These costs are directly related to the production location, and are included as a cost per unit volume of output. Distribution cost is equal to the sum of transportation and warehouse cost, necessary to move the finished goods from the production facility towards the customer. The transportation cost is affected by the production facility, and pre-determined for all possible production facility-customer combinations. They are considered as a fixed price per unit volume, as fixed truckloads are assumed. Finally, transportation cost is independent of the product that is distributed. Third, the cost of production is equal to all costs that are directly involved with the transformation of raw materials into end products. The production cost depend on the produced product, the production location, as well as the production efficiency, and are thus directly influenced by the production allocation decisions. As noted before, the production efficiency is related to the production facility-product combination. The production cost is assumed to be linear, hence economies of scale are *not* considered. Only the variable, or operational production cost is considered (including raw material cost), as the fixed cost believed to be sunk, and not affected by the decisions variables of the model.

**[Assumption: For each product and each production facility the production cost is linear]**

The investment cost are included in order to determine whether a potential product transition is expected to increase the total profitability. As explained before in Section 3.4.2, the investment costs are one-off and depreciated over the product life cycle. A binary variable is included in the model and determines whether or not to invest (and hence include the investment cost). Finally, costs that affect a company as a whole, e.g. administrative, marketing, sales, research and development, will not be included in the model. These costs are independent of the model decision variables.

### 3.5. Summary of Conceptual Model

Now that all model aspects have been introduced, a schematic representation of an example of the conceptual model (for a single period) is depicted in Figure 20. In between the brackets, the example shows the value of the decision variables, i.e. the amount of demand that is fulfilled as well as the total amount of production at each facility. The lines above the production facilities illustrate the products that are produced at that facility.

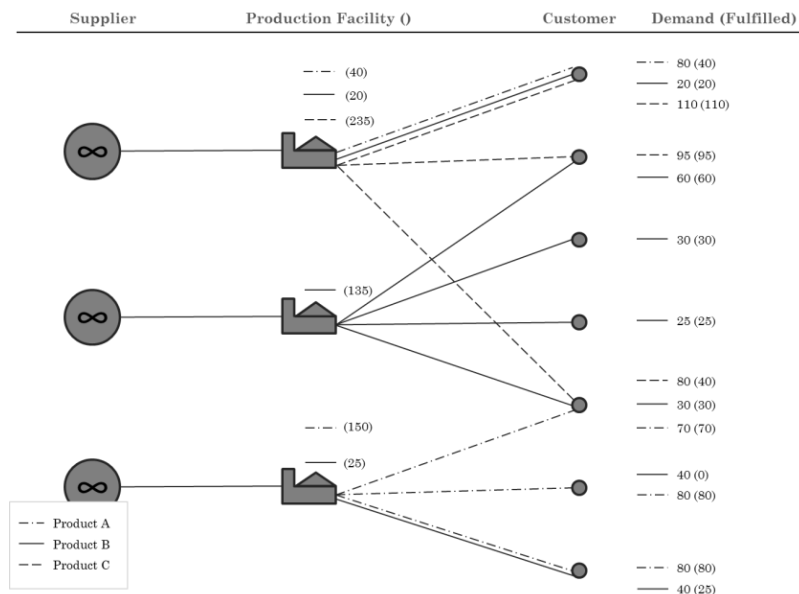


Figure 20: Conceptual model , considering a single period, three production facilities, three products and seven customers.

Furthermore, Table 3 gives a short overview of the most important profit parameters and the accompanying decision variables.

<b>Profit Parameter</b>	<b>Decision variable</b>
Revenue per unit volume of a product sold to a customer	Total volume of each product shipped from a production facility to a customer
Transportation cost per unit volume	Idem
Production capability investment cost	Decision to invest in increasing the capabitliy of a production facility
Raw material cost, production cost	Total volume of each product that is produced at a production facility

Table 3: Profit parameters with the corresponding decision variables.

## Modeling and Scientific Model

According to Sagasti and Mitroff (1973), the scientific model should translate the conceptual model into a fully formalized scientific (in this case mathematical optimization) model. In this chapter, first the model components are described by section 4.1, hereafter the complete scientific model is presented in section 4.2, and finally the model extensions are formulated in section 4.3.

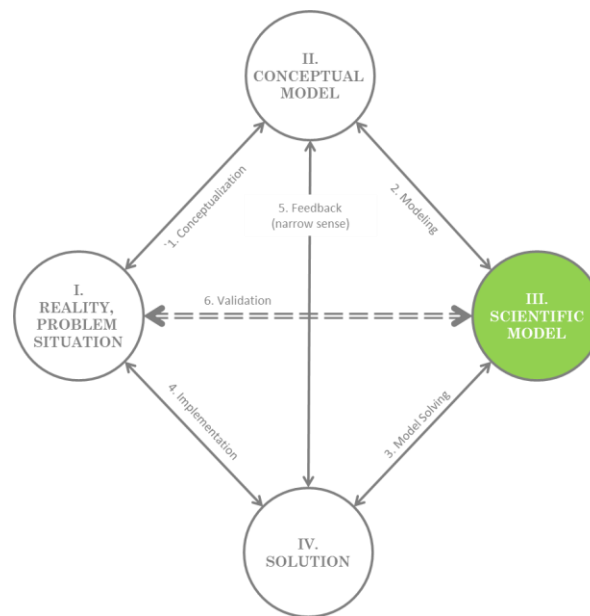


Figure 17: Schematic view of phase III, Scientific Model. Adapted from Sagasti and Mitroff (1973)

### 4.1. Formulation of Model Components

In order to give a clear explanation of the scientific model as a whole, there has been chosen to decompose the model and describe the different components independently. The demand-related components are described in section 4.1.1, production in 4.1.2, sourcing in 4.1.3, and ultimately the parts that relate to distribution and inventory are formulated in section 4.1.4.

#### 4.1.1. Demand

The demand is denoted as  $D_{klt}$  for each product  $k \in K$ , from each customer  $l \in L$  at the beginning of each period  $t \in T$ . For each period  $t \in T$  the amount of demand that is fulfilled of product  $k \in K$  to customer  $l \in L$  in period  $t \in T$  from production facility  $j \in J$  is determined by the decision variable  $S_{kljt}$ . The notation for these three variables and the associated subsets is as follows;

- $K$  = the set of products, indexed by  $k$
- $L$  = the set of customers, indexed by  $l$

- $J$  = the set of production facilities, indexed by  $j$   
 $T$  = the set of periods, indexed by  $t$
- $D_{klt}$  = the total unit volume of demand of product  $k \in K$  from customer  $l \in L$  at the beginning of period  $t \in T$   
 $p_k$  = the price per unit volume of product  $k \in K$   
 $S_{kljt}$  = the total unit volume of demand fulfilled, in unit volume of product  $k \in K$  to customer  $l \in L$  from production facility  $j \in J$  in period  $t \in T$  **(decision variable)**

The revenue component of objective function is described by (1a); it is the sum of the multiplication between the fulfilled demand and product price (for all the fulfilled demand of all products  $k \in K$ , from all production facilities  $j \in J$  and in all periods  $t \in T$ ). The price is dependent upon the product  $k \in K$ .

$$\sum_{kljt} S_{kljt} p_k \quad (1a)$$

As the objective function maximizes the total profit, it might be the case that there is excess production capacity in period  $t \in T$ , while there is insufficient capacity in a subsequent period  $t + n \in T$ . In order not to lose any sales opportunities, the model is formulated such that any unfulfilled demand, or backorders are considered by the model as an auxiliary variable. The following notation is used;

- $I_{klt}^-$  = the total unit volume of unfulfilled demand of product  $k \in K$  from customer  $l \in L$  at the end of period  $t \in T$

The demand is modeled such that the total demanded volume for all products  $k \in K$ , all customers  $l \in L$ , at the beginning of each period  $1 \leq t \leq T$ , is equal to the sum of the actual demand  $D_{klt}$  and the unfulfilled from the previous period  $I_{kl(t-1)}^-$ . This is modeled by constraint (2), stating that for each product  $k \in K$  to customer  $l \in L$ , in each period  $1 \leq t \leq T$ , the total fulfilled demand  $\sum_j S_{kljt}$  by all production facilities  $j \in J$ , is bounded by the total demanded volume. Constraint (3) serves as a balancing constraint for the amount of backorders.

$$\sum_j S_{kljt} \leq D_{klt} + I_{kl(t-1)}^- \quad 1 \leq t \leq T, \quad \forall k, l \quad (2)$$

$$I_{klt}^- = D_{klt} + I_{kl(t-1)}^- - \sum_j S_{kljt} \quad 1 \leq t \leq T, \quad \forall k, l \quad (3)$$

#### 4.1.2. Production

To decide whether or not production can take place at a certain production facility, consider binary decision variable  $q_{kj}$  for each product  $k \in K$  at each production facility  $j \in J$ . The fixed, one-of cost to enable production is equal to  $c_{kj}^F$ .

- $q_{kj} = 1$  if product  $k \in K$  is produced at plant  $j \in J$ , **(decision variable)**  
 $q_{kj} = 0$  otherwise. **(decision variable)**  
 $c_{kj}^F =$  fixed, one-off cost, to enable production for product  $k \in K$  in production facility  $j \in J$

Furthermore, constraint (4) is included to ensure the binary outcome of decision variable  $q_{kj}$ .

$$q_{kj} \in (0,1) \quad \forall k, j \quad (4)$$

The fixed costs in order to enable production are included in the objective function through (1b), i.e. the sum of all the multiplications of the binary variable  $q_{kj}$  with the cost  $c_{kj}^F$  (again  $\forall k, j$ ).

$$\sum_{kj} c_{kj}^F q_{kj} \quad (1b)$$

In order to include the actual produced volumes per unit time, three variables are introduced for product  $k \in K$ , at production facility  $j \in J$ , in period  $t \in T$ . First, auxiliary variable  $I_{kjt}^+$  which indicates the amount of inventory at the end of period  $t \in T$ . Second, decision variable  $x_{kjt}$ , as an integer variable representing the number of batches that are produced. Subsequently, the actual production volume  $A_{kjt}$  follows from the multiplication of the number of batches  $x_{kjt}$  with the accompanying input parameter for the batch size  $\theta_{kj}$ .  $\kappa_j$  serves as a parameter that indicates the quality rate of production. Other input parameters cover the production throughput rate  $\tau_{kj}$ , the total unit time of capacity available for production  $\Gamma_{jt}$ . The following formal description is adopted;

$$\begin{aligned} x_{kjt} &= \text{total integer number of batch sizes produced for product } k \in K \text{ in production facility } j \in J \text{ in period } t \in T. & \textbf{(decision variable)} \\ \theta_{kj} &= \text{batch size volume of product } k \in K \text{ in production facility } j \in J \\ A_{kjt} &= \text{actual production volume of product } k \in K \text{ in production facility } j \in J \text{ for period } t \in T \\ \kappa_j &= \text{quality rate of the production output volume at facility } j \in J \\ \tau_{kj} &= \text{throughput rate (output volume per unit time of production) for product } k \in K \text{ in production facility } j \in J \\ \Gamma_{jt} &= \text{total capacity (unit time) available for production at facility } j \in J \text{ in period } t \in T \\ \mu &= \text{upper bound on the utilization rate for each production facility } j \in J \\ \Gamma_{jt}^a &= \text{total capacity (unit time) available for production at facility } j \in J \text{ in period } t \in T, \text{ at utilization rate } \mu; \\ & \text{i.e. } \Gamma_{jt}^a = \Gamma_{jt} \mu \end{aligned}$$

Constraints (5-11) all are all related to production. First, (5) forces the model to produce only full batch sizes, i.e.  $x_{kjt}$  is a non-negative integer, and (6) indicates the total actual production volume  $A_{kjt}$ .

$$\begin{aligned} x_{kjt} &\in \mathbb{N} & \forall k, j, t & (5) \\ A_{kjt} &= x_{kjt} \theta_{kj} & \forall k, j, t & (6) \end{aligned}$$

Second, equation (7) is included such that the model will choose to produce product  $k \in K$  in production facility  $j \in J$  **only if** a facility holds the capability to produce that specific product.  $M$  is defined as a generic number that is sufficiently large, i.e. it should be chosen such that it is always larger than total production for product  $k \in K$  in production facility  $j \in J$  for each period  $t \in T$ .

$$\sum_t A_{kjt} \leq q_{kj} M \quad \forall k, j \quad (7)$$

Through constraint (8) the model is bounded to run production for, at maximum, a number of time units equal to the total time units of capacity available  $\Gamma_{jt}$ . The unit volume of actual production  $A_{kjt}$  is converted to unit time of actual production by dividing it by the accompanying throughput rate  $\tau_{kjt}$ .

$$\sum_k \frac{1}{\tau_{kjt}} A_{kjt} \leq \Gamma_{jt}^a \quad \forall j, t \quad (8)$$



By means of equation (9) there is secured that the unit volume of outgoing production (i.e. the amount of demand that is fulfilled from a facility to all of its customers  $\sum_l S_{kljt}$ ), is lower than the unit volume production that fulfills all quality requirements  $\kappa_j A_{kjt}$  of that period, plus the unit volume of inventory at the end of the previous period  $I_{kj(t-1)}$ .

$$\sum_l S_{kljt} \leq \kappa_j A_{kjt} + I_{kj(t-1)}^+ \quad 1 \leq t \leq T, \quad \forall k, j \quad (9)$$

The inventory balancing equation is posed by means of constraint (10) such that the inventory level  $I_{kjt}^+$ , at the end of period  $t \in T$  is equal to inventory level at the end of the previous period  $I_{kj(t-1)}^+$ , minus the unit volume of outgoing deliveries for that period  $\sum_l S_{kljt}$ , plus the unit volume of actual production  $\kappa_j A_{kjt}$ .

$$I_{kjt}^+ = I_{kj(t-1)}^+ + \kappa_j A_{kjt} - \sum_l S_{kljt} \quad 1 \leq t \leq T, \quad \forall k, j \quad (10)$$

The costs of production and inventory are considered by the model as a variable cost per unit volume. The production cost per unit volume as well as the holding cost depend on the product  $k \in K$ , and the production facility  $j \in J$ . Both parameters are formulated as;

$$\begin{aligned} c_{kj}^p &= \text{production cost per unit volume of output for product } k \in K \text{ in production facility } j \in J \\ c_{kj}^h &= \text{holding cost per unit volume} \end{aligned}$$

Hence the cost is included in the objective function as seen in formulations (1c) and (1d), representing the sum of produced output volume  $A_{kjt}$  times the associated costs  $c_{kj}^p$ , and the sum of the total inventory at the end of each period  $I_{kjt}$  times the cost  $c^h$ ;

$$\sum_{kjt} c_{kj}^p A_{kjt} \quad (1c)$$

$$\sum_{kjt} c^h I_{kjt}^+ \quad (1d)$$

The cost for backorders is also formulated as a variable cost per unit volume that is not fulfilled in each period. The backorder cost per unit volume is independent of production location, product, and customer and they are fixed over time. For that reason;

$$c^b = \text{backorder cost per unit of volume}$$

Backorder cost are included in the objective function by (1e), representing the sum of the backordered volumes  $I_{klt}^-$  times the attaining cost  $c^b$ .

$$\sum_{klt} c^b I_{klt}^- \quad (1e)$$

#### 4.1.3. Sourcing

The sourcing cost is modeled one-to-one with the production output volume. The cost per unit output volume parameter  $c_{kj}^r$  is dependent on the product  $k \in K$  and production location  $j \in J$ . Therefore it is formulated as;

$$c_{kj}^r = \text{raw material cost per unit output volume for product } k \in K \text{ in production facility } j \in J$$

The component of the objective function that describes the total raw material cost is captured by (1f), denoting the sum of the total produced volume  $x_{kjt}\theta_{kj}$  times the corresponding cost  $c_{kj}^r$ .

$$\sum_{kjt} c_{kj}^r A_{kjt} \quad (1f)$$

#### 4.1.4. Distribution

The cost parameter of distribution per unit volume  $c_{jl}^d$  is reliant on the combination of the customer  $l \in L$  and the production facility  $j \in J$ , therefore it is formulated as;

$$c_{jl}^d = \text{distribution cost per unit volume from production facility } j \in J \text{ to customer } l \in L$$

The constraints regarding the maximum customer demand that is fulfilled (i.e. distributed)  $S_{kljt}$  for each product  $k \in K$ , by production facility  $j \in J$ , towards customer  $l \in L$ , have readily been proposed in the previous section. The accompanying cost is included in the objective function by means of (1f);

$$\sum_{kljt} c_{lj}^d S_{kljt} \quad (1f)$$

## 4.2. Summary of Model Description

In this section the complete mathematical model is presented by including all constraints, input parameters and the decision variables. The model components are used as described in the previous section, and the objective function is formulated by rearranging the objective function components (1a-1f). Furthermore, the raw material cost and the production cost are combined to a parameter referred to as the variable production cost  $c_{kj}^v = c_{kj}^r + c_{kj}^p$  for product  $k \in K$  at production facility  $j \in J$ . The scientific model is concluded as follows;

### Objective function:

$$Profit = Max \sum_{kljt} S_{kljt} p_k - \left( \sum_{kj} c_{kj}^F q_{kj} + \sum_{kjt} c_{kj}^v A_{kjt} + \sum_{kjt} c_{kj}^h I_{kjt}^+ + \sum_{klt} c^b I_{klt}^- + \sum_{kljt} c_{lj}^d S_{kljt} \right) \quad (1)$$

### Subject to

$$\sum_j S_{kljt} \leq D_{klt} + I_{kl(t-1)}^- \quad 1 \leq t \leq T, \quad \forall k, l \quad (2)$$

$$I_{klt}^- = D_{klt} + I_{kl(t-1)}^- - \sum_j S_{kljt} \quad 1 \leq t \leq T, \quad \forall k, l \quad (3)$$

$$q_{kj} \in (0,1) \quad \forall k, j \quad (4)$$

$$x_{kjt} \in \mathbb{N} \quad \forall k, j, t \quad (5)$$

$$A_{kjt} = x_{kjt} \theta_{kj} \quad \forall k, j, t \quad (6)$$

$$\sum_t A_{kjt} \leq q_{kj} M \quad \forall k, j \quad (7)$$

$$\sum_k \frac{1}{\tau_{kjt}} A_{kjt} \leq \Gamma_{jt}^a \quad \forall j, t \quad (8)$$

$$\sum_l S_{kljt} \leq \kappa_j A_{kjt} + I_{kj(t-1)}^+ \quad 1 \leq t \leq T, \quad \forall k, j \quad (9)$$

$$I_{kjt}^+ = I_{kj(t-1)}^+ + \kappa_j A_{kjt} - \sum_l S_{kljt} \quad 1 \leq t \leq T, \quad \forall k, j \quad (10)$$

---

**Input Parameters:**

$K$	=	the set of products, indexed by $k$
$L$	=	the set of customers, indexed by $l$
$J$	=	the set of production facilities, indexed by $j$
$T$	=	the set of periods, indexed by $t$
$D_{klt}$	=	the total unit volume of demand of product $k \in K$ from customer $l \in L$ at the beginning of period $t \in T$
$p_k$	=	the price per unit volume of product $k \in K$
$\theta_{kj}$	=	batch size volume of product $k \in K$ in production facility $j \in J$
$\kappa_j$	=	quality rate of production output at facility $j \in J$
$\tau_{kjt}$	=	total unit throughput volume per unit time of production for product $k \in K$ in production facility $j \in J$ in period $t \in T$
$\mu$	=	the upper bound on the utilization level attained at each individual production facility
$\Gamma_{jt}$	=	the total actual capacity (unit time) available for production at facility $j \in J$ in period $t \in T$
$\Gamma_{jt}^a$	=	$\mu \Gamma_{jt}^a$ , i.e. the total actual capacity (unit time) available for production at facility $j \in J$ in period $t \in T$ , given the utilization level upper bound $\mu$
$\tau_{kj}$	=	total unit throughput volume per hour of production of product $k \in K$ in production facility $j \in J$
$\theta_{kj}$	=	production batch size for product $k \in K$ at facility $j \in J$
$M$	=	a sufficiently large generic number
$c_{kj}^f$	=	fixed, one-off cost, to enable production for product $k \in K$ in production facility $j \in J$
$c_{kj}^v$	=	total variable production cost per unit output volume for product $k \in K$ in production facility $j \in J$
$c_{kj}^h$	=	holding cost per unit volume for product $k \in K$ in period $t \in T$
$c^b$	=	backorder cost per unit of volume
$c_{jl}^d$	=	distribution cost per unit volume from production facility $j \in J$ to customer $l \in L$

---

**Auxiliary variables:**

$I_{klt}^-$	=	the total unit volume of unfulfilled demand of product $k \in K$ from customer $l \in L$ at the end of period $t \in T$
$I_{klt}^+$	=	the total unit volume of physical inventory of product $k \in K$ at production facility $j \in J$ at the end of period $t \in T$
$A_{kjt}$	=	actual production volume of product $k \in K$ in production facility $j \in J$ for period $t \in T$

---

**Decision variables:**

$S_{kljt}$	=	the total unit volume of demand fulfilled, in unit volume of product $k \in K$ to customer $l \in L$ from production facility $j \in J$ in period $t \in T$
$q_{kj}$	=	binary variable that indicates if product $k \in K$ can be produced at plant $j \in J$ ,
$x_{kjt}$	=	total integer number of batch sizes produced for product $k \in K$ in production facility $j \in J$ in period $t \in T$ .

## Model Solving

Now that the scientific model is formulated, the next step in the OR process is solving the model in order to obtain the model solution. This section gives a summary of the model solving process, and subsequently proposes the model solution.

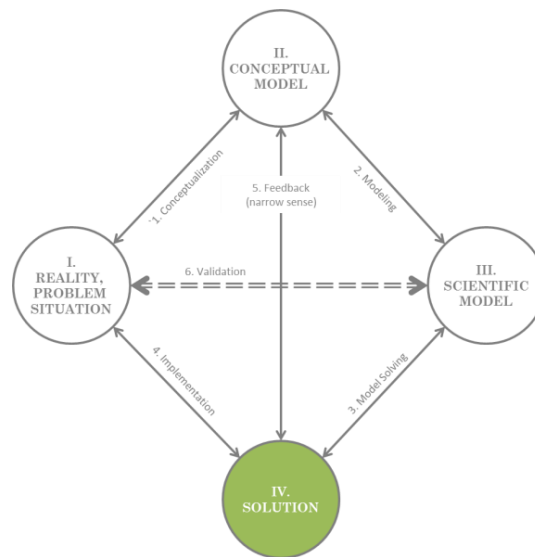


Figure 21: Schematic view of phase IV, Solution. Adapted from Sagasti and Mitroff (1973)

The selected software, as well as the reasons to use the software are described in Section 5. Thereafter the model inputs are discussed in Section 5.3. Then, in Section 5.4, the model and its assumptions are verified and validated for the DCR case under consideration. Hereafter, the model solution is discussed in Section 5.5.

### 5.1. Selected Software

The scientific model as proposed in Chapter 4 is formulated as a Mixed Integer Linear Programming problem (MILP). MILP refers to mathematical optimization problems of which both the objective function as well as the model constraints are linear. At the same time, some of the model decisions variables are constrained to integer values, whereas others are allowed to be non-integers. One of the characteristics of MILP models is that the solution space of the problem increases exponentially with respect to the number of integer variables considered (Kaufmann and Henry-Labordère, 1977). This makes these type of problems NP-hard, even if only a small number of variables and constraints are considered. As a result, solutions to MILP problems are obtained with the use of algorithms that search through the solutions space in an efficient way such that a (sub)optimal solution can be obtained within a reasonable solving time.

In order model the DCR case, there is chosen to use the software package AIMMS. This mathematical modeling software package is chosen for a couple of reasons. First, it is widely accepted by researchers and practitioners. It is used by university scholars and students, as well as by multiple (multinational) companies covering various industries (AIMMS Customers,

2014). This increases the likelihood of acceptance of the model analysis. Furthermore, the AIMMS package is supported by the Windows OS, as currently used at all DCR computer devices. Thirdly, it allows the user to create and operate his own user interface, which will eventually simplify the sensitivity analysis in later chapters. Finally, the program makes use of the current, state of the art (commercial) MIP solvers, i.e. XPRESS, Gurobi and CPLEX (Mittelman, 2014; Hvattum, Lokketangen, and Glover, 2012). For this research the Gurobi solver has been chosen, as it is currently considered the fastest MILP solver to overall optimality. Also it is the second fastest to feasibility (on average 0,99 times CPLEX its computation time), and the fastest to detect overall infeasibility. Finally, Gurobi scores highest on renowned benchmark tests for overall solver performance (Mittelman, 2014).

Microsoft Excel and Visual Basic for Applications (VBA) were used in order to preprocess the input data. Excel and AIMMS interface through custom written code in AIMMS. This enables the program to load the preprocessed Excel input data into the model. Subsequently the model was solved in AIMMS and after solving the model output was saved and written back to Excel. The model was solved with a 2.5 GHz Intel Core i5-2520M personal computer with 4,00 GB of memory installed. An overview of the software used for model solving is found in Table 4.

Software Package	Version
Microsoft Windows	7, Enterprise 64-bit
Microsoft Excel	14.0
AIMMS	4.0
Gurobi	5.6

Table 4: An Overview of the software used for model solving

## 5.2. Solver Configuration

For small problem sets the model was able to reach global optimality within a few seconds. However, due to the complexity of model for the DCR case under consideration, the solver was unable to find the global optimal solution within reasonable time limits. In order to find a good solution within a reasonable time frame, the solver was configured such that it adequately suited the problem under consideration. Since no problem is identical, guidelines for tuning the solver parameters can be followed, but the best configurations are usually found through testing (Gurobi Optimization Inc., 2014). Therefore, a number of experiments was conducted in order to determine a sound configuration for the considered problem.

Two important Gurobi settings are the “Threads” and the “MIPFocus” parameters (Gurobi Optimization Inc., 2014). The first controls the number of threads used to solve the model. By default, the solver uses all the machine’s cores leading to the most effective results. The second parameter allows for modification of the high-level solution strategy. Depending on the goals of the user, there can be chosen to focus on; finding new feasible solutions, proving optimality, or on a strategy that balances between the two (default). Finally, if the best linear bound of the objective solution is moving very slowly, there can be chosen to focus on improving the best linear bound. The solver performance with the aforementioned strategies is plotted in Figure 22. The figure shows the Optimality Gap, which is defined as the relative difference between the best known linear bound on the solution objective, and the best integer solution found by the solver. It follows that, except for the Best Bound strategy, the obtained results for all strategies are similar. Both the optimality, the feasibility and the balanced strategy end up with an optimality gap of 0.9 % after 50 minutes.

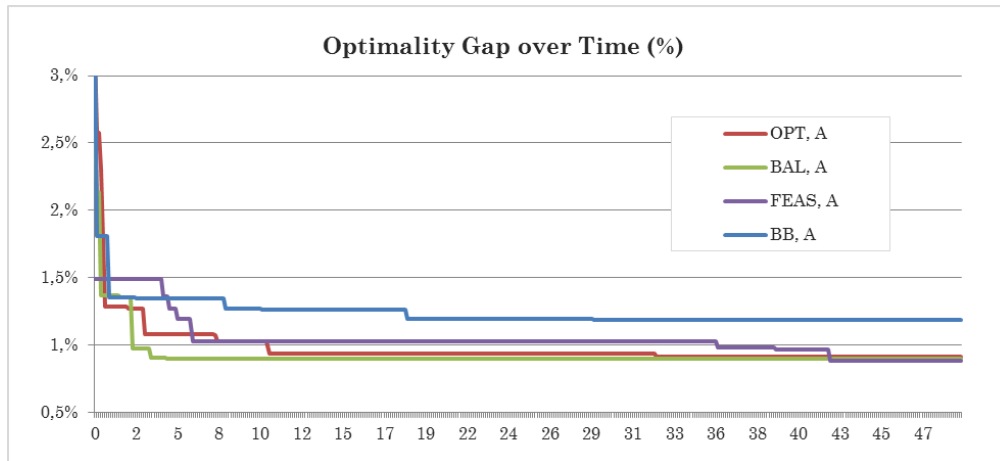


Figure 22: Solver Optimality Gap of Solver Solutions over Time (%), total running time 50 minutes.

Additionally, experiments were conducted through the adjustment of specific cutting plane strategies, the pre-solve behavior, and changing over the high-level solutions strategy at a certain optimality gap. None of the experiments led to significant improvements of the model solution. A summary of the experiments is found in Appendix B3. There is concluded that the solution to the objective function is not significantly impacted by the elected strategy. The improvement of the solution over time stagnates just below the one percent optimality gap. As a result, it was decided to use a default solver configuration. The solving process was stopped after obtaining a relative optimality gap below one percent or when total solving time surpassed ten minutes. Hereby permitting the model solver to complete the solving process within a reasonable time frame.

### 5.3. Model Inputs

After the development of the mathematical model and the software selection, this section explains the model input for the DCR case study. For a useful model outcome, it is important that all model input is valid, reliable, consistent and recent. Since the data at DCR is often stored at and maintained by different actors, the data was collected at various business departments within DCR. Hereafter, the data was validated by a representative of the division responsible for owning the data, and cross-validated with representatives from other departments (usually the planning department). Also, it was checked if the data was in line with other obtained data. Possible erroneous data entries were removed in consultation with the actors responsible for owning the data. An short overview of the format, the source and the validation of the data can be found in Appendix B2. For all the input data holds that it is as recent as possible (i.e. September 2014). The data to describe the demand and the availability was based on the latest 2015 forecasts.

#### 5.3.1. Facilities

The model considers three facilities: facility 1-1, 1-2 (that represent both production facilities in WW) and facility 2 (PA). As facilities 1-1 and 1-2 are located at the same production site, they share similar costs for distribution and raw materials.

#### 5.3.2. Demand

Considering the demand, the model input was taken from the monthly sales forecast of 2015. The demand input describes the demand volume per period, per product, and per customer region. Demand to all countries outside of Europe was clustered into one region for all different products. This decision was made in order to reduce the model complexity, and is justified as

there was no significant difference found for the cost to serve customers outside of Europe, from the considered production facilities.

### 5.3.3. Production

Regarding production, three different aspects were included. The first relates to the different production facilities and the accompanying production capabilities. The capabilities in current state are displayed in Table 2 of Section 2.1.2. Second, the batch sizes serve as input. Batch sizes are fixed due to both volume constraints on the bottleneck reactor, and the chemical nature of the processes. The processes are carefully designed by the R&D department and are only stable for a specific batch size. Third, the (estimated) throughput rates for the bottleneck reactors were calculated. They were found by dividing the production batch size by the total routing time at the bottleneck reactor.

The third aspect relates to availability (MRTA), i.e. the total amount of hours available for production.  $\Gamma_{jt}$ , in hours, at each production facility was determined by the following formula;

$$\Gamma_{jt} = \text{Total Operational Time} - \text{Planned Downtime} - \text{Expected Unplanned Downtime}$$

Capacity or availability was measured in hours, as the total output volume is determined by the allocation of production to the production facilities and is thus one of the model decision variables. After the determination of the total available hours at each production facility, the expected available hours needed to produce the total demanded volume for the out of scope products was subtracted from the total capacity at each production facility. The quality parameter  $Q_j$  that constrains the actual deliveries in each period was inputted as the total percentage of the time that a batch is produced within the specifications to sell it directly to the customer.

### 5.3.4. Financial Drivers

The model is driven by the cost and revenue parameters. To ensure data consistency, there was chosen to use the cost drivers for one specific packaging type. The selected packaging type is the most common one (it is used in around 60 percent of all the orders). Also, it is the only packaging type for which the SAP system holds prices for considered products.

#### Revenue

The product prices out of the SAP system were used as input  $p_k$  for the revenue of a delivered product.

#### Investment cost

The investment costs to increase the capability of a production line, were estimated in consultation with the research and development department. As these cost are one-off, and the model only considers a full year, the cost were scaled to a full year. In order to do this, the investment cost was depreciated linearly over the estimated remaining product life time.

#### Operational production cost

The variable or operational cost of production can be split-up into two different components. The first is the raw material cost. For each product, if it was produced at a production facility in the current state, the total raw material cost was calculated by the finance department. If a product was not produced at a production facility in the current state, the total raw material cost was estimated. To do this, the bill of materials (BOM) or product recipe was used combined with the actual cost prices of all the raw materials on the BOM. The latter information was also used to validate the raw material prices as calculated by the finance department. Second, the variable production, or extrusion cost was considered. It consists of the direct costs for energy, labor, maintenance and packaging that can be attributed to production of specific products. They are

calculated for each production stage by means of the routing time multiplied by the cost of operating a specific production stage per unit time. The costs for all production stages were summed and finally divided by the batch size in order to compute the total extrusion cost per unit volume. Because of the way that the model was formulated, the extrusion cost and the raw material cost were summed to constitute a single input parameter, i.e.  $c_{kj}^v$ .

#### **Distribution cost**

The distribution costs to all the different regions were predetermined by the third party logistic provider. The prices to all regions were inputted as a price per unit volume, considering a fixed truck fill rate of 85%. Transportation costs to regions outside of Europe were fixed to the weighted average price to serve a customer outside of Europe.

#### **Holding and Backorder cost**

The holding cost was calculated by summing the warehouse costs, opportunity costs of capital and the costs of depreciation. Since for the backorder costs, no relevant indicators were identified within DCR, a rough estimate of three times the average holding cost was used. This estimate was made in consultation with employees from the customer service, the demand control, and the planning departments.

### **5.4. Verification and Validation**

After the definition of the model input, the model still has to be verified and validated before its solution is used. Through verification (Section 5.4.1) it is checked whether the model behavior can be described as logical. Through validation, it is checked if the model (5.4.2) and the accompanying assumptions (5.4.3) correspond to reality. The validation phase is visualized as the dotted line in Figure 21.

#### **5.4.1. Verification**

The model was verified in two different ways. First, a number of infeasible inputs were generated, where after the model was run in order to check the model behavior given those inputs. The model outcome was checked with both negative capacity and negative batch sizes as model input. In both instances the predicted model behavior was observed. To the former, the model responded that no feasible output was possible, while for the latter, the model produced zero output. Second, extreme values were set for certain parameters to check how the model responded. The variable production cost was set such that it exceeded the product price, and again, the model reacted as expected (i.e. no production). Furthermore, the investment costs were set to zero (enabling the production capabilities for all products at all production facilities) and were set to a very high generic number (again, leading to zero production in each period).

#### **5.4.2. General Validation**

To check whether the model output corresponds to reality was more challenging. First off all, the total capacity generated by the model given the initial situation was compared with the capacity as indicated by the initial aggregated production plan for 2015. In order to estimate the production capacity that could be generated by the model in the initial state, the model was solved while fixing the current production capabilities (i.e. no product transitions were possible). Results showed a positive difference of just 2.3 percent between the best solution found by the model, and the capacity indicated by the actual production plan. Comparing this with the differences in the throughput rates and the actual product mix in the initial situation, as described previously in Section 2.1.2, the outcome makes sense. For the given situation, the model is expected to increase the focus on maximizing production output such that it can fulfill all customer demand. It deliberately chooses production facility-product combinations with a higher throughput rate, thereby explaining the positive difference. Secondly, the model was



validated according to the expectations of the management at DCR. Two products were under consideration for a transfer to facility 2. The model suggests that four products should be transferred, including both the products that were already investigated by DCR (B-3 and B-4).

#### **5.4.3. Assumption Validation**

In order to constitute the scientific model, a number of assumptions was made. This section validates the specific assumptions for the case of DCR.

**All deliveries are accepted by the customer, i.e. no returns of goods.**

The 2013 order data at DCR shows that only a negligible percentage of the goods were returned (less than 0,5 percent). Therefore the assumption is valid.

**All customers are indifferent of the production facility that supplies their products.**

Customers are indifferent of the production location if DCR can ensure that a product can be produced with the right specifications regardless of the production location. The initial investment cost include, among others, the R&D cost to ensure this. Therefore, the assumption is valid.

**For each customer within the same geographical region, the transportation cost is equivalent to the transportation cost to serve center of the geographical region**

This assumption is valid as the transportation costs are pre-determined to each geographical region by the 3PL. The prices are actually equal for all locations within the same region.

**The total (remaining) life time of the production resources is always longer than the total (remaining) product life cycle of each individual product**

Conservative estimates were made on the remaining product life cycle for all considered products. The remaining life time of the assets at each production facility is expected to be far beyond these estimates.

**There exists an ample supply of raw materials for both production facilities and production for each product requires only one raw material**

Procurement lead times at DCR are short (order of days), and multiple suppliers exist for the same raw material. Furthermore, only a selected number of “main” ingredients are specific to each product. These three characteristics combined, lead to a situation where delays in production because of raw materials stock-outs very rarely occur. The price of raw materials is included in the model as the total, combined cost of raw material per unit of output. Hence both assumptions are valid.

**The distribution of goods takes place directly from production facility to customer, truckloads are fixed and delivery is direct**

The actual distribution takes place after consolidation with other DCR products, with an average truckload of 85 percent, this holds for all the regions under consideration. Delivery might, or might not be direct; that is up to the 3PL, but the prices that are calculated by the 3PL are based on the volume shipped to a specific region. Hence, the assumption is valid.

**For each product and each production facility, the production cost are linear**

Since the production cost solely depends on the batch size and the total routing time at each production stage, the production cost is independent of the volume that is produced. Either a batch is produced at a certain cost per kilogram of output, or it is not produced. The production process is the same, regardless of whether two batches of the exact same product are produced in a sequence, or two different batches are produced in a sequence.

## 5.5. Model Solution

Now that the model is validated and the model input has been defined, this section discusses the solution found by the model for the base case situation. After a total solving time of 120 seconds, the model found a feasible solution that was 0.97 percent worse than the best LP bound. The actual profit and costs that follow from the solution with base case parameter setting remains undisclosed due to confidentiality restraints. They do serve as a reference for the remainder of the report. The production capability matrix of the solution is displayed in Table 5. Comparing the capabilities in the old situation (Section 2.1.2) with the renewed capabilities proposed by the model, it is suggested to invest in enabling production for the products **B-3, B-4, B-8 and B-9** at **facility 2**.

Product	Capabilities		
	F 1-1	F 1-2	F 2
A-2	1	0	1
A-3	1	0	1
A-4	1	0	1
A-5	1	1	1
B-1	1	1	0
B-2	1	1	1
B-3	1	1	1
B-4	0	1	1
B-5	1	1	1
B-6	0	1	1
B-7	1	1	1
B-8	0	1	1
B-9	0	1	1
B-10	1	1	0
B-11	1	1	1
B-12	1	1	1
B-13	0	1	1
B-14	1	1	0

Table 5: Matrix indicating the production capabilities for the model solution

In Figure 23, the aggregated relative distribution of production is displayed. Comparing this figure to Figure 16 from Section 2.1.2. It follows that the model solution suggests a different production strategy for multiple products. The differences are the largest for the products A-5, B-2 and B-13 (were previously, the greater part was produced in PA), and the products B-3, B-4, B-8 and B-9 (previously WW).

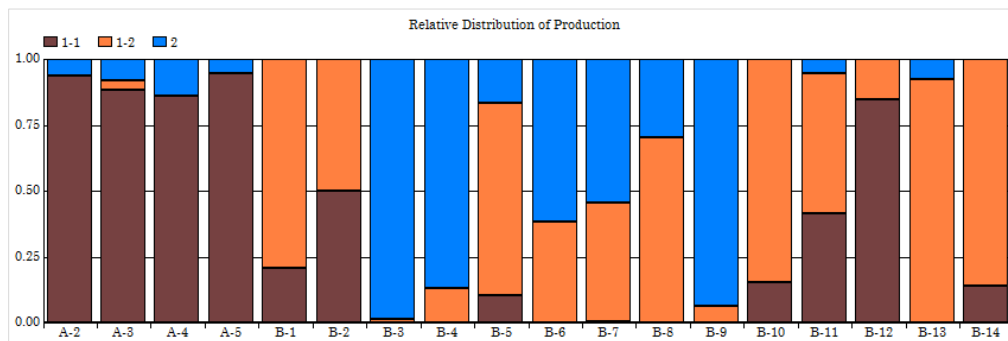


Figure 23: Model solution for the relative distribution of production to the production facilities for each product

Through the abovementioned distribution of the production the total capacity increases, leading to a feasible production plan. The capacity increases due to an increased overall throughput rate. For example, products B-3 can be produced significantly faster in facility 2 than in both facilities 1-1 and 1-2, while for product A-5 all facilities have similar throughput rates. Hence reallocating A-5 to facility 1-1 and B-3 to facility 2, leads to less available hours that will be needed to produce the total demanded volume for A-5 and B-3. The remaining available hours can be used to produce other output, thus increasing capacity. In total, the proposed model solution produces 3.3 percent more total output, without violating the utilization objective in any of the production periods (see appendix C1.1). Although the model solution demonstrates

significant improvements in production efficiency, the high pressure on the supply network remains. Appendix C1.2 to C1.4 show that in multiple periods (i.e. 1, 6 and 10) the demand is higher than the actual production, leading both building up stock, and backorder deliveries. For the aforementioned periods this furthermore leads to an expected average service level of 92.8 percent (i.e. below the 95 percent target), but this is only because the model lacks the ability to build up stock for the demand peak in the first period. Without considering the first two periods, the average service level would be 95.0 percent. Note that the service levels for the model outcome are not the same as the actual (expected) service levels, as stock levels are not explicitly considered. However, it does give an indication of the ability of the supply network to cope with the actual demand.

The model suggest production and delivery through a local-for-local strategy. The customers supplied from PA are typically located in Spain, Portugal, the south of France, and Switzerland, while customers from Germany, Holland, Belgium and Great Britain are served from WW. Still, not all customer regions are supplied by the nearest production location. A more detailed overview actual delivery location per region can be found in Appendix C1.6.

The main cost drivers of the model are similar to those found earlier in Section 2.1.5, only now, the investment and the backorder costs are included, as can be seen in Figure 24: Breakdown of cost drivers, as a percentages of the total cost (%). It shows that the investment costs add up to around 1.1 percent of the total yearly operational cost.



Figure 24: Breakdown of cost drivers, as a percentages of the total cost (%)

## Sensitivity Analysis

Besides the current situation, multiple other scenarios are likely to occur in the near future. In order to draw robust conclusions, this section identifies scenarios that are likely to occur. Furthermore, this section investigates how deviating the model input parameters affects the optimal solution. Section 6.1 structures the possible scenarios after which the most likely scenarios are analyzed in detail in Section 6.2.

### 6.1. Structure to Construct Scenarios

After interviews with multiple DCR employees, an overview was made of the scenarios that are likely to occur. Multiple relevant scenarios were discovered that could affect the model solution. Since these scenarios could take place simultaneously and are often interdependent, there was decided to structure all scenarios first. Hereafter, in consultation with DCR, specific scenarios can be chosen for a detailed analyses. The first presented scenarios relate to restricted investments. The possibility exist that due to either high perceived risk for product transitions, or due to a limited budget to realize investments, it can be decided not to choose the optimal investment strategy. Secondly, the total hours of availability at each production facility could be affected. Thirdly, there exists a possibility for alternative demand scenarios, both with the current product portfolio, as due to new product introductions. Finally, the cost parameters are likely to deviate. Figure 25 displays an overview of the identified scenarios.

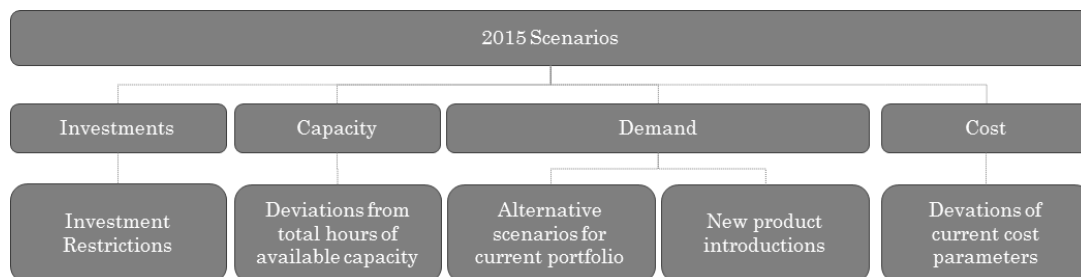


Figure 25: Overview of the identified scenarios

### 6.2. Detailed Analysis

#### 6.2.1. Investment Decisions

One of the goals for the case study at DCR was that the company wanted to know which investment decisions would be most beneficial to them. In order to demonstrate the impact of individual investments, it is decided to start a couple of scenarios where the investments are predetermined, and to compare the solutions with the optimal solution for the base case model. This option for sensitivity analysis was preferred above deviating the cost for the investments, as it is more realistic. The investment costs are very accurate as they are estimated with a lot of experience of previous and similar product transitions. The uncertainty towards the future investments relates mainly to the total available funds for investing in transitions. Therefore, for DCR, it is preferred to gain insights in the effects of individual or a combination of specific investments for product transitions. In order to analyze this, variable  $q_{kj}$  was set to fixed input

parameter (i.e. instead of a decision variable) that reflected the capabilities in the current situation. The base case without investments led to an operational profit decrease of 3.25 percent compared to the base case. The relative distribution of production is depicted in Figure 26.

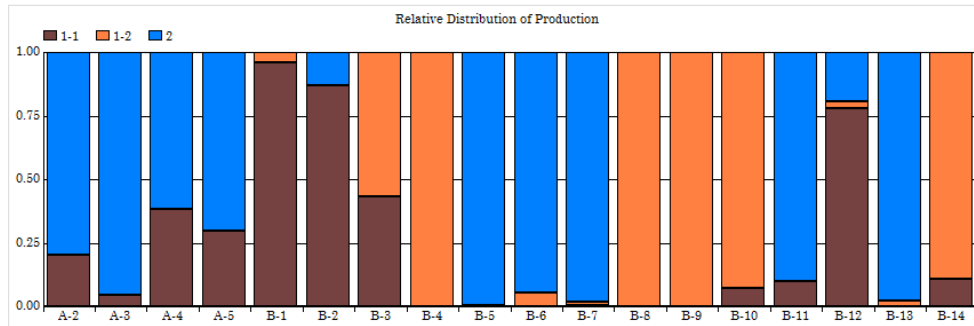


Figure 26: Model solution for the relative distribution of production for the case with no investments

Figure 25 shows that the model is driven towards generating sufficient output in order to cope with the demand, e.g. the A-type products are now produced for a large part in Facility 2. This leads to both increased costs of production and distribution. Furthermore this leads to poor service levels (86.8 percent on average, see Appendix C2.1), and elevated backorder cost. Other pre-fixed investment scenarios are selected because of both quantitative (demand volume, throughput delta, and cost delta) and qualitative (risk mitigation strategies and increased flexibility through dual options for production) characteristics. The absolute financial results and the service levels for each investigated investment scenario are displayed in Figure 27. For the absolute cost and profit changes, the “no investment” scenario functions as a baseline. From Figure 26 the following conclusion is drawn: In terms of cost and profit, investing a transition of product B-3 has the biggest impact, leading to significant decreases in both production and distribution cost. However, in order to attain the desired service level target of 95 percent, the base-case, optimal solution is preferred.

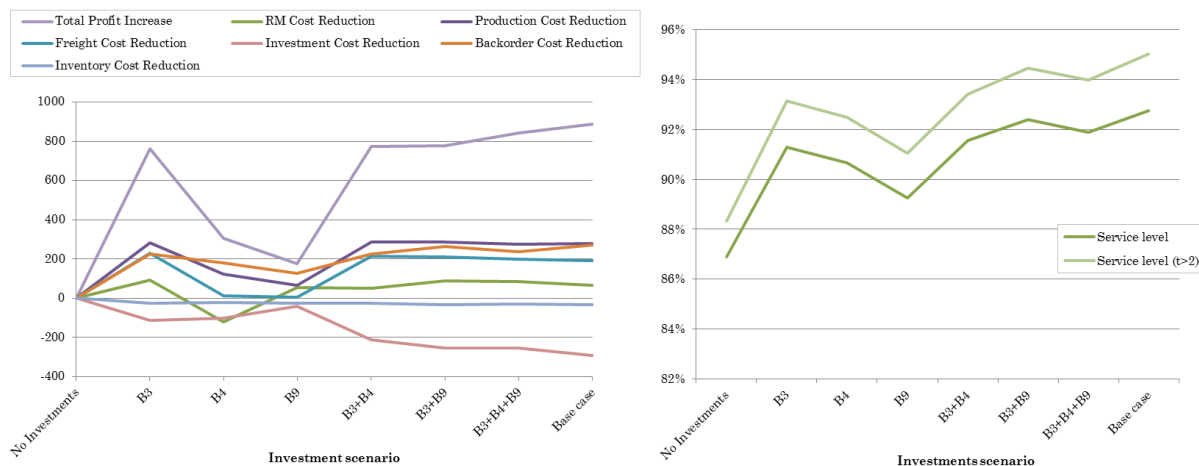


Figure 27: Absolute financial results compared to the no investment case\* (left) and the expected service levels (below), for the considered investment scenarios.

\*results are scaled conform a confidentially agreement.

In appendix C2.3, the relative distribution of the production is displayed for the different scenarios. The graphs clearly show that there exists a preference for producing B3, B4 and B9 in location 2 (instead of, the A-type products, B-11 and B-13). When enabling facility 2 for the

production of B-3, an immediate shift of the production for the A-type, B-11 and B-13 products towards facilities 1-1 and 1-2 becomes apparent.

### 6.2.2. Increased Demand and Availability

#### Effects of increased availability

It is likely that the available hours for production are increased in the near future, since currently other (i.e. out of scope) products are also produced at the same production facilities. Some of these products can be allocated to other (again, out of scope) facilities on different continents, hence increasing the available hours that can be allocated to the products under consideration. Three scenarios and their accompanying input ( $\Gamma_{jt}$ ) changes are displayed in Appendix C3.2. The scenarios hold increased capacity for increasing for location 1, location 2 and both locations respectively. For all scenarios the same effects occur, where the new optimal production strategy leads to a lower total operational cost, and improved service levels. It also decreases the overall utilization rates, which in turn improves the flexibility or responsiveness of the production facilities.

The first scenario proposes only a small increase in availability at location 1, leading an investment preference for B-1 instead of B-4. The impact of capacity expansion becomes more clear when looking at the other two scenarios. Both indicating that a higher availability of the production facilities, forces the model to focus on the most cost effective production strategy. In this case this means that there is chosen to make the extra investment on B1 (compared to the Base Case scenario), since this will eventually lead to a lower overall operational cost, thereby recovering the initial investment on B-1 and increasing the total profit with 0,6 percent for the increased availability at location 2, up to 1,5 percent for the case with ample availability. It illustrates the optimal strategy when the demand is low compared to the production capacity. This demonstrates that the for products A-3, B-2, B-5, B-10, B-11, B-12, and B-14, the production model is indifferent of producing at facility 1-1 or 1-2. Moreover, it shows that, except for customers that are located very close to facility 1, facility 2 is preferred for production of B-1, B-3, B-4, B-6, B-7, B-8 and B-9. Similarly, for the A-type products 1-1 is the preferred production facility. This being said, it should be noted that increased availability causes the overall utilization rate to drop, leading to high facility idle times. This implies excess cost that are currently not considered by the model. So there is a trade-off between the negative effects of idle time and positive effects of cost efficient production and enhanced responsiveness.

#### Effects of increased demand

The scenarios for increased availability become more interesting when possible scenarios for increased demand are considered. In the current state, the demand for two specific products (i.e. B-3 and B-4) is rapidly growing. DCR is contemplating to launch these two products into different market segments, creating new sales opportunities and expediting the demand increase in the near future. Multiple scenarios for increased demand of B-3 and B-4 are considered, including scenarios where there is extra availability allocated to both location 1 and location 2. For detailed results and graphs there is referred to B1, as well as Appendices C3.1 to C3.4.

First, from B1 it becomes apparent that the model has more difficulties to solve cases with insufficient capacity. The optimality gap of the model solution increases (up to 2,12 percent after 600 seconds of solving time) for cases where the demand is higher. Due to the tight capacity constraints, the model seems to only consider feasible solutions with a utilization rate extremely close to the upper bound. It is therefore more likely to come up with infeasible solutions. Note that a larger optimality gap makes it more difficult to compare multiple

scenarios, however, it is assumed that the optimality gap is still small enough to make statements on the different model outcomes.

When considering the summary of the model results in Appendix C3.1, it is concluded that the increased demand forces the model to focus on the most effective strategy to produce maximum output. As the demand increases, the operational cost also increases, but simultaneously the revenue is increased as well, up until a maximum is reached, i.e. the actual capacity of the production network. The profit will increase at first, but will eventually decrease again, due to poor service levels and eventually due to a total backorder cost that exceeds the operational profit margin. This is also the reason that the model solutions are similar for both cases 3 and 4 in Appendix C3.3, as well as cases 3 and 4 in Appendix C3.4. These solutions indicate the strategies to produce maximum output in order to fulfill as much demand as possible. These strategies lead to the production figures as depicted in Figure 28, illustrating the production capacities according to the model (the optimal solution for the base case serves as a baseline).

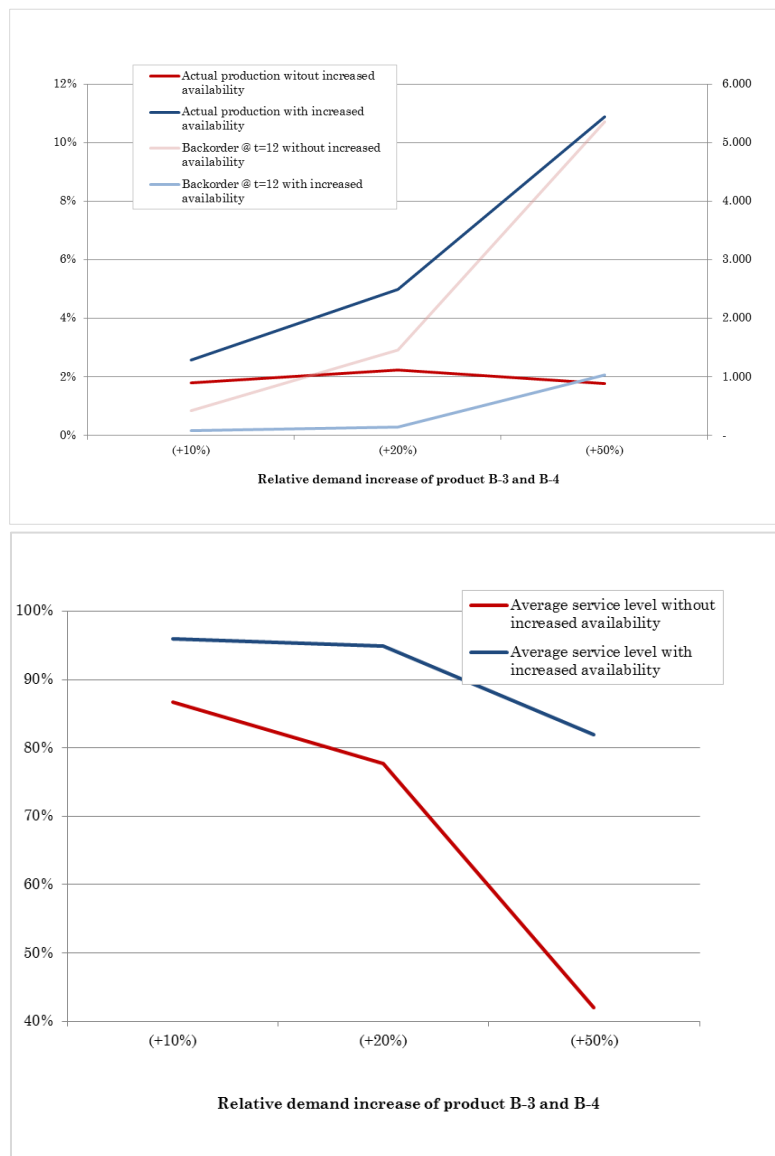


Figure 28: Actual production (above) and the expected service levels (below), with and without increased availability, for all considered scenarios of increased demand for B3 and B4.

From the graphs it is deduced that through the liberation of extra availability through removing both product “X” and product “Y” from locations 1 and 2 respectively, the total production can be increased by around 5 percent (compared to base case) while maintaining reasonable service levels. Furthermore, the graph shows the total backorder in the last period of the model (compared to base-line indexed as 100). From this, it is concluded that if the demand for B3 and B4 would increase with over 20 percent, the increased availability by removing “X” and “Y” is still sufficient in order to cope with the total demand. If the demand will increase further, DCR either has to find different solutions to increase capacity, or has to consider rejecting demand in order to avoid high backorder costs. Candidates for rejection proposed by the model (i.e. demand that was consequently in backorder until period twelve), were identified as the customer region outside of Europe (for all products), customer demand for B-4 (regardless of the customer region) and the customer region SE04.

### **6.2.3. Effects of cost parameter deviations**

The main cost drivers of the model have already been identified in both the problem situation and the model solution phase, yet this does not necessarily mean that the optimal solution is affected predominantly by these main cost drivers. In order to determine which cost parameters will affect the model outcome, a sensitivity analysis on the cost parameters was performed. An overview of all scenarios and the accompanying results is found in Table C4.1, for details regarding the solution process there is again referred to B1.

#### **Effects of total production cost deviations**

First the effects of deviations of the production costs were tested. Since the variable production cost model parameter  $c_{kj}^p$  is constituted by both variable production and raw material costs, it is chosen to deviate the raw material costs and generalize the results. Two different procedures were carried out, starting with deviating the raw materials costs for each product in the network. Model solutions are displayed in Appendix C4.2 (1-6). Neither these solutions, nor the results of Table C4.1, suggest that overall increases in raw material costs affect the optimal solution. No real trends can be found in the results of the different model solutions.

Secondly, it was decided to select a number of products for which the raw material costs will be deviated. Products were chosen based on their percentage of the total production volume, including both large, and smaller products for which the costs were deviated. Also there was aimed for a set of products that are representative for all products under consideration (i.e. B3 is close to B4 and B1, A3 is close to A1 to A4 etc.). This resulted in the selection of the products B3, A3, B5, B6, and B11. Finally, since the variable production costs (in the current state) are generally lower at facility 2, it was chosen to emphasize on decrease of the cost in facility 1-1 and 1-2, in order to make model shifts clearly visible. The model solutions for the different scenarios are displayed in Appendix C4.3, model results are depicted in Figure 29: Cost changes (compared to base case) for deviations of the raw material cost for products B3, A3, B5, B6 and B11. The results clearly indicate that deviations of the raw material cost for specific products, lead to a shift in the preferred production facility for those products. From graph 1 to 5 in Appendix 5.3, it can be observed that as the raw material costs for the considered products decrease, gradually the relative production distribution shifts towards the facility where the raw materials are the cheapest. This is the case for all the products under consideration, except for product A3, but this is probably due to capacity constraints of the current network; i.e. in the current state, it is impossible to produce all demand for B3, A3, B5, B6 and B11 in facility 2 without rejecting part of the demand.



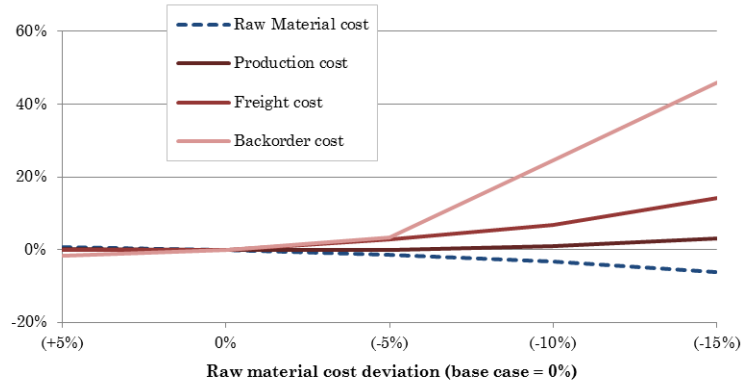


Figure 29: Cost changes (compared to base case) for deviations of the raw material cost for products B3, A3, B5, B6 and B11.

Figure 29 exemplifies the model results, where it is clear that a decrease in raw materials leads to increased costs for the remaining cost drivers of the model (inventory cost was left out, as for all given scenarios they accounted for less than 0.25 percent of the total cost). This suggests that increased raw material costs affect the optimal solution, as the focus shifts towards producing where procurement costs for raw materials are lowest, while accepting a negative impact for the remaining cost drivers.

As already mentioned before, raw material cost and variable production cost are treated similarly by the model as the parameter  $c_{kj}^v$  is equal to the sum of both costs. Hence, similar effects are expected with deviations of the variable production costs. However, the impact will be less severe because the extrusion cost per unit volume of output is generally around a third of the raw material cost.

### Effects of freight cost deviations

In order to see the impact of freight cost on the optimal solutions, it was decided to deviate the freight costs (for all different facilities, to all different customer regions) with up to 10 percent. It was expected that when the freight costs increased, the model would come up with a solution where for each customer region goods were produced at, and distributed from the nearest location (or cheapest distribution location). The results and solutions for the different scenarios can be found in Figure 30 and Appendix C4.4. No significant changes to the optimal solution were observed in any of the cases. Therefore, it is concluded that deviations in the freight costs do not affect the optimal solution.

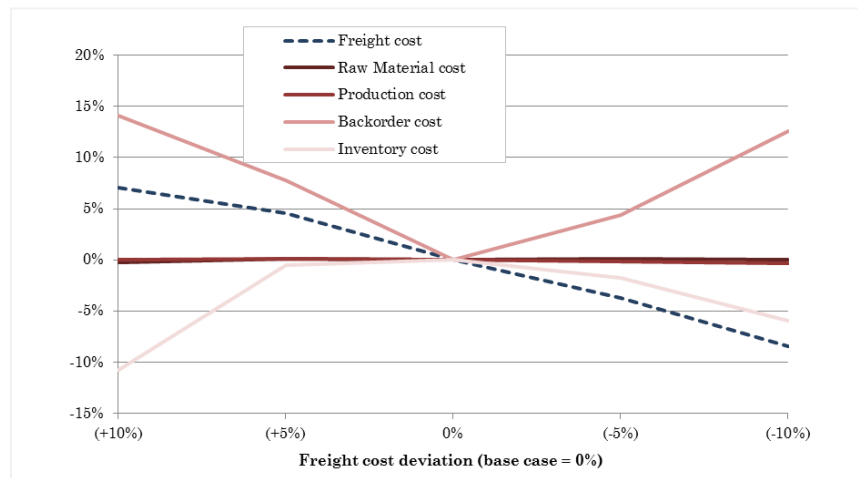


Figure 30: Cost changes (compared to base case) for deviations of the freight cost

### Effects of backorder cost deviations

As mentioned before in Section 5.3.4, the model input parameter for the backorder cost is a rough estimation, as no indicators of the actual backorder cost were found within DCR. Therefore it is decided to solve the model with a backorder cost input parameter of multiple magnitudes, ranging from a backorder cost equal to the average holding cost, up to a backorder cost that is 16 times the average holding cost. The model solutions are found in Appendix C4.5, the financial results compared to the base case (i.e. backorder is 3 times average holding cost) are displayed in Figure 31. In Figure 31, the left axis is used for the raw material, production and freight cost changes, while the right axis is used to depict the backorder and inventory cost changes.

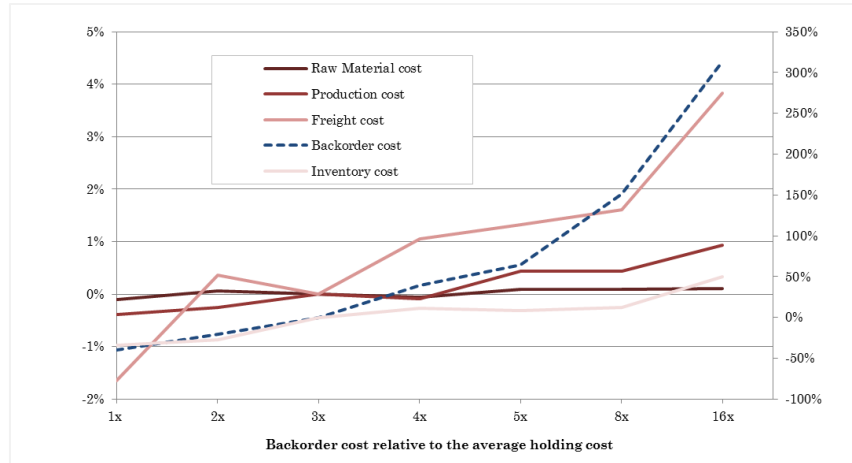


Figure 31: Cost changes compared to the base case for deviations of the backorder cost (base case = 3x average holding cost)

From the results changes can be observed for high input values of the backorder cost. When the backorder cost is increased, the solution changes in a similar fashion as with increasing demand in Section 0. Furthermore, it can be seen from B1 that with increased backorder cost, the model struggles to find a feasible solution within the allowable optimality gap, as was the case in Section 0. By heavily increasing the backorder cost, the model is less likely to tolerate backorders (i.e. increases its service level) and for that reason it tries to increase production. Besides this, the model solution is affected when the backorder cost is set equal to the holding cost. In this case an investment was proposed for B-1 instead of B-4. This shift could be due the increased flexibility of the model, as it becomes indifferent of delivering goods from stock, or from backorder. In the end, it is concluded that the backorder cost deviations affect the optimal solution, but only for extreme values.

### Effects of holding cost deviations

The holding cost comprises a very low percentage of the total cost, so therefore deviations of the holding cost were expected to have no impact on the optimal solution. In order to proof this, the model was tested for relatively large deviations of the holding cost, ranging from 0,5 up to 2,5 times the current value of the holding cost. Results were as expected, although increasing the holding cost did lead to increased backorders. For the case where the holding cost was almost equal to the backorder cost (i.e. holding cost is 2,5x the current holding cost), the model solution shifted towards the same solution as found in the previous section where the backorder cost was set equal to the holding cost. Again, it is concluded that increased holding cost do affect the optimal solution, but only for extreme values.

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## Model Extension

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The model as described in the previous chapter is able to support decision making with regard to the allocation of production to different production facilities. After the previous analysis and the feedback at from DCR's management, there was some discussion on the feasibility of implementing the current solution. The discussion was directed towards the assumption on the input parameters and more specifically towards the throughput rates at the bottleneck reactor. For a few product-production line combinations, it was expected that from a certain volume threshold the bottleneck would shift towards a different stage in the production process. Hence, idle times occur on the bottleneck reactor, depending on the total production volume. Therefore, the model is extended with "penalty" or idle times for allocating large volumes to a single production facility. Thereby aiming to increase the accuracy of the model.

### 7.1. Conceptualization of Model Extension

In order to model the idle times, a set of production stages is introduced. The production stage forces the model to produce (for each product, production facility and period) in a specific state. The input comprises the associated idle times as well as the upper bounds on the total volume that can be produced in that production stage. The idle times are strictly increasing with the determined upper bounds for production stage, but it is assumed that within a production stage, the idle times are equal, regardless of the actual produced output. As such, non-linear constraints can be avoided. For each production facility-product combination, in each period, the model will choose one production stage, with an accompanying idle time and upper bound the total production volume.

### 7.2. Mathematical Formulation of Model Extension

This section gives an overview of additional model sets, parameters, variables and constraints, as well as the changes made to the model formulation as described in Chapter 4. For the complete formulation of the extended model, reference is made to Appendix D. In order to formulate the model extension, the following variables and parameters are introduced;

$N$	=	the set of production stages, indexed by n	
$\zeta_{kjn}$	=	the total capacity volume for production of product $k \in K$ at facility $j \in J$ when producing in production stage $n \in N$	
$\varphi_{kjn}$	=	the penalty time, or idle time awarded for producing product $k \in K$ at facility $j \in J$ in production stage $n \in N$	
$\varphi_{jt}^{total}$	=	Total idle time incurred at facility $j \in J$ in period $t \in T$	
$y_{kjnt}$	=	variable that indicates if production takes place for product $k \in K$ at facility $j \in J$ in production stage $n \in N$ in period $t \in T$	<b>(decision variable)</b>

The following constraints and equations are added to the model. First a binary constraint  $y_{kjnt}$ , that indicates if a production stage is chosen.

$$y_{kjnt} \in (0,1) \qquad 1 \leq t \leq T, \quad \forall k, j, n, t \qquad (11)$$

Secondly, constraint (12) will ensure that at maximum one production stage is chosen for each product, at each facility, in each production period.

$$\sum_n y_{kjt} \leq 1 \quad 1 \leq t \leq T, \quad \forall k, j, t \quad (12)$$

Thirdly, the actual production is constrained by the associated capacity of the selected production stage by equation (13).

$$A_{kjt} \leq \sum_n y_{kjt} \varsigma_{kjn} \quad 1 \leq t \leq T, \quad \forall k, j, t \quad (13)$$

Equation (8) from the initial model poses an upper bound on the total amount of unit time available for actual production. Therefore, in the extended model, this constraint is adapted such that this upper bound is diminished by the total penalty time. From the original model, constraint (8) is modified to;

$$\sum_k \frac{1}{\tau_{kjt}} A_{kjt} \leq \Gamma_{jt}^a - \varphi_{jt}^{total} \quad \forall j, t \quad (8)$$

Where the total idle, or penalty time is equal to;

$$\varphi_{jt}^{total} = \sum_{kn} y_{kjt} \varphi_{kjn} \quad \forall j, t \quad (14)$$

### 7.3. Model Extension Validation and Input

For the DCR case only three product-production facility combinations were considered, i.e. the products A-2, A-4, and A-5, at facility 1-1. So for the remaining variables this leads to a single production stage with no constraints on capacity. Estimates for the idle times at each production stage were calculated after consulting both detailed schedulers and the management of the planning department. The model was validated by running the model with both very high, and very low idle times. Results were as expected; the model responded with zero production (for A-2, A-4 and A-5 at facility 1-1) for the case with high idle times at each production stage, and with a solution similar to the base-case solution for the case with low idle times at each production stage. The assumption that the idle times within each production stage are independent of the actual produced output is valid as an approximation, as long as the intervals between the capacity bounds in subsequent production stages are relatively small. This is the case, as a intervals are limited to at most two batch sizes. Also, the idle times were estimated conservatively to secure a feasible model solution.

### 7.4. Solution of Extended Model

The extended model results in a solution that falls within 1.56 percent of the best linear bound, resulting in a total profit which is only one percent lower than the solution of the base case model. The results are according to expectation.

From the relative distribution of production in Figure 32 it can be observed that the model suggests not to invest in a transition of product B-4, while it allocates a larger percentage of the production of A-2, A-4 and A-5 to facility 2. Facility 1-2 takes over the full production of B-4. Also, the capacity available at facility 1-1 is not allocated to the production of B-1 and B-2. Finally, as facility 2 is no longer producing B-4, its remaining capacity is allocated for production of B-7 and B-8. The decreased profit is mainly explained by a 4 percent drop of the service level, resulting in increased backorder cost of 50 percent, as well as a decrease in production cost of 1 percent. On the other hand, there is not invested in a transition of product B-4 to facility 2, thereby mitigating part of the increased cost.

From the results of the model extension, it is concluded that including a penalty for allocation of large volumes to a specific production facility has a significant effect on the model outcome. Even though the model solution is still similar to the base case, the penalization prevents the model from fully loading production for certain production onto one specific facility. This eventually also causes a different allocation of the remaining products.

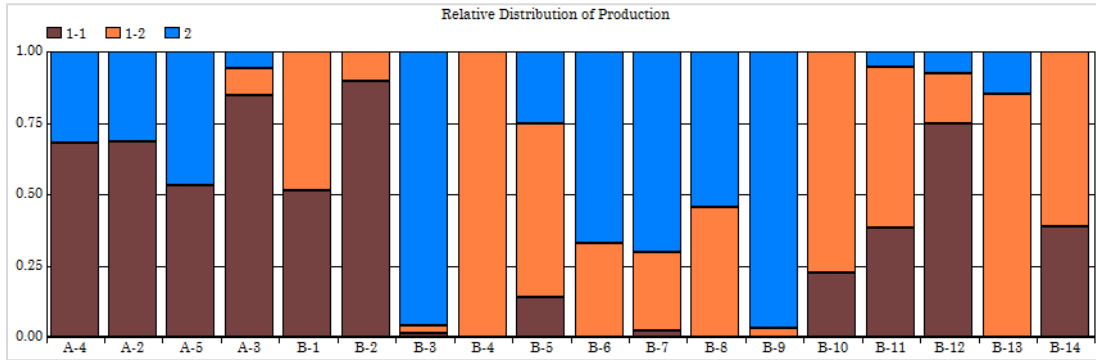


Figure 32: Extended model solution for the relative distribution of production to the production facilities for each product

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## Conclusions, Recommendations and Limitations

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According to Sagasti and Mitroff (1973), the last step of the operations research process is the implementation of the solution, translating it back to reality. For the current research the actual implementation of the model solution is out of scope. This would not be feasible within the time frame of the research, nor does the researcher have the authority to implement the model solution. However, the researcher does have the ability to make suggestions about the steps that are to be taken by the company according to the most important conclusions of the research. To this extent, Section 8.1 describes the conclusions and recommendations that follow from this research. Section 8.2 elaborates the limitations of the model and proposes directions for future research.

### 8.1. Conclusions & Recommendations

The objective of the research was to reconsider the current production network for the WBU product family, and come up with a strategy to allocate the production for the individual products to the existing production facilities. Moreover, the chosen strategy had to be feasible, in other words, it could not violate the utilization objective. A profit maximization model has been chosen, because through the analysis of the current situation uncertainty existed if, with the current resources, the model could cope with the total expected demand. The model solution shows that through the proposed investment decisions, combined with the allocation of the production to the different facilities, DCR is able to significantly increase its production. The model proposes a feasible solution, that is able to increase total production, with acceptable service levels.

#### Model performance

The model performance depends heavily upon the size of the problem, for small datasets, the model converges to the optimal solution within a couple of seconds. For the DCR case, the model performs well. In most scenarios, the model was able to find a solution of around one percent of the best linear bound with a runtime of at maximum 10 minutes. The model is perceived to have more difficulties in solving extreme (less realistic) scenarios, leading to an increased gap between the obtained solution and the best linear bound. The model covers the most important elements of the supply network. Furthermore, multiple assumptions were made, creating an accurate and a robust representation of reality. Through the results of the sensitivity analysis, it was addressed which elements impact the optimal allocation of production, and which factors are of less importance. It also showed the flexibility of the model to focus on output maximization, cost minimization, or a combination of both, depending on the situation. Finally, the model extension that was created after feedback from the DCR management, makes the model more accurate, and provides additional insights. The extension is useful, as it causes the optimal solution to change significantly.

#### Effects on production efficiency and utilization rates

Reconsidering the allocation of the production to the different production facilities leads to increased production efficiency. By making investments for product transitions, the overall average throughput rate can be reduced, leading to increased production capacity.

For the base case solution at DCR, the total output is equal to the total demand, which is 3.3 percent higher than estimated output for the current situation. Hence no demand was rejected by the model. By means of the sensitivity analysis for increased demand from section 6.2.2, it was demonstrated that the model is able to increase the actual capacity by an extra 1.8 percent, leading to a total increase of 5.1 percent compared to the current situation. That is, if there were to be focused solely on generating maximum output. Note that this result can be obtained without increased availability. Certainly, capacity would increase even more while increasing the total time available for production. The utilization rates are equal for all model outcomes (again except for the case of increased availability). For each scenario, the average utilization rate is close to 95 percent on all of the production facilities. Thereby demonstrating, that the model focusses on minimizing the total cost, while it is bounded by capacity constraints.

### **Effects of Investment Decisions**

Choices that are made in order to enable production at a production facility, affect the optimal strategy. After incurring a fixed cost, the production network gains the capability to produce at a different location. Depending on the production characteristics of the previously mentioned capability, this can lead to both savings in the total operational cost, as well as increased total production capacity. This also implies increased service levels and enhanced flexibility of the supply network to respond to unexpected behavior within the market, making the supply chain network less vulnerable to market dynamics. If the fixed cost are lower than the expected increased profit, there should be invested. The model is able to point out for which investments this is the case.

For the DCR case, the total investment cost is relatively low compared to the total operational cost. Therefore, the model is clearly affected by investment decisions. Both the optimal solution for the base case and the extended model suggest that DCR should invest in enhancing capabilities at production facility 2 for production B-3, B-8 and B-9. Through these investments, capacity is increased, making the production plan feasible while attaining service level targets in almost every period except for the first two. Poor service levels in the first two periods can be avoided by building up stock before the first period, thereby mitigating the demand peak in period 1. The investment on B-3 is the most beneficial in terms of cost and increased production, while for the remaining investments the benefits are less substantial. However, as the total investment costs were very conservative estimates, and the model still indicates that a benefit can be obtained by investing, it is advised to undertake all the investments suggested by the model outcome. Finally, in order to achieve desired service levels, all the investments are required, underlining the importance all proposed investment decisions.

### **Effects of increased availability and demand**

Through sensitivity analysis, it is demonstrated that through increasing availability and demand respectively, the model aim shifts from minimizing total cost to maximizing total output. For the reusability of the model this is important, as the model is able to find a feasible solution independent of the circumstances under which it is applied. Increased availability leads to a higher total profit, up to a certain point where the best, most cost effective strategy is found. Note that this is because the model does only include the operational cost, and does not include the cost of idle resources due to excess availability. Increased demand forces the model to focus on maximizing output, and increases the total profit up until the total demand is fulfilled, or production capacity of the supply network is reached. Demand that is still in backorder in period 12 is considered as demand that cannot be fulfilled.

For the DCR case, increasing the availability is not deemed necessary for the current situation. Increasing the availability will only lead to slight increases of the total profit and service levels, while the negative effect of the total idle times remains uncertain. As within the company there

is some uncertainty about the demand forecast for products B-3 and B-4, it is advised to fully reevaluate these forecasts. This optimal production strategy will be affected by the total demand of these two products. Depending on the outcome, the total availability can be increased.

#### **Effects of cost parameters**

The most important cost parameter considered is the variable production cost, consisting of the raw material and the extrusion costs. The model solution is affected by the extrusion cost. A decrease in the raw material or variable production costs (for a specific product-production facility combination) leads to an increase of the relative production volume for the considered combination. The optimal solution is hardly affected by changes in the overall production cost. The same holds for the deviations of freight, backorder, and holding cost. Where only extreme deviations cause the model solution to change. It can be concluded that the optimal solution of the model is affected only when the cost *differences* between production locations change. Note that, again, the influence of the differences is dependent on the total available time for production. With a low availability compared to the total demand, the model will focus on output maximization, while with an increased availability, the model will focus on cost minimization, striving for the cheapest configuration that is able to fulfill the total demand. Furthermore, remark that even though variations of the freight costs do not impact the optimal solution, it is still an important determinant of the allocation of demand to production facilities. The solution shows that for each product, given the production strategy, the total delivery cost is minimized.

According to the purchasing department, the cost of raw material for a specific product can be decreased, when they are bought from the same supplier. For each product, DCR should investigate the benefits that can be obtained by production, and hence procurement of raw materials, at a single location. For basically all products (except for B-6, B-7 and B-9 of the base case solution), the model solution already proposes to deliver the majority of the demand from a single production location. It is recommended that for each product, the raw materials cost is recalculated by estimating the potential economies of scale, and see what effect this will have on the optimal solution.

#### **Effects of Model Extension**

The model extension demonstrates the effect of penalty idle times, while the total production of a specific product, on a specific production facility increases. It shows that the model solution is affected such that idle times at the bottleneck reactor can be avoided. Estimates were used to calculate the idle times associated with different stages of production for each specific product. As the optimal solution is heavily impacted by the potential idle times, there is suggested that DCR further investigates the exact production level for which the bottleneck is expected to shift to a different production stage (again for products A-2, A-4 and A-5). Also, it should be investigated what exactly causes the bottleneck to shift, and what the cost would be to prevent this shift from occurring.

#### **Summary of proposed action plan**

In order to guide DCR with the implementation of the recommendations, a summary of the proposed actions is described in order of execution.

1. Make investments on transitions of B-3, B-8 and B-9 to facility 2 as these investments are suggested by the model the base-case, the extended model case, and virtually all other considered scenarios.
2. Reconsider the current aggregate production plan, redistributing the production over the different facilities, thereby creating a feasible production plan for 2015. Change the corresponding system parameters that trigger the initial production plan accordingly.



3. Recalculate the current stock levels based on the model outcome. This includes elaborating on the calculations or estimations of holding and the backorder cost parameters.
4. Build up stock to cope with the demand peak in January 2015
5. For products A2, A-3 and A-5 at facility 1-1, investigate the exact production levels for which the bottleneck shifts towards a different production stage. Estimate the costs for debottlenecking and compare this to the extra profit that can be obtained by the optimal model solution. Hereafter decide whether these investments are preferred.
6. Reevaluate the raw material costs and estimate possible economies of scale for procurement of raw materials in the new situation.
7. Quantify the future demand increase for products B-3 and B-4, based upon this decide to increase the total availability for the products under consideration.

## 8.2. Limitations and Directions for Future Research

This section describes the limitations and weaknesses of the model, in order to help future researchers to build upon this research. This is referred to by Sagasti and Mitroff (1973) as “feedback in a wider sense”, where the conceptualization of reality is again adapted, based upon the knowledge acquired from accomplishing all of the steps in the Operations Research Process.

### Economies of Scale for Procurement of Raw Materials

For the current research, the raw material cost per unit volume was used as a fixed input parameter. This means that the model is unable to account for economies of scale when procuring raw materials (and subsequently producing) at a single location. Furthermore, raw materials were modeled one-to-one with the end products, where the raw material cost was dependent on the end product. This means the model would be unable to capture economies of scale from end products that share one or more identical raw materials. Combined with the knowledge that the cost of raw material is the most important model driver, it is suggested that future models should elaborate on a more realistic inclusion of raw material procurement.

### Rejection of Demand

The model has a flaw, since it is not able to reject demand explicitly. It could be considered that rejected demand, is equal to the demand that is still not fulfilled at the end of the final period, but this is not the same as explicit rejection of demand. From DCRs perspective this makes sense, as they would never consider rejecting demand. However, from a theoretical perspective, not rejecting demand is undesirable. If demand cannot be fulfilled by the model, the backorders are carried up until the end of the last period, unnecessarily increasing the total cost. Also, it might be more profitable to immediately reject demand, than to pay backorder cost for e.g. three periods, before fulfilling the demand. Therefore, future models should attempt to include a mechanism for demand rejection.

### Penalty Cost or Constraints for Total Emissions

The distribution was modeled fairly simple, because of the present situation at DCR where the actual distribution of goods is fully outsourced to a 3PL. Freight cost were therefore predetermined for all different regions and could be used accordingly. However, as DCR strives for a sustainable, environmental friendly character, large (road) distribution distances might carry implicit costs due to high emissions. If the model proposes that some products are only produced at one facility, for some customers these products need to be transported over relatively large distances. Including constraints on emissions or penalty cost for large distribution distances, would improve the accuracy of the model.

### **8.3. Applicability to other Products and Industries**

Because of the way that the model is formulated, it should be very applicable to other industries as well. The model itself does not include any characteristics that are specific to the current case study under consideration. It is universal in its formulation and, apart from a couple of model assumptions, the input parameters are the only aspects that make the results specific to the investigated situation. As long as a newly to be investigated situation has a similar problem and similar characteristics regarding the model assumptions (i.e. batch-wise production, 3PL service for distribution of goods, different throughput times at different facilities etc.), the model is expected to be perfectly reusable with different input data. Especially for other DCR product groups this is the case, and the model can be reused without any noteworthy adaptations.

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## A1. List of Abbreviations

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3PL	Third Party Logistic
APP	Aggregate Production Plan
BOM	Bill Of Materials
CRF	Capacity Requirement Factor
EBIT	Earnings Before Interest and Taxes
EMEA	Europe Middle East and Africa
ERP	Enterprise Resource Planning
FLP	Facility Location Problem
OEE	Overall Equipment Efficiency
OR	Operations Research
PA	Parets
RM	Raw Materials
WBU	Waterborn Urethanes
WBU/A	Waterborn Urethanes Acrylics
WW	Waalwijk

---

## A2. List of Parameters

---

$K$	=	the set of products, indexed by $k$
$L$	=	the set of customers, indexed by $l$
$J$	=	the set of production facilities, indexed by $j$
$T$	=	the set of periods, indexed by $t$
$N$	=	the set of production stages, indexed by $n$
$D_{klt}$	=	the total unit volume of demand of product $k \in K$ from customer $l \in L$ at the beginning of period $t \in T$
$p_k$	=	the price per unit volume of product $k \in K$
$\theta_{kj}$	=	batch size volume of product $k \in K$ in production facility $j \in J$
$\kappa_j$	=	quality rate of production output at facility $j \in J$
$\tau_{kjt}$	=	total unit throughput volume per unit time of production for product $k \in K$ in production facility $j \in J$ in period $t \in T$
$\mu$	=	the upper bound on the utilization level attained at each individual production facility
$\Gamma_{jt}$	=	the total actual capacity (unit time) available for production at facility $j \in J$ in period $t \in T$
$\Gamma_{jt}^a$	=	$\mu \Gamma_{jt}^a$ , i.e. the total actual capacity (unit time) available for production at facility $j \in J$ in period $t \in T$ , given the utilization level upper bound $\mu$
$\tau_{kj}$	=	total unit throughput volume per hour of production of product $k \in K$ in production facility $j \in J$
$\theta_{kj}$	=	production batch size for product $k \in K$ at facility $j \in J$
$M$	=	a sufficiently large generic number
$\varsigma_{kjn}$	=	the total capacity volume for production of production $k \in K$ at facility $j \in J$ when producing in production stage $n \in N$
$\varphi_{kjn}$	=	the penalty time, or idle time awarded for producing product $k \in K$ at facility $j \in J$ in production stage $n \in N$
$c_{kj}^f$	=	fixed, one-off cost, to enable production for product $k \in K$ in production facility $j \in J$
$c_{kj}^v$	=	total variable production cost per unit output volume for product $k \in K$ in production facility $j \in J$
$c_{kj}^h$	=	holding cost per unit volume for product $k \in K$ in period $t \in T$
$c^b$	=	backorder cost per unit of volume
$c_{jl}^d$	=	distribution cost per unit volume from production facility $j \in J$ to customer $l \in L$

### Auxiliary variables:

---

$I_{klt}^-$	=	the total unit volume of unfulfilled demand of product $k \in K$ from customer $l \in L$ at the end of period $t \in T$
$I_{klt}^+$	=	the total unit volume of physical inventory of product $k \in K$ at production facility $j \in J$ at the end of period $t \in T$
$A_{kjt}$	=	actual production volume of product $k \in K$ in production facility $j \in J$ for period $t \in T$
$\varphi_{jt}^{total}$	=	Total idle time incurred at facility $j \in J$ in period $t \in T$

### Decision variables:

---

$S_{kljt}$	=	the total unit volume of demand fulfilled, in unit volume of product $k \in K$ to customer $l \in L$ from production facility $j \in J$ in period $t \in T$
$q_{kj}$	=	binary variable that indicates if product $k \in K$ can be produced at plant $j \in J$ ,
$x_{kjt}$	=	total integer number of batch sizes produced for product $k \in K$ in production facility $j \in J$ in period $t \in T$ .
$y_{kjnt}$	=	variable that indicates if production takes place for product $k \in K$ at facility $j \in J$ in production stage $n \in N$ in period $t \in T$

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## B1. Data saves and solution process information

Data output file	Short description	#iterations	Gap (%)	Solving Time	Index
Base Case.data	Base Case Normal	465786	0.97%	120.85	1
Removed "UV" From Portfolio.data	Base Case with additional total capacity in hours available increased	48794	0.98%	14.02	1,00557
Removed "R441" From Portfolio.data	Base Case with additional total capacity in hours available increased for facility 1	523913	0.97%	149.20	1,00109
Fixed Production Capabilities no investments.data	Base Case with production capability binary as a fixed parameter instead of a decision variable, case for which no investments are	2509387	1.52%	600	0,96876
Fixed production capabilities, B3 Investment.data	Base Case with production capability binary as a fixed parameter instead of a decision variable, case for which there was invested only	921693	0.97%	277.31	0,99562
Fixed production capabilities, B4Investment.data	Base Case with production capability binary as a fixed parameter instead of a decision variable, case for which there was invested only	2495442	1.20%	600	0,97956
Fixed production capabilities, B9 Investment.data	Base Case with production capability binary as a fixed parameter instead of a decision variable, case for which there was invested only	2712654	1.52%	600	0,97493
Fixed production capabilities, B3+B4 Investment.data	Base Case with production capability binary as a fixed parameter instead of a decision variable, case for which there was invested only	1145715	0.99%	340,98	0,99597
Fixed production capabilities, B3+B9 Investment.data	Base Case with production capability binary as a fixed parameter instead of a decision variable, case for which there was invested only	77374	0.90%	13,53	0,9997
Fixed production capabilities, B3+B4+B9 Investment.data	Base Case with production capability binary as a fixed parameter instead of a decision variable, case for which there was invested only	2439972	1.05%	600	0,99836
Ample Capacity.data	Base case with excess capacity for each facility in each period	215821	0.43%	120,01	1,01467
B3 and B4 10% Increase in Demand.data	Base case with increased demand for production B3 and B4 10%	1904342	1.94%	600	1,01409
B3 and B4 20% Increase in Demand.data	Base case with increased demand for production B3 and B4 20%	1840223	1.97%	600	1,00471
B3 and B4 50% Increase in Demand.data	Base case with increased demand for production B3 and B4 50%	1941034	2.12%	600	0,93731
B3 and B4 100% Increase in Demand.data	Base case with increased demand for production B3 and B4 100%	1864082	2.01%	600	0,81929
Extra Demand 10% B3+B4 and Extra Capacity X + Y.data	Increased both demand 10% and availability at both locations	48598	0.99%	15,72	1,03592
Extra Demand 20% B3+B4 and Extra Capacity X + Y.data	Increased both demand 20% and availability at both locations	56298	0.98%	14,01	1,06534
Extra Demand 50% B3+B4 and Extra Capacity X + Y.data	Increased both demand 50% and availability at both locations	1987913	1.66%	600	1,11427
Extra Demand 100% B3+B4 and Extra Capacity X + Y.data	Increased both demand 100% and availability at both locations	1973213	2.02%	600	0,99887
All RM Increase 15%.data	Increased RM cost (15%) for all production	183926	1.08%	600	0,89
All RM Increase 10%.data	Increased RM cost (10%) for all production	184432	1.15%	600	0,92332
All RM Increase 5%.data	Increased RM cost (5%) for all production	1921142	1.08%	600	0,9603
All RM Decrease 5%.data	Decreased RM cost (5%) for all production	445679	1.00%	147,33	1,03412
All RM Decrease 10%.data	Decreased RM cost (10%) for all production	744526	0.90%	182,51	1,07109
All RM Decrease 15%.data	Decreased RM cost (15%) for all production	2892821	1.01%	600	1,10879
B3 A3 B5 B6 B11 - 5% RM Increase.data	Increased RM cost (5%) B3 A3 B5 B6 B11 @ facilities 1-1 and 1-2	169226	0.97	597,53	0,99479
B3 A3 B5 B6 B11 - 5% RM Decrease.data	Decreased RM cost (5%) B3 A3 B5 B6 B11 @ facilities 1-1 and 1-2	2434422	1.06	600	1,00659
B3 A3 B5 B6 B11 - 10% RM Decrease.data	Decreased RM cost (10%) B3 A3 B5 B6 B11 @ facilities 1-1 and 1-2	3159582	1.05	600	1,01678
B3 A3 B5 B6 B11 - 15% RM Decrease.data	Decreased RM cost (15%) B3 A3 B5 B6 B11 @ facilities 1-1 and 1-2	3122347	1.47	600	1,0271
Freight cost increase 5%.data	Increased overall freight cost with 5%	2291019	1.09	600	0,99681
Freight cost increase 10%.data	Increased overall freight cost with 10%	2058772	1,1	600	0,99478
Freight cost decrease 5%.data	Decreased overall freight cost with 5%	509773	0.98	114,68	1,00181
Freight cost decrease 10%.data	Decreased overall freight cost with 10%	658665	0.97	148,76	1,00238
Backorder cost is average holding cost.data	Backorder cost set to average the holding cost	85258	0.78	18,25	1,00668
Backorder cost is 2x average holding cost.data	Backorder cost set to 2x average the holding cost	654288	0.93	154	1,00225
Backorder cost is 4x average holding cost.data	Backorder cost set to 4x average the holding cost	1316133	1,37	600	0,99421
Backorder cost is 5x average holding cost.data	Backorder cost set to 5x average the holding cost	1425884	1,48	600	0,99161
Backorder cost is 8x average holding cost.data	Backorder cost set to 8x average the holding cost	1864874	2,13	600	0,9806
Backorder cost is 16x average holding cost.data	Backorder cost set to 16x average the holding cost	1749533	2,95	600	0,9605
Holding cost x0,5.data	Holding cost is multiplied by 0,5	2060414	1,08	600	0,99974
Holding cost x1,5.data	Holding cost is multiplied by 1,5	2267483	1	600	0,99852
Holding cost x2,0.data	Holding cost is multiplied by 2,0	2108389	1,07	600	0,99692
Holding cost x2,5.data	Holding cost is multiplied by 2,5	1946976	1,13	600	0,99624

## B2. Overview of the obtained data

Input parameter	Obtained Data	From Format	Source	Validated by
Customer Demand	Sales forecast of 2015 for each customer, product and period.	SAP output of the detailed monthly sales forecast for 2015 (kg).	Sales Department	Business Analyst Sales Department, Manager Planning Department
Production Capabilities	Capabilities in as-is state	Interviews with WW and PA production manager	Production manager of PA factory, Production manager of WW factory	Production manager of PA factory, Production Manager of WW factory.
Production Batch sizes	Batch sizes for each product and production facility	SAP output of the batch sizes (WW and PA)	Production manager of PA factory, Production manager of WW factory	Production manager of PA factory, Production manager of WW factory, Detailed Scheduler at Planning department.
Production Routing times at bottleneck reactor	Routing times for each product and production facility	SAP output of the routing times (WW and PA)	Production manager of PA factory, Production manager of WW factory	Production manager of PA factory, Production manager of WW factory, Detailed Scheduler at Planning department.
Capacity	Planned Downtime in each month of 2015	Excel capacity calculation file	Production manager of PA factory, Production manager of WW factory	Production manager of PA factory, Production manager of WW factory, Detailed Scheduler at Planning department.
	Expected Unplanned downtime in each month of 2015	Excel capacity calculation file	Production manager of PA factory, Production manager of WW factory	Production manager of PA factory, Production manager of WW factory, Detailed Scheduler at Planning department.
	Quality rate	Excel capacity calculation file	Production manager of PA factory, Production manager of WW factory	Production manager of PA factory, Production manager of WW factory, Customer Service Employee
Transition cost		Interview with R&D employees	R&D Department	Lab
Product Prices	Product prices for specific product packaging type	SAP output file	Customer Service Department	Employee Customer Service Department, Data of Realized Customer Orders
Raw material cost	Raw material cost per product	Excel product costing file	Finance Department	Operational Controller, Data BOM combined with data Purchasing department
	Bill of Material/ Product recipes Raw material prices	Excel file SAP output file	R&D Department Purchasing Department	R&D Lab Employee, Operations Controller
Production cost	Operational cost per product	Excel product costing file	Finance Department	Operations Controller, Purchaser
Distribution cost	Distribution cost per kilogram to all regions	Excel file 3PL	3PL	Operations Controller, Data Batch Sizes, Routing Times and Detailed Planner Planning Department, Employee Customer Service Department
Inventory cost	Weighted average cost of capital	-	Finance department	Operations Controller, Manager Planning Department
	Warehouse cost	Excel file warehouse	Warehousing Department	Warehouse Manager, Manager Planning department
	Inventory Depreciation cost	Excel file aged stock overview and rationalization of aged stock	Finance Department	Operations Controller, Manager Planning Department
Backorder cost	-			

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### B3. Summary of testing for model configuration

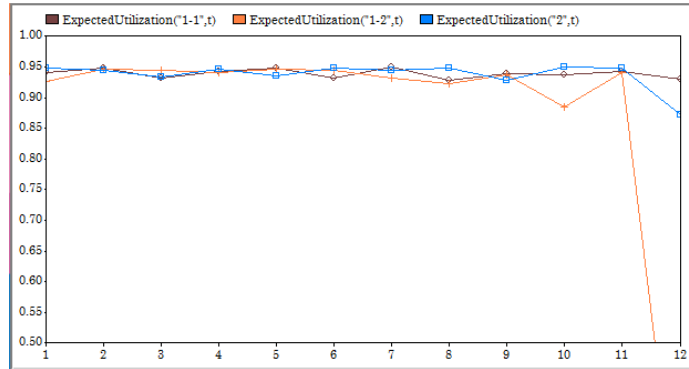
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If not mentioned otherwise, default parameters settings are considered

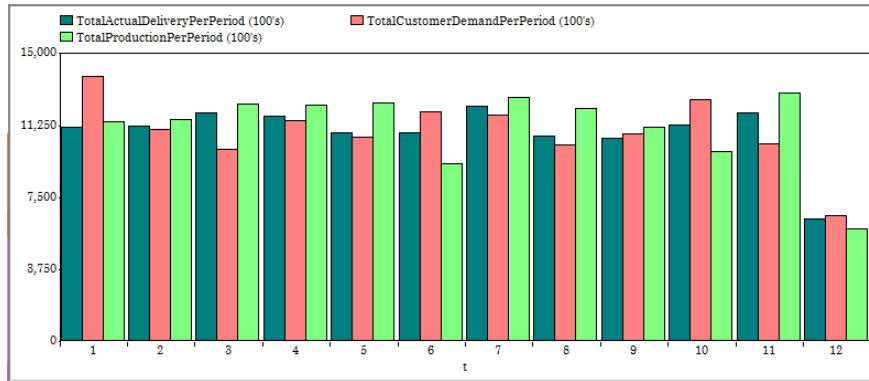
Solver terminated after 300 seconds

<b>Strategy</b>	<b>Optimality Gap (%)</b>	<b>#iterations</b>
Default	1,13%	925230
MIPFocus: Optimality	1,08%	981457
MIPFocus: Feasibility	1,03%	151207
MIPFocus: Best Bound	1,35%	801308
Global Cut Control: Very Aggressive	1,18%	1382170
Global Cut Control: Aggressive	1,10%	1219728
Global Cut Control: Conservative	1,13%	947737
MIPFocus: Best Bound, @ 150 seconds MIP Focus: Feasibility	1,28%	480700
MIPFocus: Balanced, @ 150 second MIP Focus: Feasibility	1,19%	521802
Gomory cut passes limit; 1000	1,06%	847650
Gomory cut passes limit; 10000000	1,06%	848349
Gomory cut passes limit; 10000000000	1,06%	847931
Gomory cut passes limit; 20000000000	1,06%	848084
Presolve Conservative	1,13%	937221
Presolve Aggressive	1,13%	901204

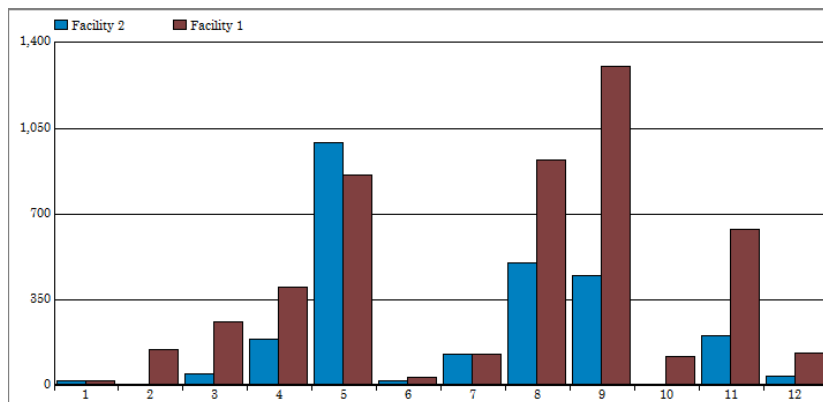
**C1. Results Base Case**



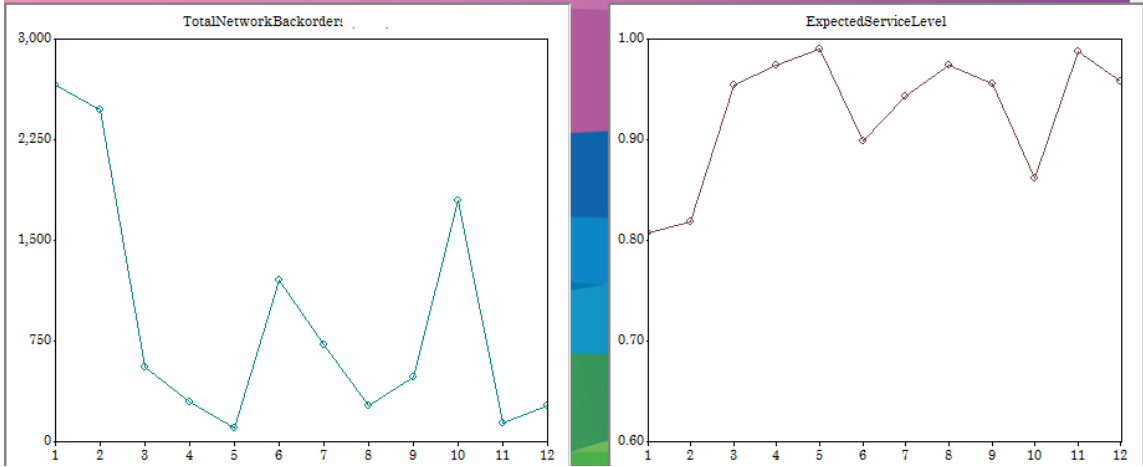
Appendix C1.1: Expected utilization rates at the different production facilities.



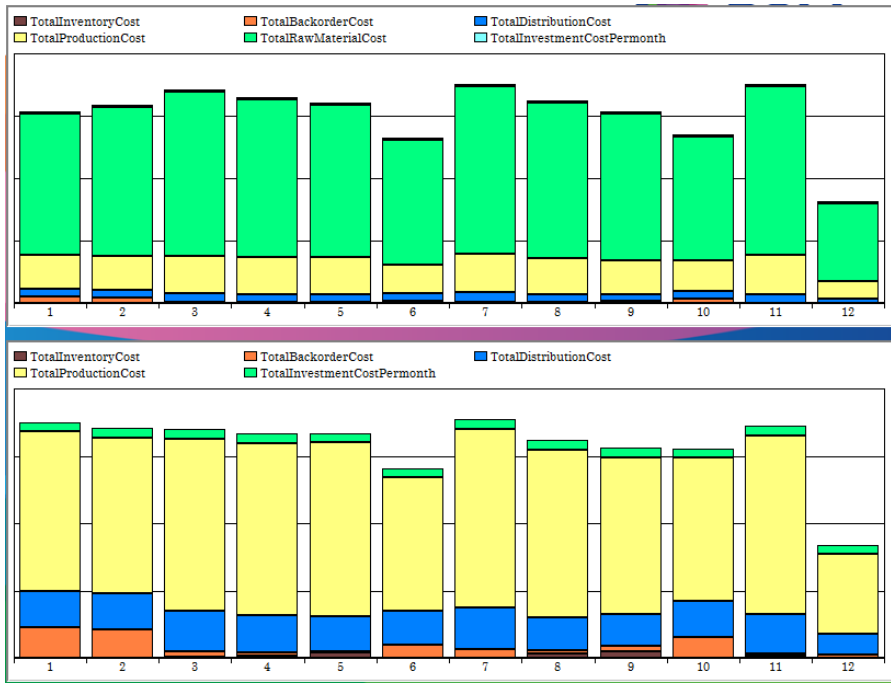
Appendix C1.2: Total customer demand, actual deliveries, and actual production per period.



Appendix C1.3: Inventory levels at the end of each period, for each production location.



Appendix C1.4: Total network backorders and the resulting expected service level for each period.



Appendix C1.5: Distribution of the aggregated production cost per period; Above, with raw material cost; below, without raw material cost.

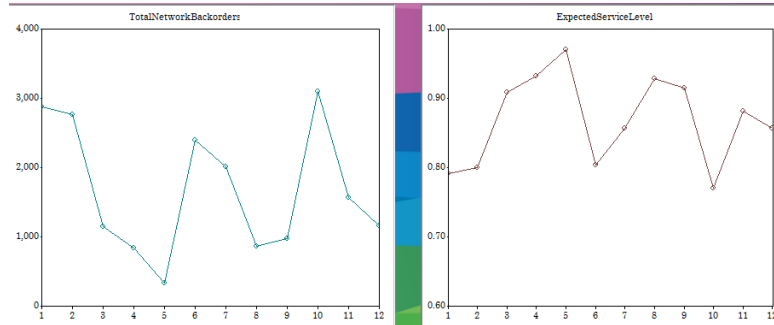
Region	Location 1	Location 2	Region	Location 1	Location 2
AT02	100%		FR05	17%	83%
AT03	96%	4%	FR07	60%	40%
BE01	90%	10%	GB03	95%	5%
BE02	100%		GB04	100%	
CH01	52%	48%	GB05	47%	53%
CH02		100%	GB06	100%	0%
DE02	100%		GB07	100%	
DE04	82%	18%	GR01	74%	26%
DE05	17%	83%	HR01	77%	23%
DE06	76%	24%	HU01	75%	25%
DE07	98%	2%	IE03	100%	
DE09	40%	60%	IT01	41%	59%
DE10	79%	21%	IT02	80%	20%
DE11	100%		IT04	27%	73%
DE12	49%	51%	IT05	100%	
DE13	87%	13%	IT08	100%	
DE14	58%	42%	LT01	79%	21%
DE15	96%	4%	NL01	94%	6%
DE18	100%		NL04	85%	15%
DE19	100%		NL05	100%	
DE20	100%		NO03	53%	47%
DE21	100%	0%	PL01	68%	32%
DK03	92%	8%	PL03	100%	
DK04	95%	5%	PL04	84%	16%
ES02	2%	98%	PT02		100%
ES03	57%	43%	SE01	100%	
ES07	9%	91%	SE03	28%	72%
FI01	75%	25%	SE04	91%	9%
FI02	61%	39%	SE06		100%
FI03	91%	9%	TR01	92%	8%
FR01	29%	71%	TR03	8%	92%
FR02	100%		TR07	100%	
FR03	71%	29%	INT	24%	76%
FR04	100%		EX	44%	56%

Appendix C1.6: Percentages of the customer demand per region, served from location 1 and location 2

\*Note that all results are scaled. The actual outcomes for DCR remain confidential.

## C2. Sensitivity analysis with pre-determined investments

### C2.1: Total backorders (scaled) and expected service level for base case without any investments

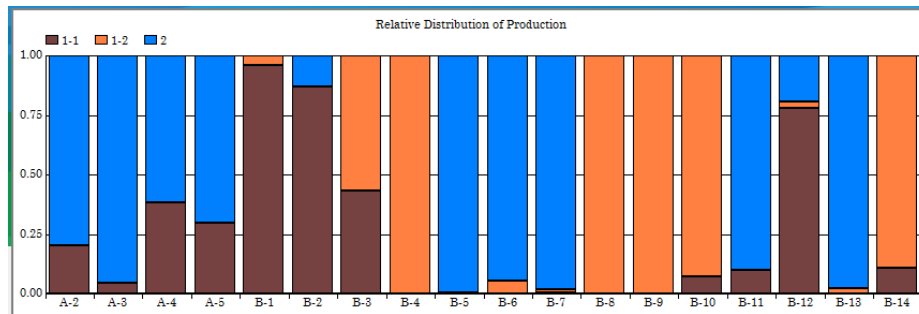


### C2.2: Freight distribution strategy for base case without any investments

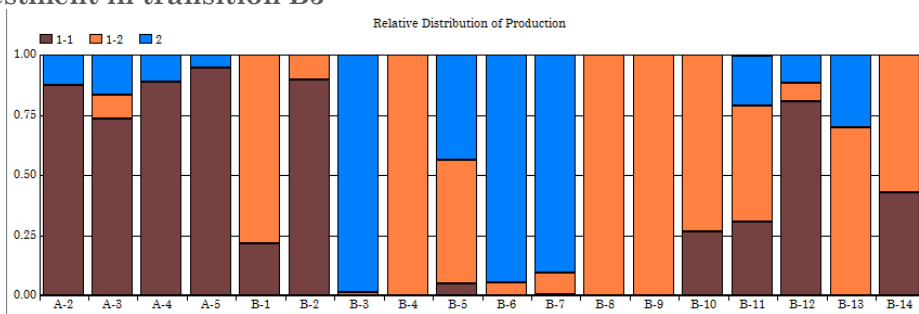
Region	Location 1	Location 2	Region	Location 1	Location 2
AT02	23%	77%	FR05	2%	98%
AT03	50%	50%	FR07	40%	60%
BE01	26%	74%	GB03	15%	85%
BE02	93%	7%	GB04	67%	33%
CH01	30%	70%	GB05	34%	66%
CH02	100%	0%	GB06	65%	35%
DE02	45%	55%	GB07	96%	4%
DE04	3%	97%	GR01		100%
DE05	98%	2%	HR01		100%
DE06	23%	77%	HU01	21%	79%
DE07	11%	89%	IE03	80%	20%
DE09	69%	31%	IT01	27%	73%
DE10	13%	87%	IT02		100%
DE11		100%	IT04	74%	26%
DE12	31%	69%	IT05		100%
DE13	11%	89%	IT08	64%	36%
DE14	100%		LT01	7%	93%
DE15	6%	94%	NL01	47%	53%
DE18		100%	NL04	92%	8%
DE19	86%	14%	NL05	100%	
DE20		100%	NO03		100%
DE21	1%	99%	PL01		100%
DK03	39%	61%	PL03	94%	6%
DK04	45%	55%	PL04	25%	75%
ES02		100%	PT02		100%
ES03	17%	83%	SE01	28%	72%
ES07	90%	10%	SE03	13%	87%
FI01	0%	100%	SE04	38%	62%
FI02		100%	SE06		100%
FI03	26%	74%	TR01	8%	92%
FR01	3%	97%	TR03	100%	
FR02	16%	84%	TR07	43%	57%
FR03	58%	42%	INT	89%	11%
FR04	100%		EX	54%	46%

## C2.3 Relative distribution of production for the different investment cases.

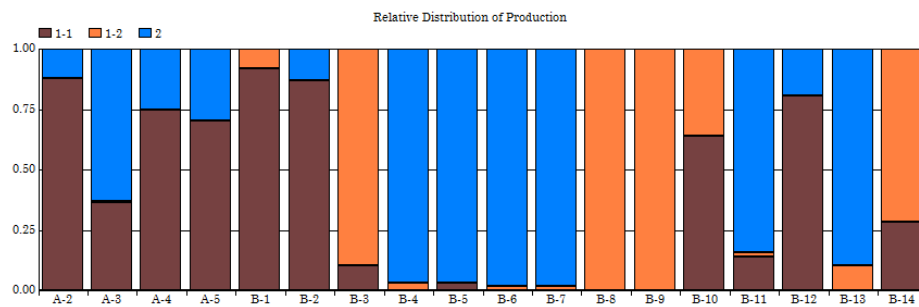
### 1. No investments



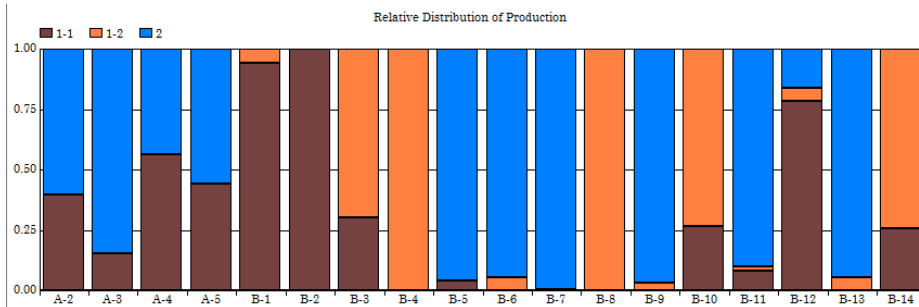
### 2. Investment in transition B3



### 3. Investment in transition B4

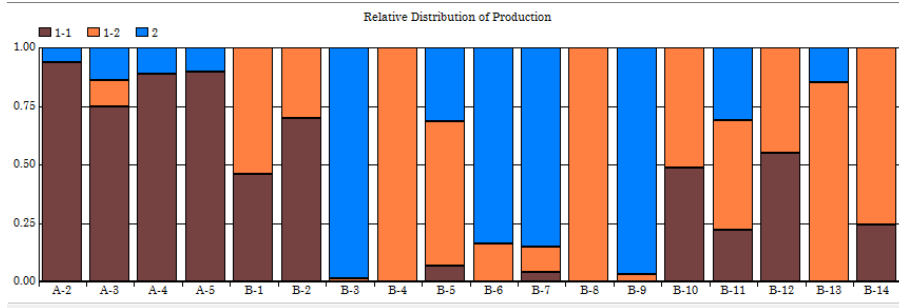


### 4. Investment in transition B9

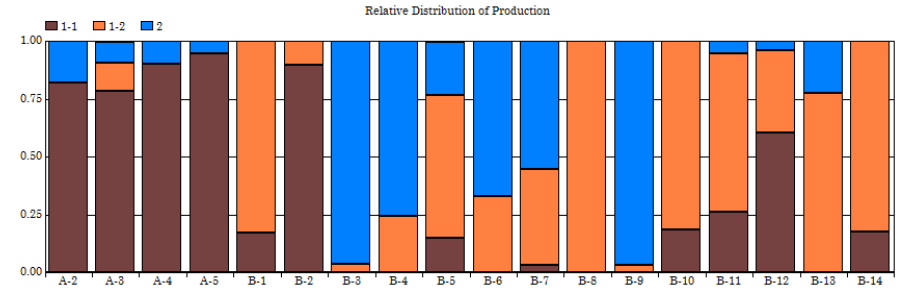


### 5. Investment in transitions of B3+B9

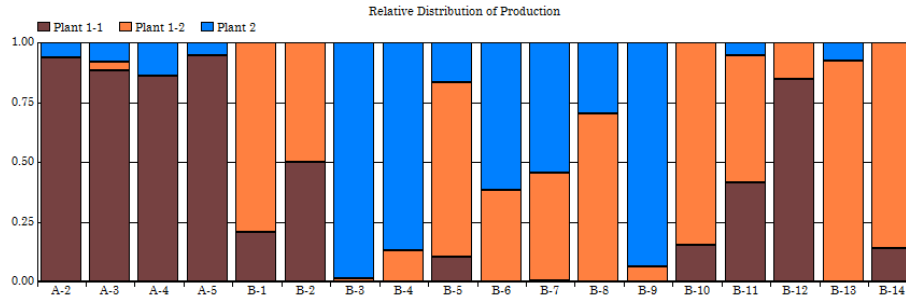




### 6. Investment in transitions of B3+B4+B9



### 7. Base case (optimal solution)



## C3. Sensitivity analysis for capacity and demand

### C3.1 Summary results for capacity and demand analysis (base-line is the optimal solution of the base case scenario)

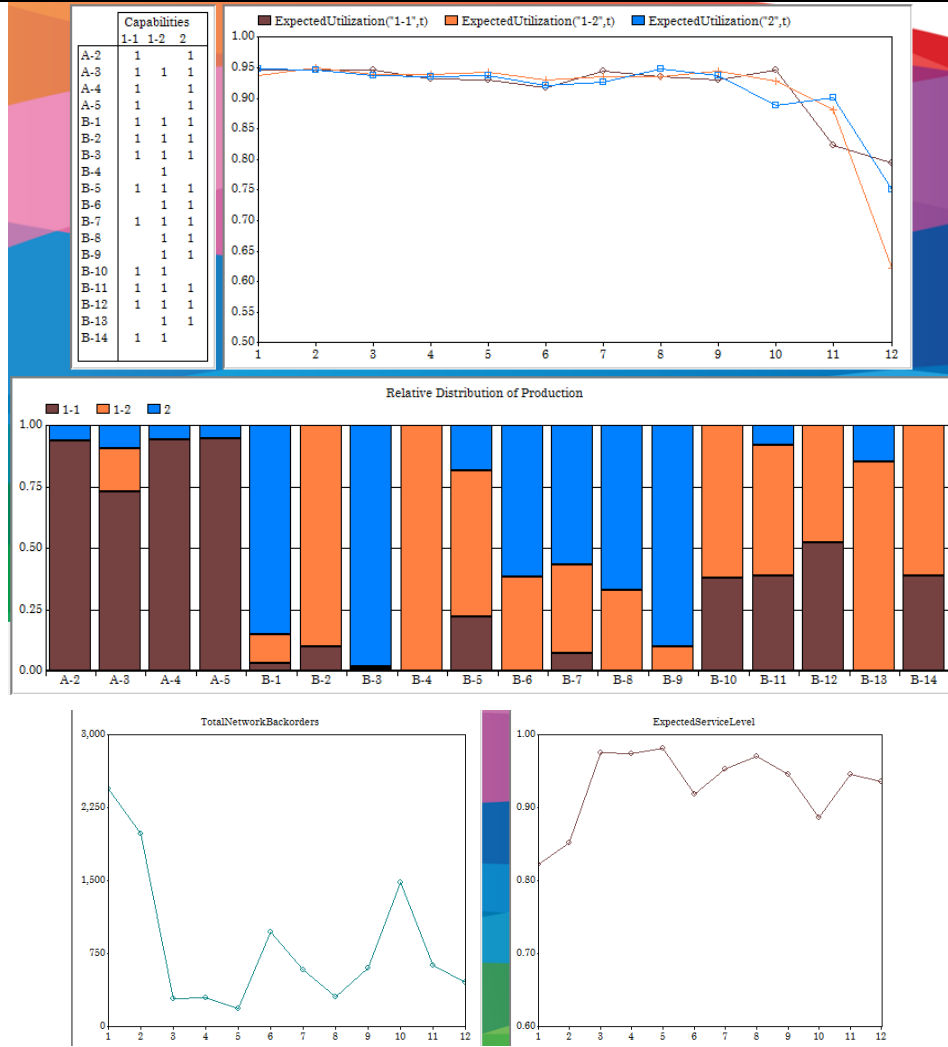
Scenarios	Actual Production (base-case = 100)	Backorder @ P12 (base-case = 100)	Level	Raw Material cost	Production cost	Freight cost	Backorder cost	Inventory cost	Investment cost	Total Cost	Revenue	Total Profit
Extra availability at location 2 (Removed "X"	-0.10%	0.961	0.13%	-2.21%	2.72%	-49.21%	3.36%	13.68%	-0.63%	-0.03%	0.6%	
Extra availability at location 1 (Removed "Y"	-0.10%	0.931	-0.15%	0.19%	-3.46%	-6.85%	16.79%	-20.51%	-0.48%	-0.18%	0.1%	
Extra Demand B3B4+10%	1.8%	421	0.868	2.31%	3.11%	4.52%	89.84%	-72.45%	0.00%	3.38%	2.38%	1.4%
Extra Demand B3B4+20%	2.2%	1.455	0.777	3.19%	5.12%	8.96%	254.22%	-83.30%	-34.19%	6.17%	3.27%	0.5%
Extra Demand B3B4+50%	1.8%	5.356	0.572	3.45%	5.55%	9.22%	888.71%	-49.54%	-34.19%	14.20%	3.79%	-6.3%
Extra Demand B3B4+100%	1.6%	11.609	0.420	3.38%	5.32%	5.70%	1899.19%	-82.76%	-34.19%	26.07%	3.62%	-18.1%
<b>Plus extra availability for location 1 and 2</b>												
Extra Demand B3B4+10%	2.6%	82	0.960	3.28%	1.26%	4.55%	-44.78%	73.62%	13.68%	2.68%	3.14%	3.6%
Extra Demand B3B4+20%	5.0%	146	0.949	6.23%	4.57%	7.63%	-29.17%	54.91%	13.68%	5.77%	6.16%	6.5%
Extra Demand B3B4+50%	10.9%	1.031	0.819	13.75%	14.35%	25.77%	195.11%	-72.90%	0.00%	16.16%	13.75%	11.4%
Extra Demand B3B4+100%	9.9%	7.639	0.526	13.53%	14.07%	21.21%	1236.81%	-94.86%	0.00%	28.28%	13.84%	-0.1%

### C3.2 Base case with extra availability

#### 1. Removing “Y” from facility 1-1 and 1-2

Input:  $\Gamma_{jt}$  (hours)

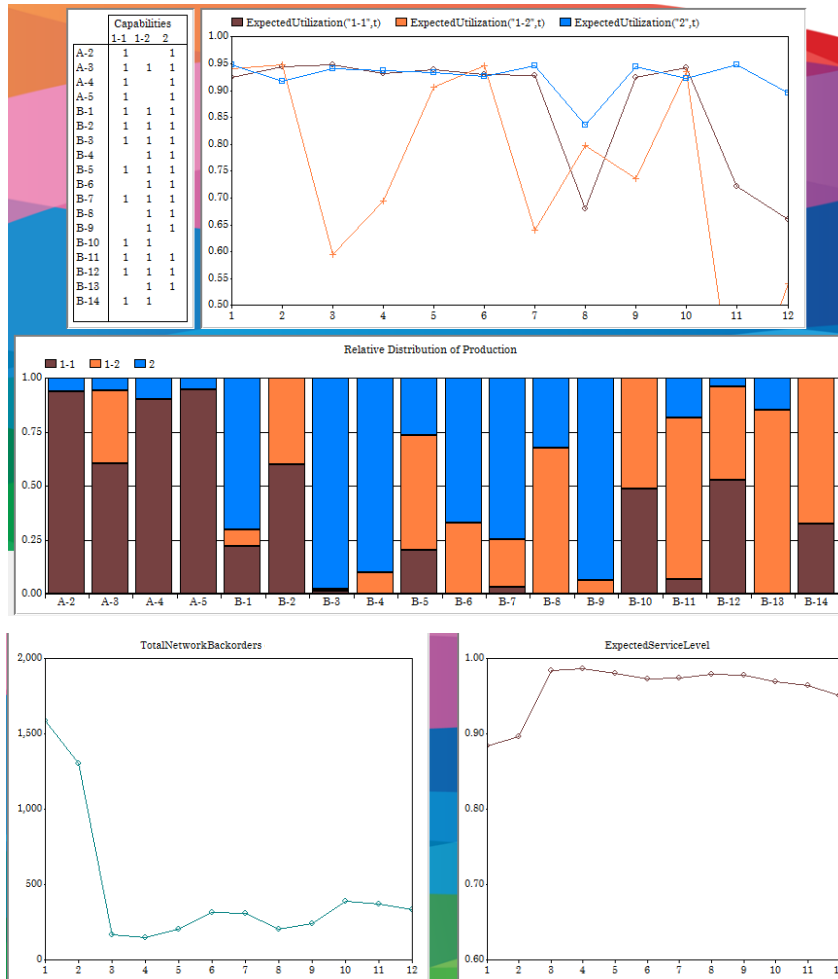
	1	2	3	4	5	6	7	8	9	10	11	12
Facility 1-1	-3,43%	-3,44%	-5,56%	-2,87%	-4,10%	-3,30%	-3,93%	-1,47%	-1,53%	-2,70%	-1,30%	-2,19%
Facility 1-2	-4,08%	-3,99%	-6,41%	-3,35%	-4,81%	-3,73%	-4,57%	-1,74%	-1,80%	-3,11%	-1,49%	-2,43%
Facility 2	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%



#### 2. Removing “X” from facility 2

Input  $\Gamma_{jt}$  (hours)

	1	2	3	4	5	6	7	8	9	10	11	12
Facility 1-1	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Facility 1-2	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Facility 2	25,59%	4,63%	13,55%	18,23%	15,25%	14,53%	13,55%	18,92%	32,10%	42,30%	25,39%	6,70%



### 3. Case with ample capacity

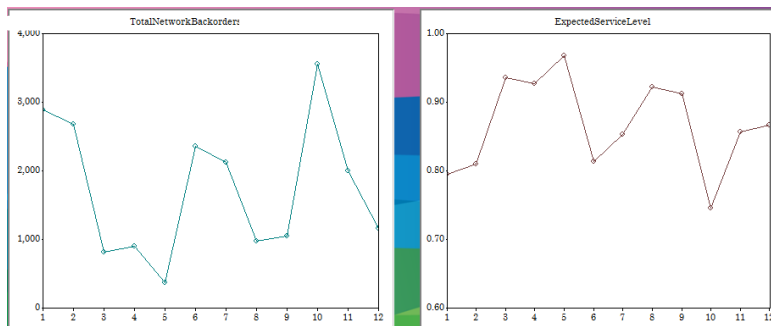
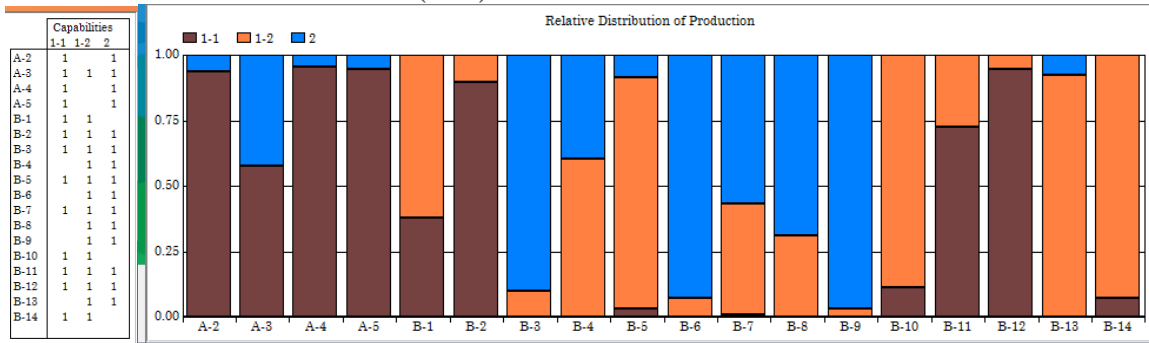
Input  $\Gamma_{jt}$  (hours)

	1	2	3	4	5	6	7	8	9	10	11	12
Facility 1-1	159%	159%	115%	116%	108%	149%	99%	117%	126%	102%	92%	226%
Facility 1-2	153%	148%	104%	107%	101%	131%	91%	111%	119%	92%	81%	196%
Facility 2	61%	46%	42%	55%	60%	129%	42%	49%	69%	167%	60%	111%

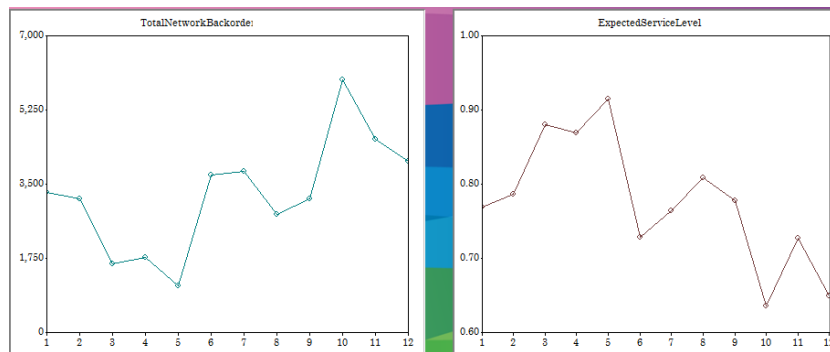
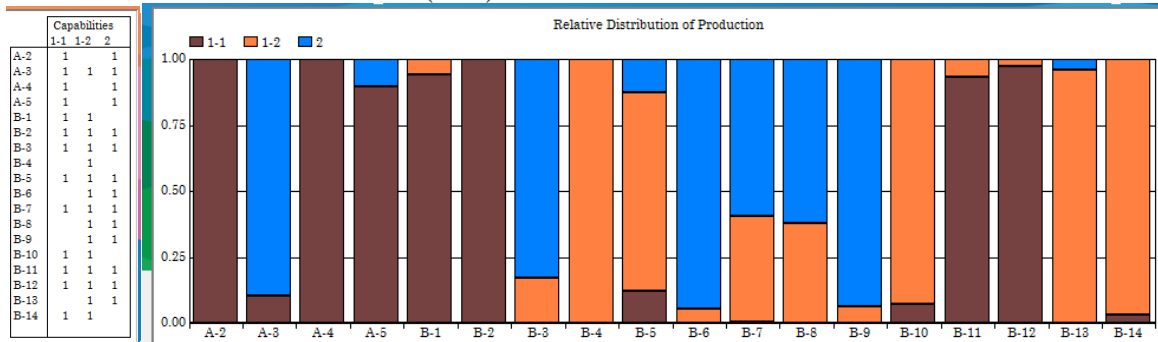


### C3.3 Base case with Extra Demand

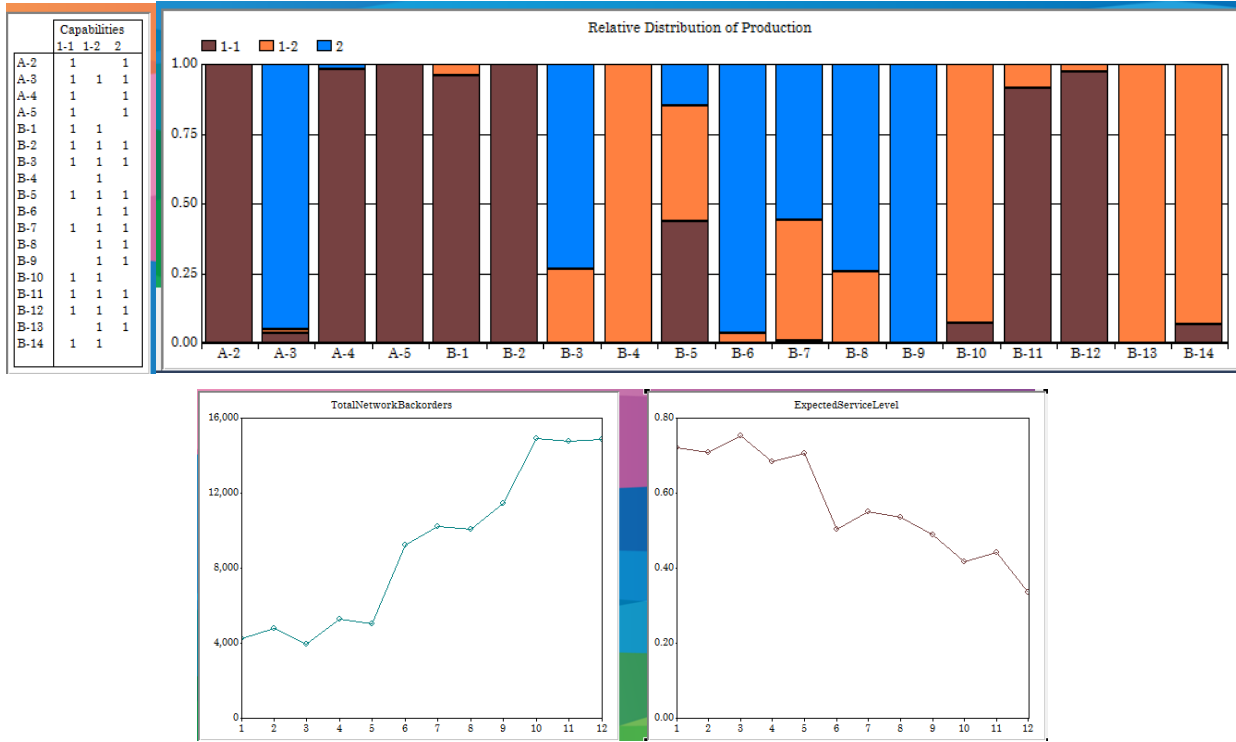
#### 1. Extra demand for B3 + B4 (10%)



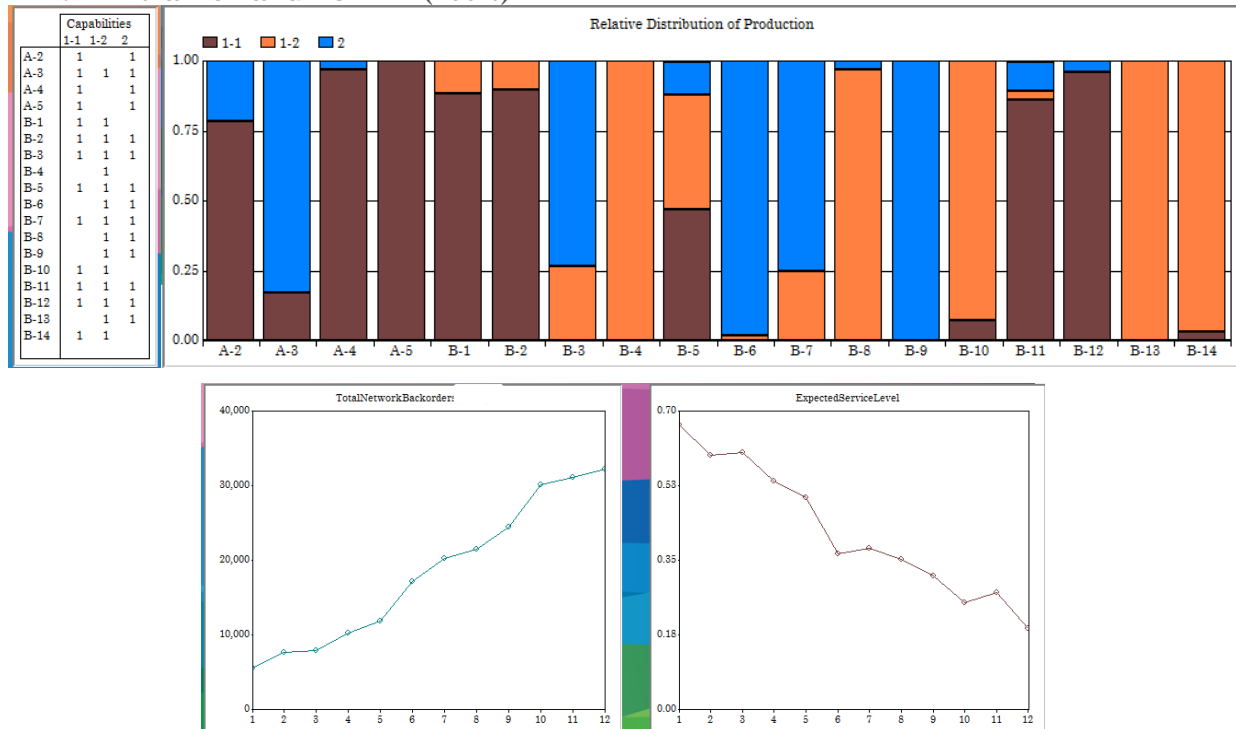
#### 2. Extra demand for B3 + B4 (20%)



### 3. Extra demand for B3 + B4 (50%)

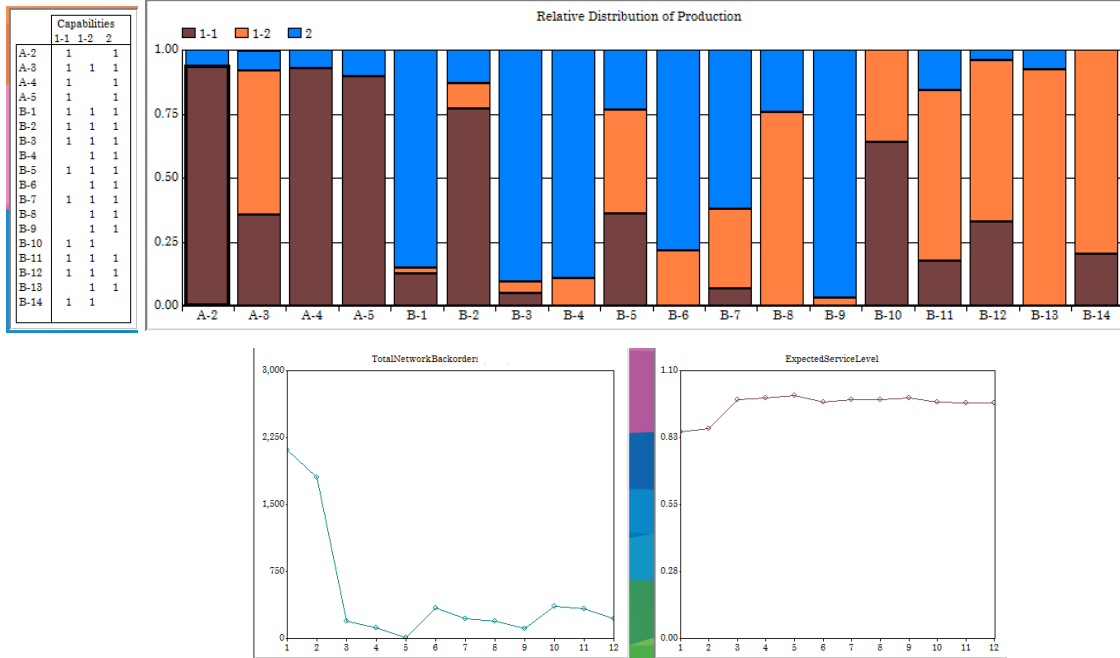


### 4. Extra Demand B3 + B4 (100%)

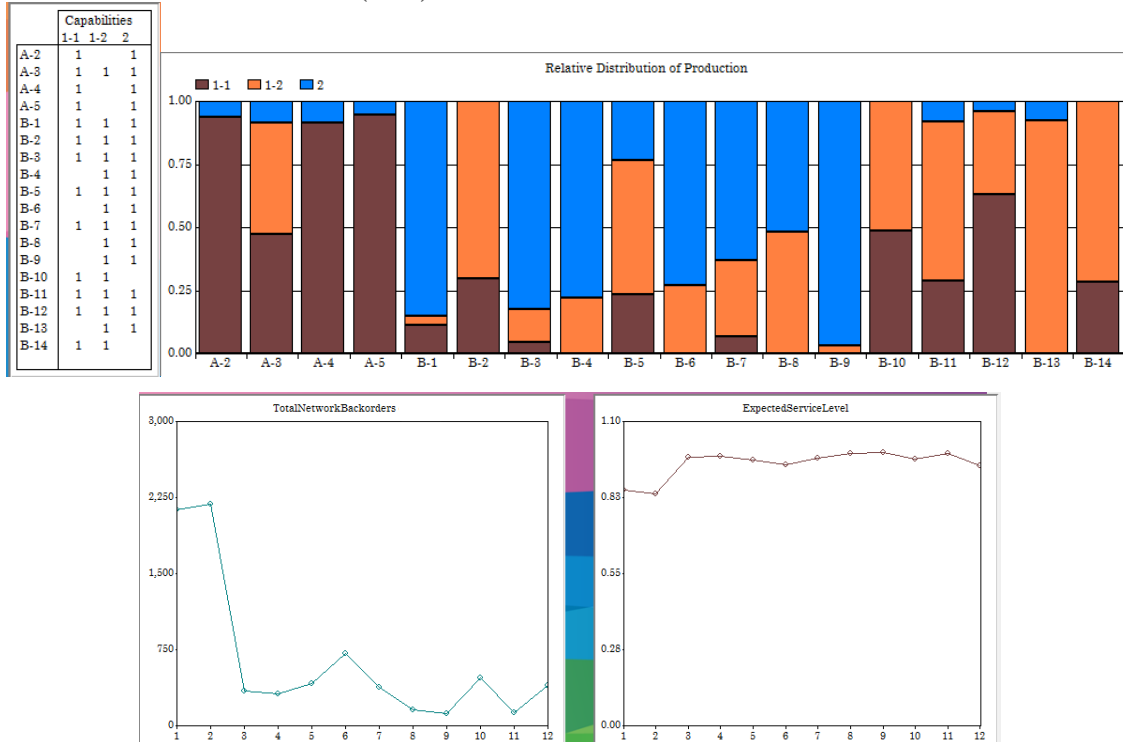


### C3.4 Base case with extra demand and extra availability location 1 and location 2 (input from C3.2)

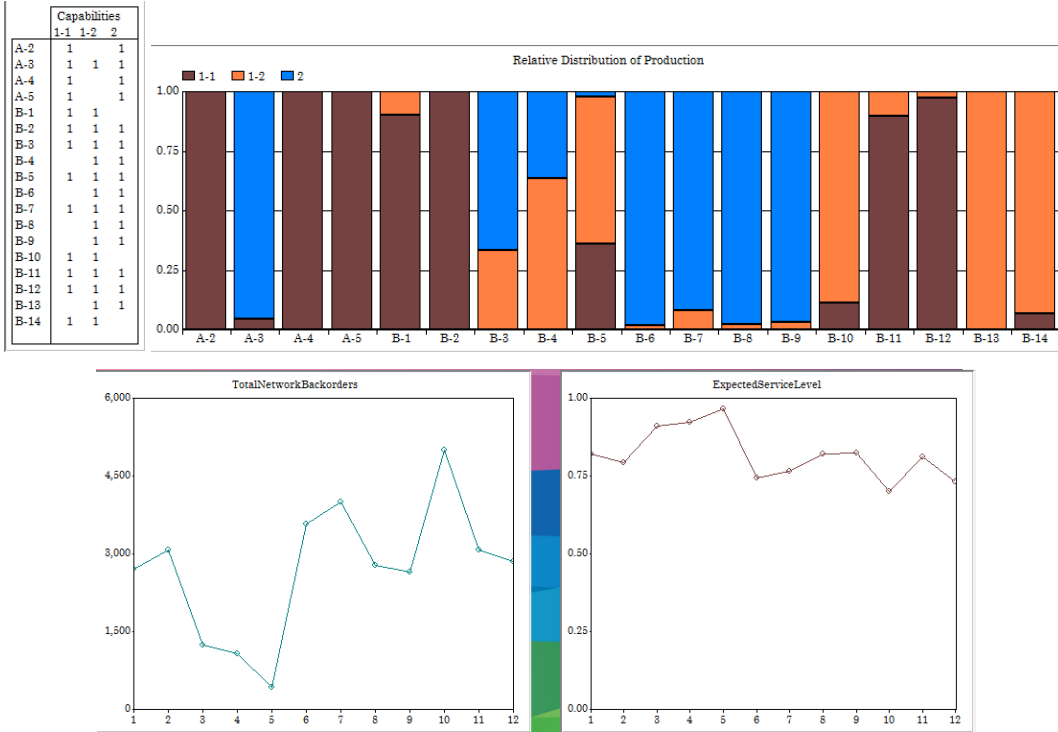
#### 1. Extra demand B3 + B4 (10%)



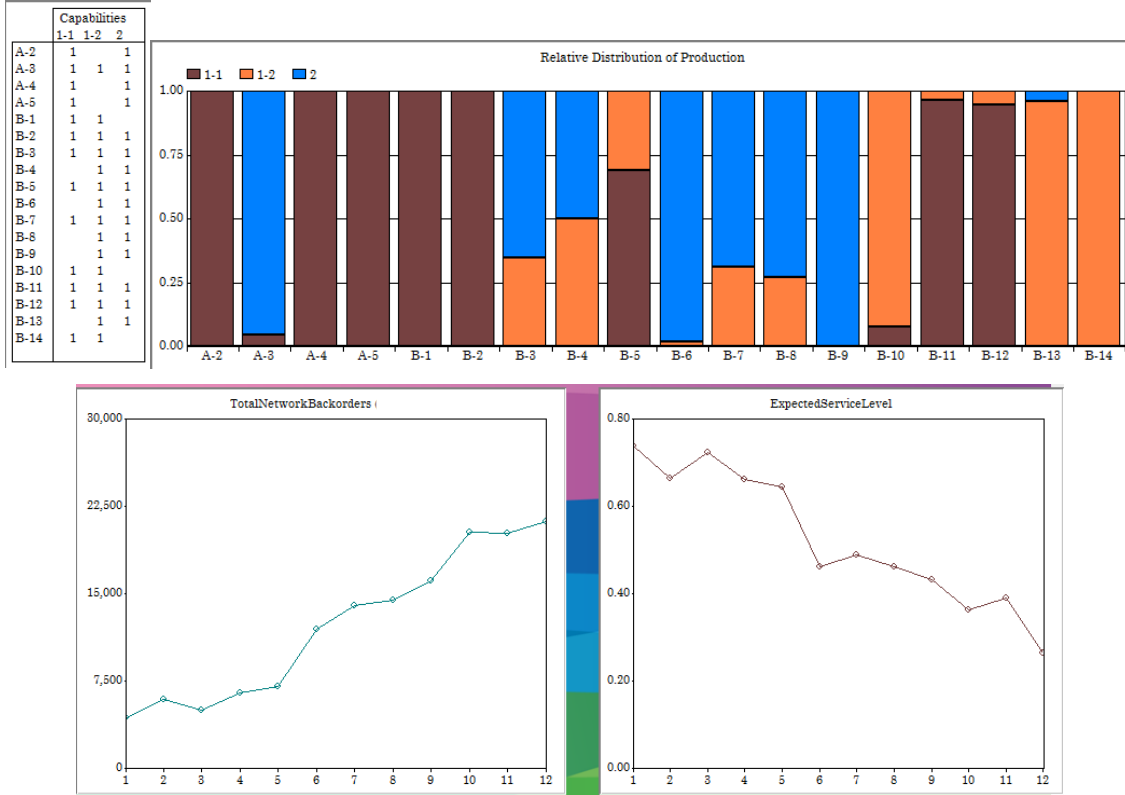
#### 2. Extra demand B3 + B4 (20%)



### 3. Extra demand B3 + B4 (50%)



### 4. Extra demand B3 + B4 (100%)





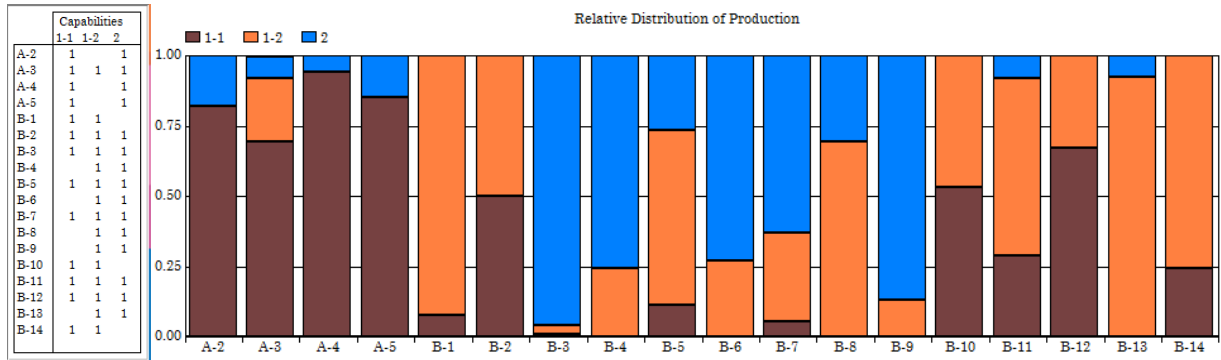
## C4. Sensitivity analysis on cost parameters

C4.1 Table with overview of sensitivity analysis on cost parameters

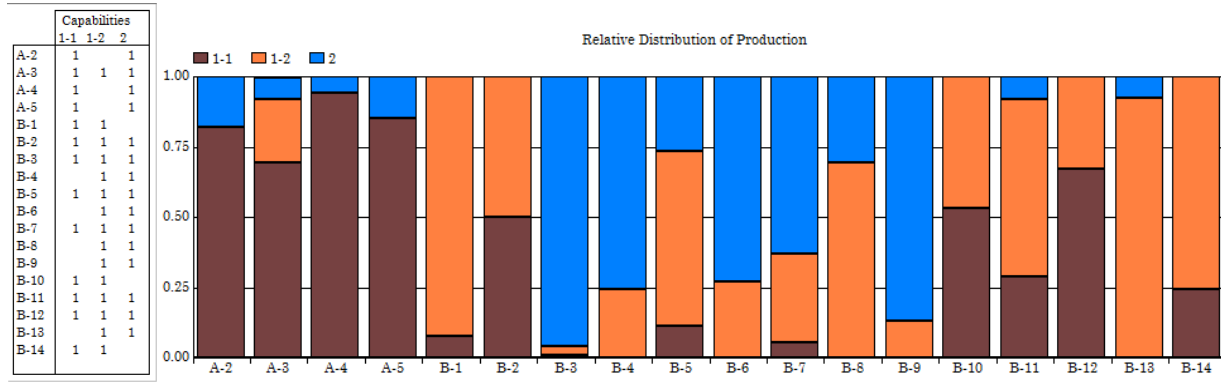
Scenarios	Average Service Level	Raw Material cost	Production cost	Freight cost	Backorder cost	Inventory cost	Investment cost	Total Cost	Revenue	Total Profit
<b>Raw Materials (Production Cost)</b>										
RM Cost Increase Overall 15%	0,923	14,78%	0,13%	-1,27%	5,07%	-15,76%	-20,51%	10,98%	-0,20%	-11,00%
RM Cost Increase Overall 10%	0,907	9,89%	0,17%	0,27%	15,83%	41,62%	0,00%	4,20%	0,04%	-3,97%
RM Cost Increase Overall 5%	0,907	5,10%	0,17%	0,27%	15,83%	41,62%	0,00%	4,20%	0,04%	-3,97%
Base case	0,928	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
RM Cost Decrease Overall 5%	0,921	-4,87%	0,03%	0,61%	9,69%	39,01%	0,00%	-3,45%	0,04%	3,41%
RM Cost Decrease Overall 10%	0,920	-9,92%	-0,28%	0,48%	10,12%	20,63%	0,00%	0,22%	-0,16%	-0,52%
RM Cost Decrease Overall 15%	0,923	-14,87%	0,39%	0,23%	6,54%	5,91%	0,00%	-11,09%	0,08%	10,88%
B3 A3 B5 B6 B11 RM Increase @ F1-1, 1-2 5%	0,927	0,74%	0,18%	-0,02%	-1,58%	3,22%	-34,19%	0,22%	-0,16%	-0,52%
Base case	0,928	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
B3 A3 B5 B6 B11 RM Decrease @ F1-1, 1-2 5%	0,924	-1,40%	-0,13%	2,74%	3,31%	-12,04%	0,00%	-0,96%	-0,14%	0,66%
B3 A3 B5 B6 B11 RM Decrease @ F1-1, 1-2 10%	0,910	-3,37%	1,06%	6,70%	24,51%	-38,78%	13,68%	-1,75%	-0,01%	1,68%
B3 A3 B5 B6 B11 RM Decrease @ F1-1, 1-2 15%	0,895	-6,19%	3,02%	14,31%	45,85%	-14,81%	-11,11%	-3,18%	-0,19%	2,71%
<b>Freight</b>										
Freight Cost Increase 10%	0,916	-0,25%	-0,03%	7,02%	14,07%	-10,79%	-20,51%	0,01%	-0,26%	-0,52%
Freight Cost Increase 5%	0,922	0,13%	0,15%	4,54%	7,78%	-0,49%	0,00%	0,40%	0,03%	-0,32%
Base case	0,928	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Freight Decrease 5%	0,925	0,07%	-0,13%	-3,73%	4,40%	-1,76%	0,00%	-0,07%	0,06%	0,18%
Freight Decrease 10%	0,919	0,02%	-0,30%	-8,43%	12,54%	-5,92%	0,00%	-0,24%	0,00%	0,24%
<b>Backorder cost</b>										
Backorder cost set as 1x average holding cost	0,873	-0,10%	-0,39%	-1,65%	-39,97%	-34,35%	-34,19%	-1,14%	-0,22%	0,67%
Backorder cost set as 2x average holding cost	0,915	0,05%	-0,26%	0,36%	-20,69%	-27,32%	0,00%	-0,31%	-0,04%	0,22%
Base case (i.e. 3x average holding cost)	0,928	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Backorder cost set as 4x average holding cost	0,924	-0,06%	-0,09%	1,06%	39,54%	11,56%	0,00%	0,48%	-0,06%	-0,58%
Backorder cost set as 5x average holding cost	0,929	0,09%	0,44%	1,33%	64,35%	7,91%	0,00%	1,00%	0,06%	-0,84%
Backorder cost set as 8x average holding cost	0,932	0,10%	0,43%	1,61%	150,92%	12,44%	0,00%	2,07%	0,03%	-1,94%
Backorder cost set as 16x average holding cost	0,945	0,11%	0,93%	3,83%	313,12%	49,98%	0,00%	4,31%	0,11%	-3,95%
<b>Holding cost</b>										
Holding cost multiplied by 0,5	0,923	0,09%	0,18%	0,72%	5,79%	-34,72%	0,00%	0,11%	0,04%	-0,03%
Base case (i.e. 3x average holding cost)	0,928	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Holding cost multiplied by 1,5	0,922	0,06%	-0,10%	0,75%	8,71%	4,36%	0,00%	0,18%	0,01%	-0,15%
Holding cost multiplied by 2,0	0,909	0,06%	-0,02%	0,31%	27,89%	0,63%	0,00%	0,39%	0,04%	-0,31%
Holding cost multiplied by 2,5	0,908	-0,15%	0,21%	-3,38%	26,63%	19,32%	-20,51%	-0,06%	-0,22%	-0,38%

## C4.2 Base case with deviations of raw material cost

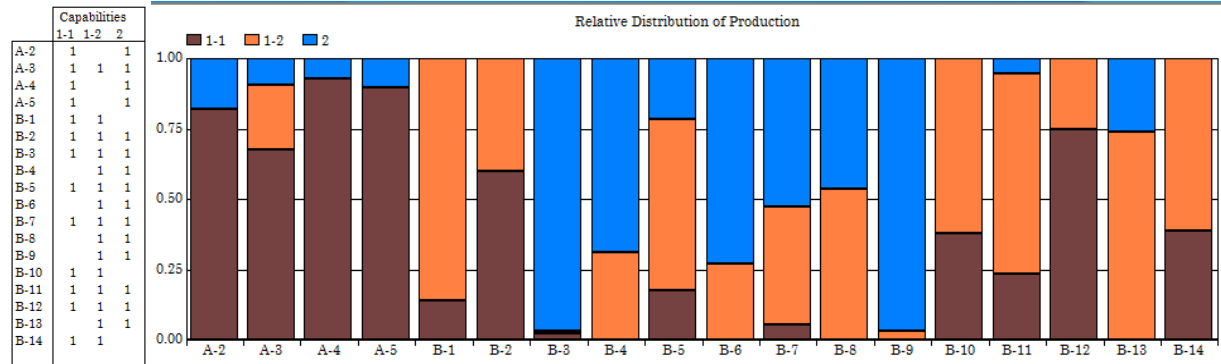
### 1. 15% decrease for all raw materials



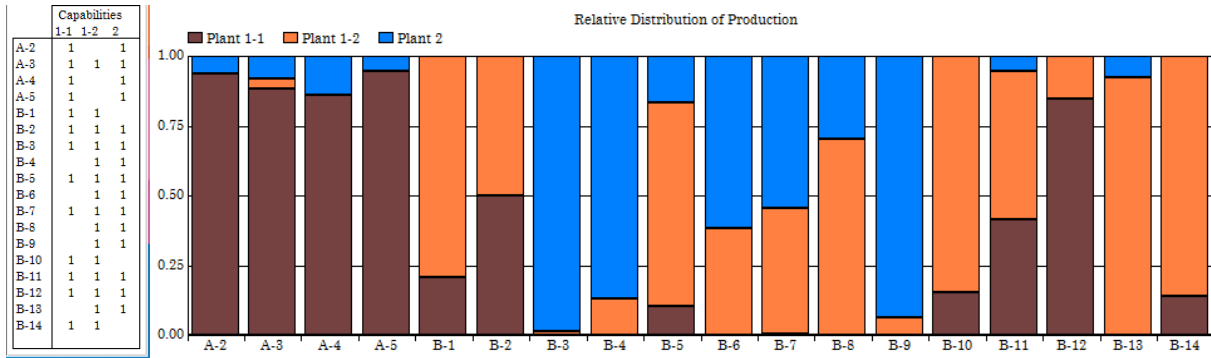
### 2. 10% decrease for all raw materials



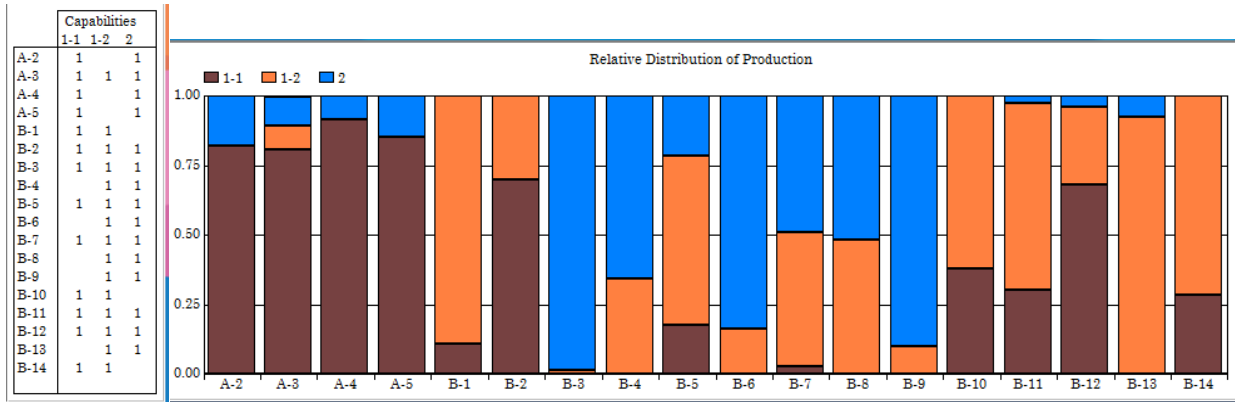
### 3. 5% decrease for all raw materials



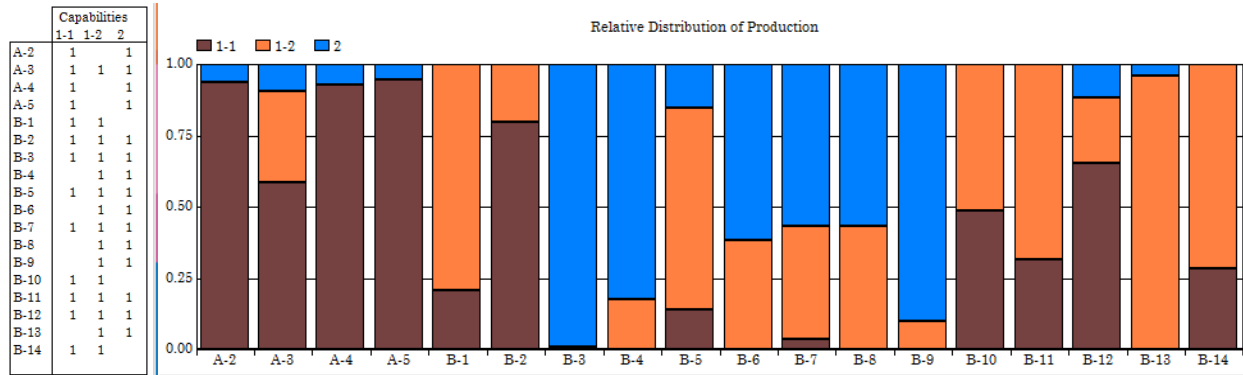
#### 4. Base case



#### 5. 5% increase for all raw materials

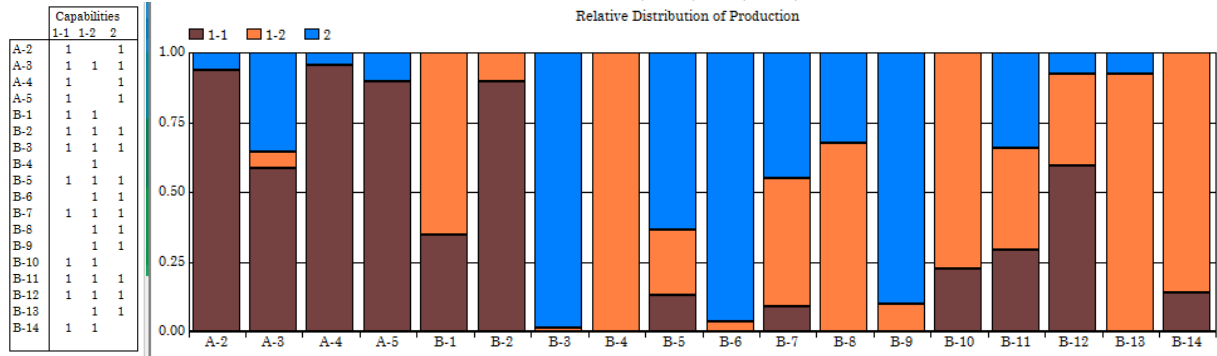


#### 6. 10% increase for all raw materials

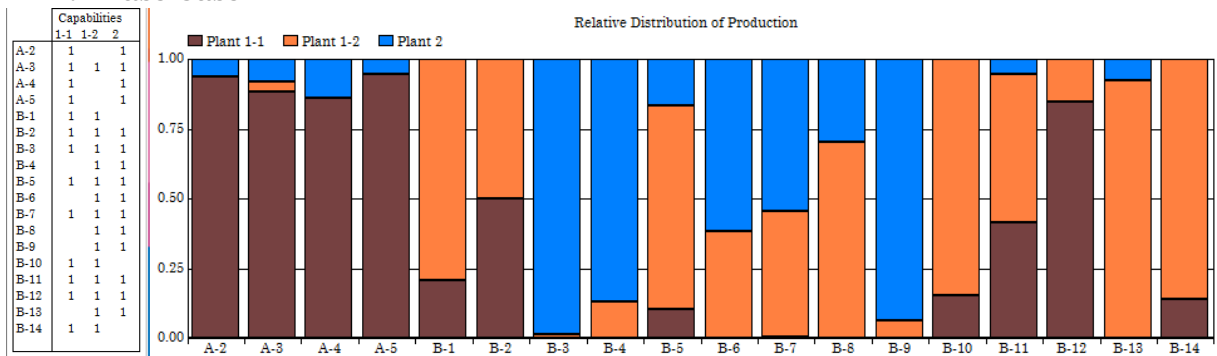


### C4.3 Base case with deviations for raw material cost of B3, A3, B5, B6, B11,

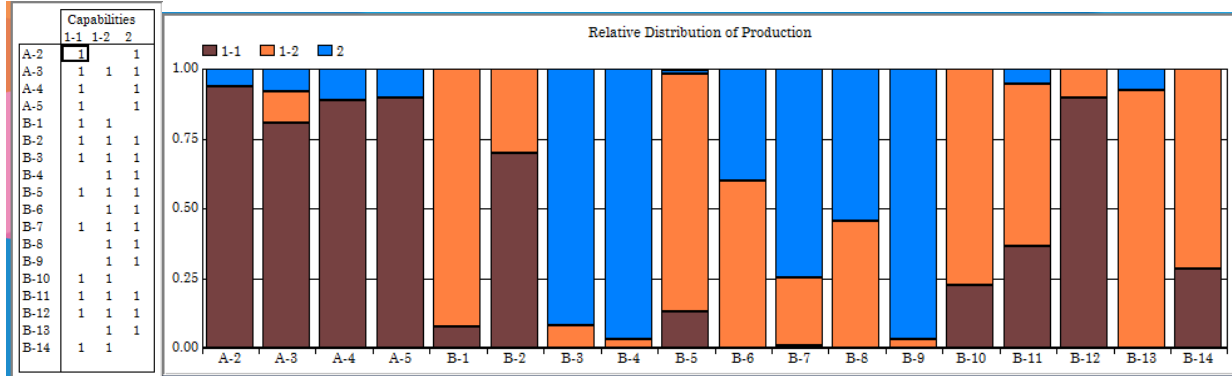
#### 1. 5% increase for raw material cost of B3, A3, B5, B6, B11 at location 1



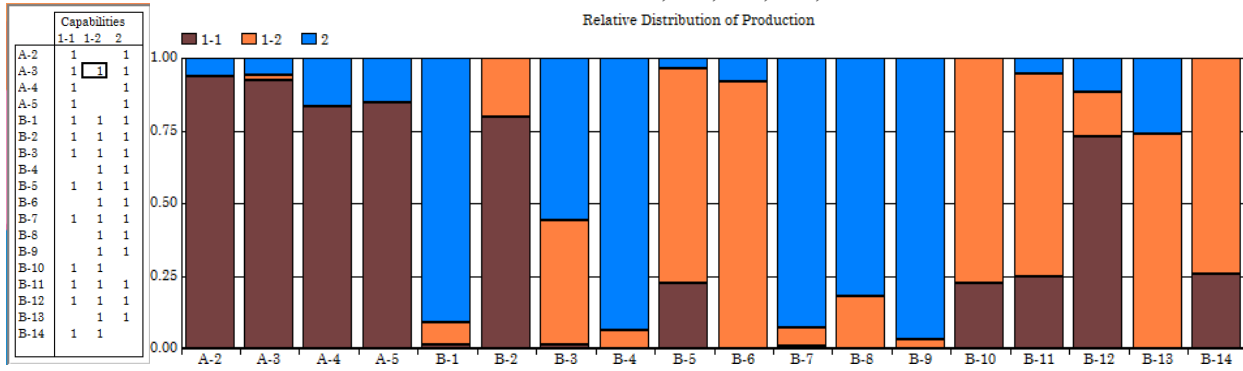
#### 2. Base Case



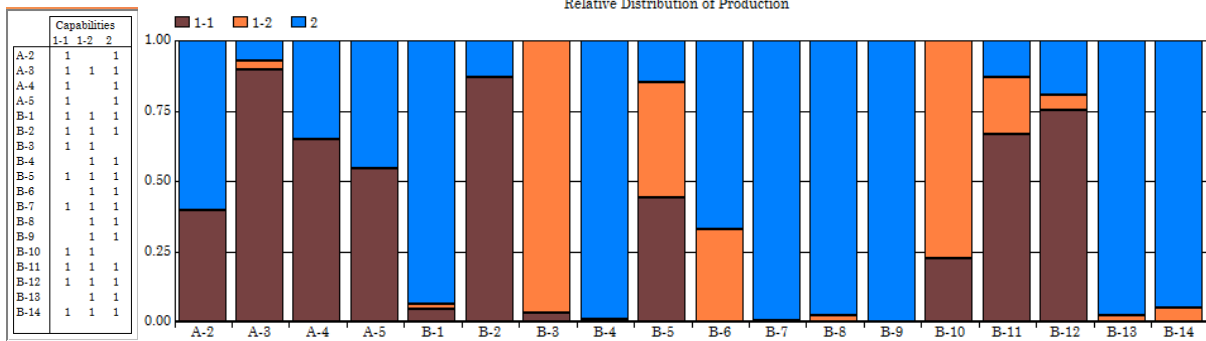
#### 3. 5% decrease for raw material cost of B3, A3, B5, B6, B11 at location 1



4. 10% decrease for raw material cost of B3, A3, B5, B6, B11 at location 1

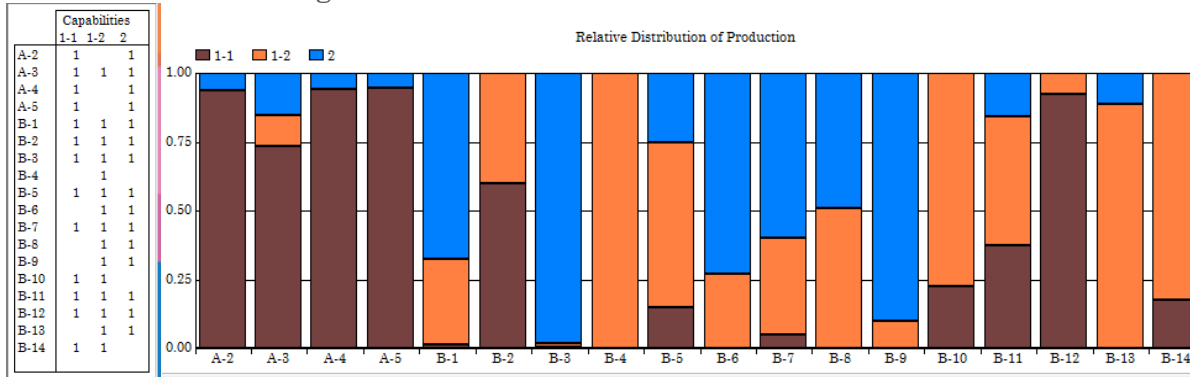


5. 15% decrease for raw material cost of B3, A3, B5, B6, B11 at location 1

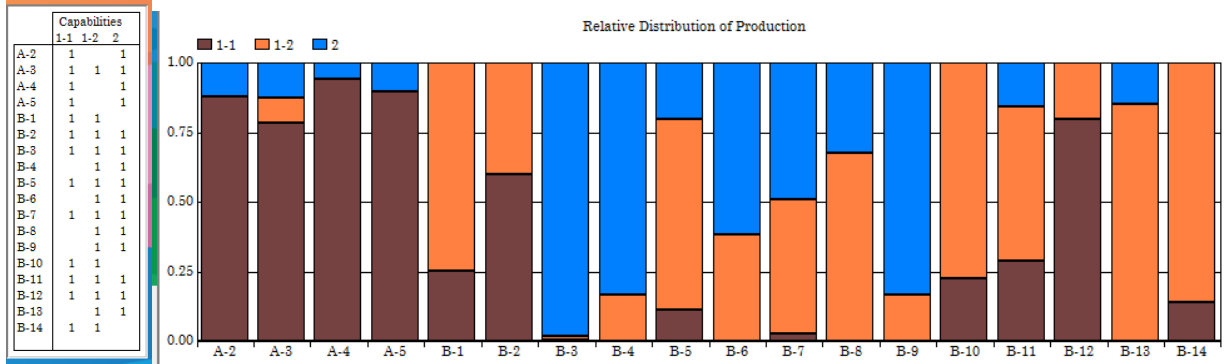


C4.4 Base case with deviations in freight cost

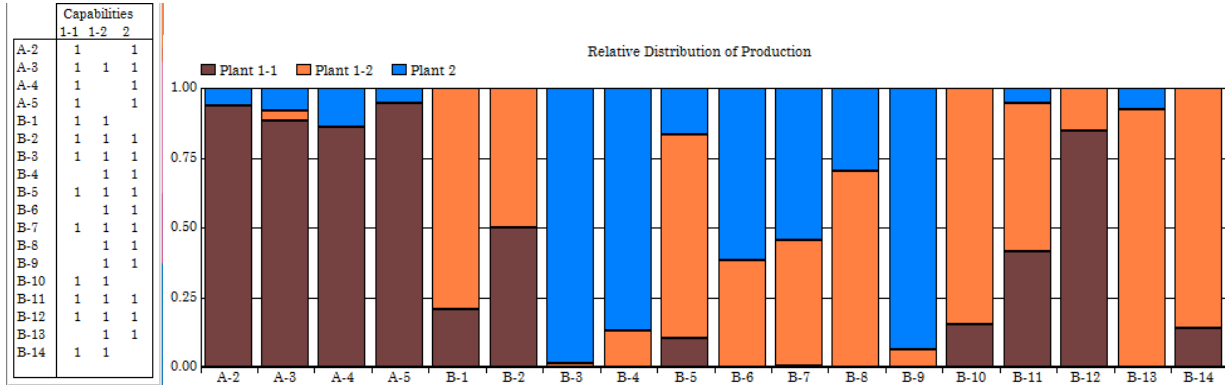
1. 10% overall freight cost increase



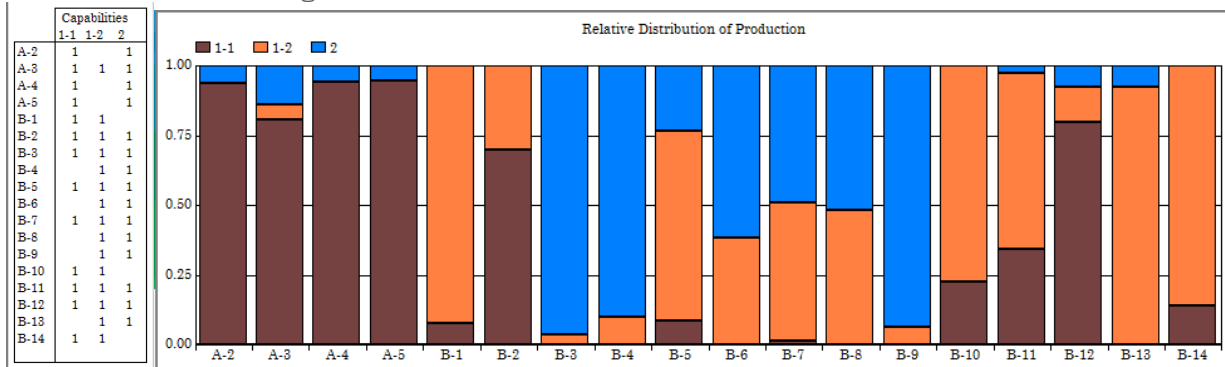
## 2. 5% overall freight cost increase



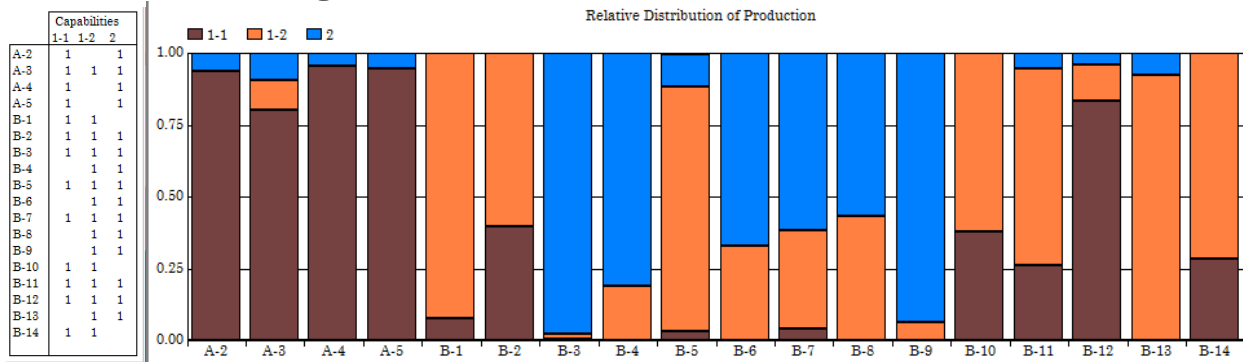
## 3. Base Case



## 4. 5% overall freight cost decrease



## 5. 10% overall freight cost decrease

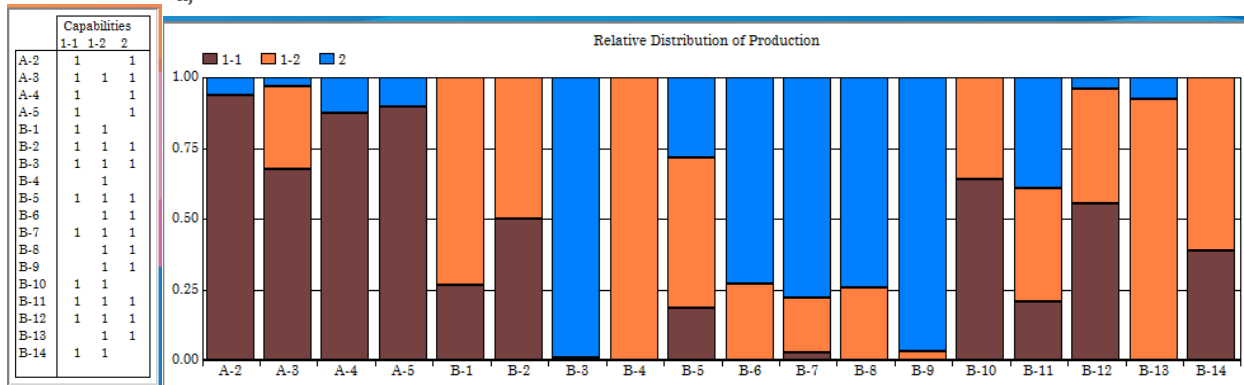


6. Table for deliveries from location 1 and 2 with 10% overall freight decrease (left), and 10% overall freight increase (right).

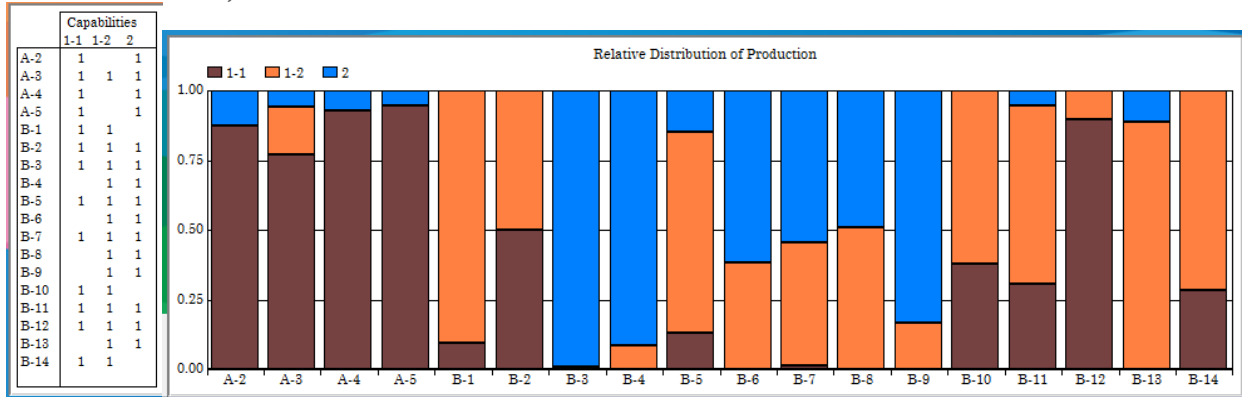
Region	Location 1	Location 2	Region	Location 1	Location 2	Region	Location 1	Location 2	Region	Location 1	Location 2
AT02	100%		FR05	100%		AT02	100%		FR05	0%	100%
AT03	96%	4%	FR07	0%	100%	AT03	94%	6%	FR07	45%	55%
BE01	81%	19%	GB03	45%	55%	BE01	73%	27%	GB03	99%	1%
BE02	100%		GB04	99%	1%	BE02	100%	0%	GB04	98%	2%
CH01	74%	26%	GB05	100%		CH01	64%	36%	GB05	88%	12%
CH02		100%	GB06	61%	39%	CH02	100%	0%	GB06	100%	
DE02	100%		GB07	100%		DE02	100%		GB07	100%	
DE04	76%	24%	GR01	100%		DE04	70%	30%	GR01	71%	29%
DE05	23%	77%	HR01	71%	29%	DE05	100%		HR01	15%	85%
DE06	81%	19%	HU01	31%	69%	DE06	75%	25%	HU01	25%	75%
DE07	96%	4%	IE03	75%	25%	DE07	96%	4%	IE03	100%	
DE09	46%	54%	IT01	100%		DE09	46%	54%	IT01	45%	55%
DE10	77%	23%	IT02	25%	75%	DE10	80%	20%	IT02	100%	
DE11	10%	90%	IT04	49%	51%	DE11	100%		IT04	35%	65%
DE12	60%	40%	IT05	100%		DE12	63%	37%	IT05	100%	
DE13	83%	17%	IT08	31%	69%	DE13	71%	29%	IT08	100%	
DE14	30%	70%	LT01	100%		DE14	62%	38%	LT01	95%	5%
DE15	61%	39%	NL01	93%	7%	DE15	89%	11%	NL01	90%	10%
DE18	100%		NL04	98%	2%	DE18	83%	17%	NL04	82%	18%
DE19	100%		NL05	93%	7%	DE19	100%		NL05	100%	
DE20	100%		NO03	73%	27%	DE20	100%		NO03	88%	12%
DE21	100%		PL01	100%		DE21	100%		PL01	58%	42%
DK03	77%	23%	PL03	57%	43%	DK03	61%	39%	PL03	100%	
DK04	100%		PL04	47%	53%	DK04	100%		PL04	99%	1%
ES02	2%	98%	PT02	100%		ES02	1%	99%	PT02		100%
ES03	33%	67%	SE01	100%		ES03	56%	44%	SE01	77%	23%
ES07	5%	95%	SE03		100%	ES07	4%	96%	SE03	32%	68%
FI01	43%	57%	SE04	84%	16%	FI01	42%	58%	SE04	87%	13%
FI02	54%	46%	SE06	61%	39%	FI02	100%		SE06	100%	
FI03	100%		TR01	90%	10%	FI03	74%	26%	TR01	42%	58%
FR01	83%	17%	TR03	100%		FR01	22%	78%	TR03		100%
FR02	16%	84%	TR07	39%	61%	FR02	100%		TR07	74%	26%
FR03	100%		INT	8%	92%	FR03	70%	30%	INT	11%	89%
FR04	67%	33%	EX	100%		FR04	100%		EX	36%	64%

C4.5 Base Case with deviations on the backorder cost

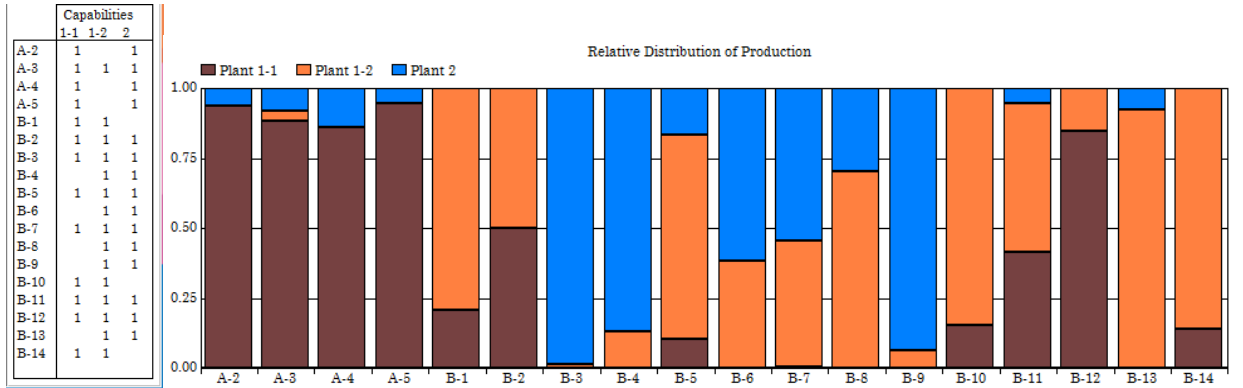
1.  $c^b = \overline{c_{kj}^h}$  (i. e. average holding cost)



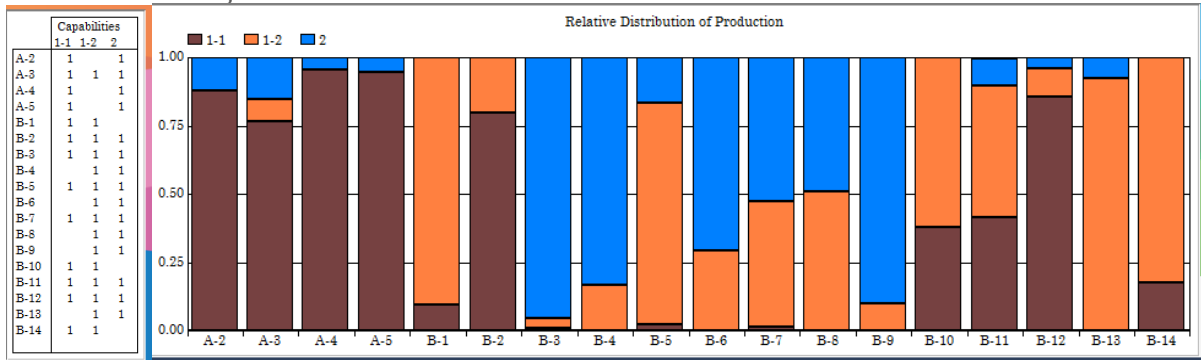
$$2. \quad c^b = 2 * \overline{c_{kj}^h}$$



### 3. Base case

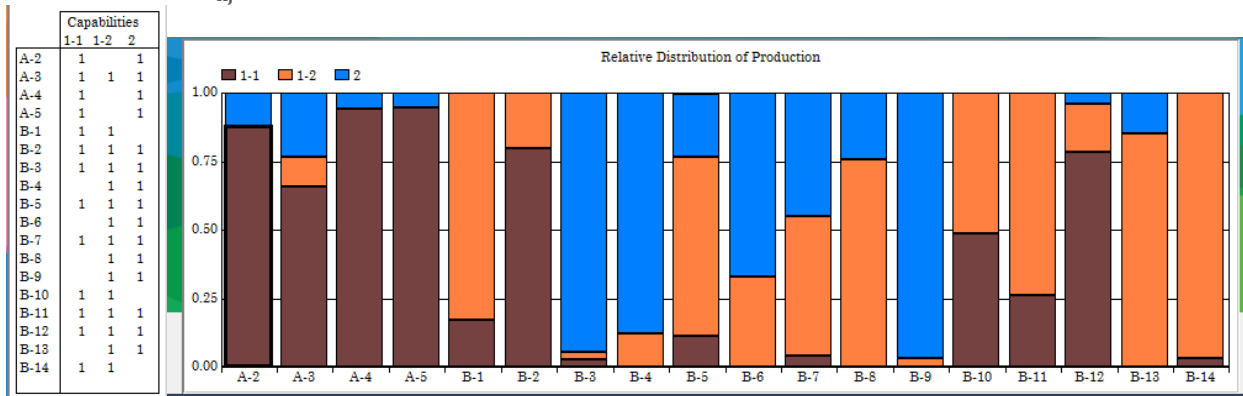


$$4. \quad c^b = 4 * \overline{c_{kj}^h}$$

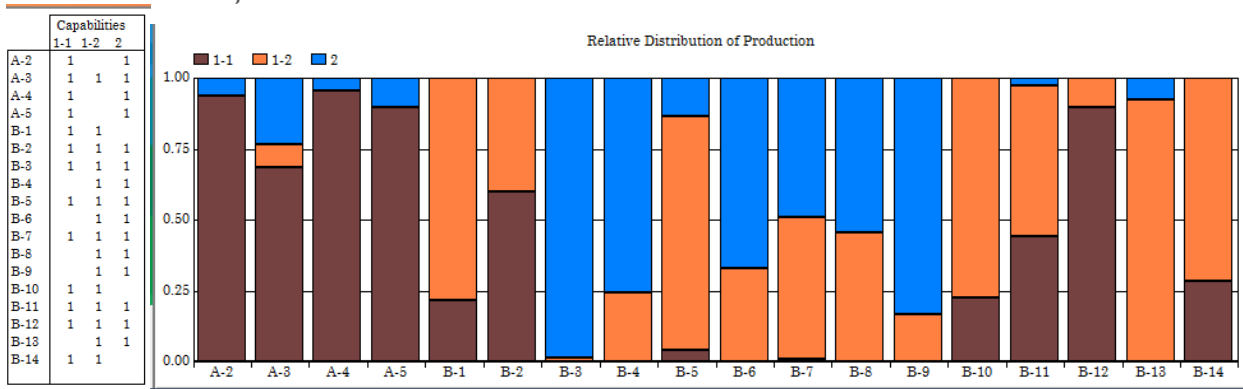




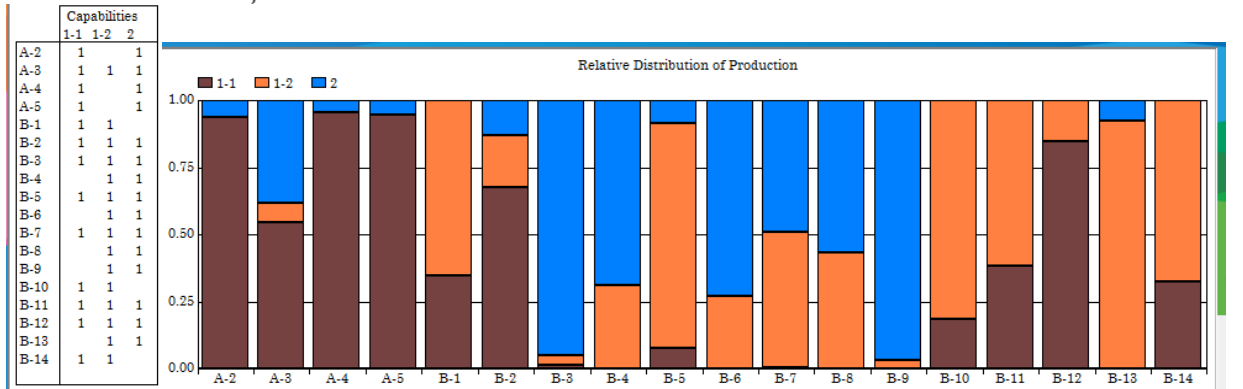
$$5. c^b = 5 * \overline{c_{kj}^h}$$



$$6. c^b = 8 * \overline{c_{kj}^h}$$

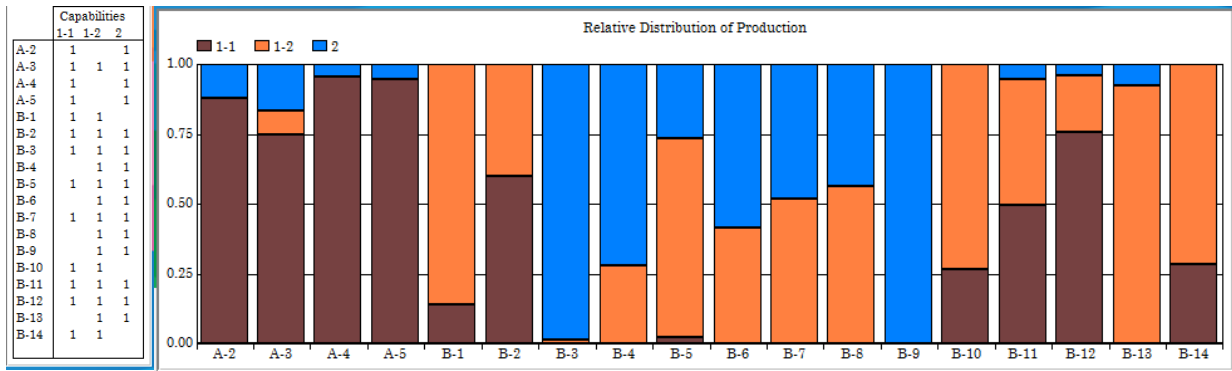


$$7. c^b = 16 * \overline{c_{kj}^h}$$

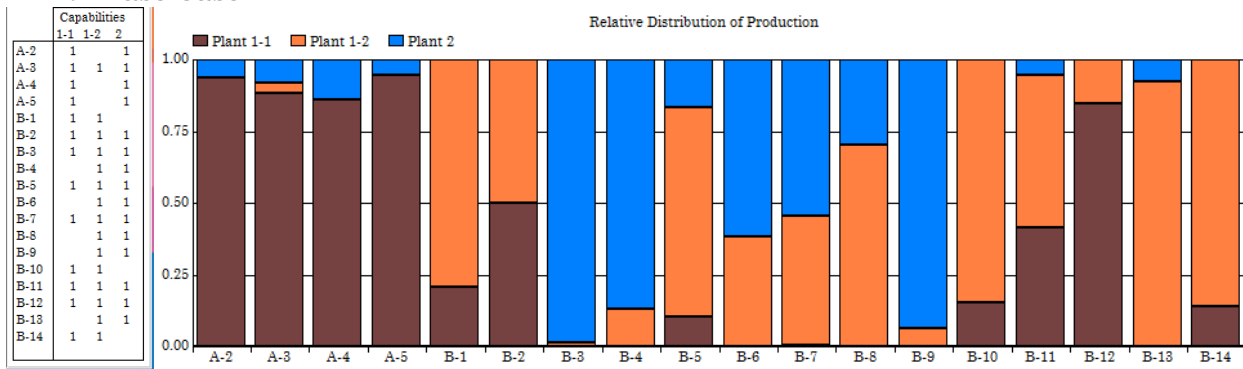


#### C4.6 Base case with deviations on the holding cost

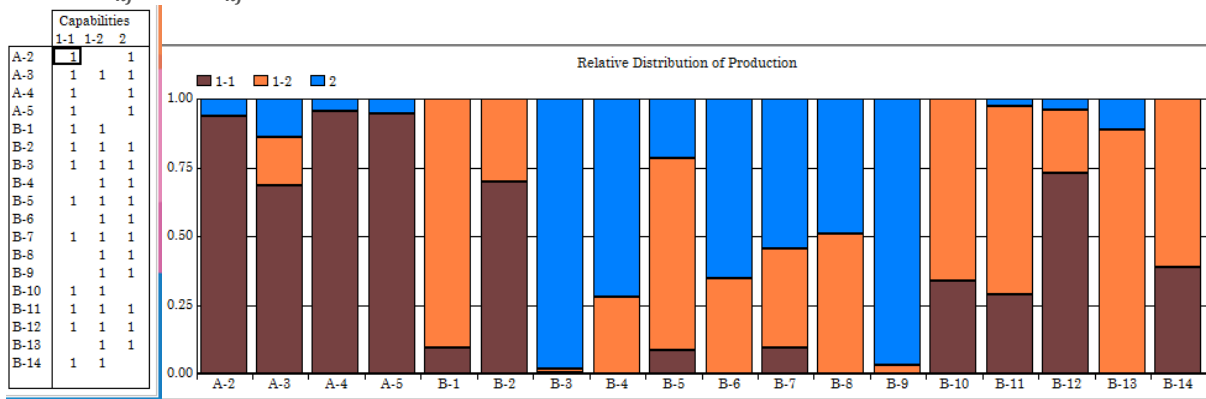
$$1. c_{kj} = 0,5c_{kj}$$



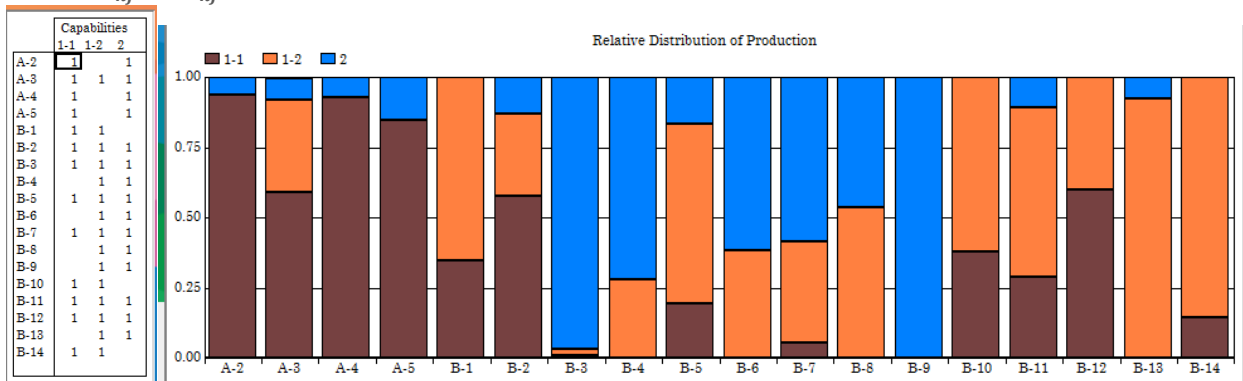
## 2. Base Case



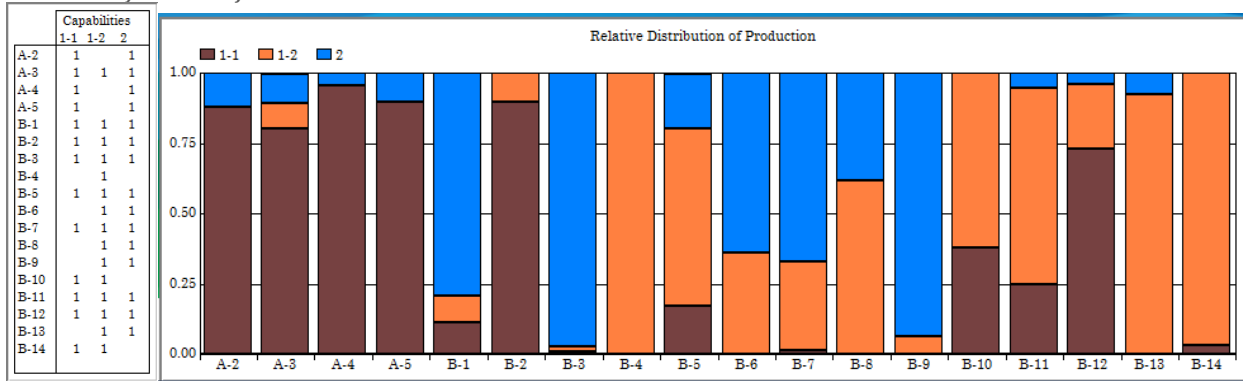
## 3. $c_{kj} = 1,5c_{kj}$



## 4. $c_{kj} = 2c_{kj}$



$$5. c_{kj} = 2,5c_{kj}$$



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## D1. Formulation of Model Extension

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### Objective function:

$$Profit = Max \sum_{kljt} S_{kljt} p_k - \left( \sum_{kj} c_{kj}^F q_{kj} + \sum_{kjt} c_{kj}^v A_{kjt} + \sum_{kjt} c_{kj}^h I_{kjt}^+ + \sum_{klt} c^b I_{klt}^- + \sum_{kljt} c_{lj}^d S_{kljt} \right) \quad (1)$$

### Subject to

$$\sum_j S_{kljt} \leq D_{klt} + I_{kl(t-1)}^- \quad 1 \leq t \leq T, \quad \forall k, l \quad (2)$$

$$I_{klt}^- = D_{klt} + I_{kl(t-1)}^- - \sum_j S_{kljt} \quad 1 \leq t \leq T, \quad \forall k, l \quad (3)$$

$$q_{kj} \in (0,1) \quad \forall k, j \quad (4)$$

$$x_{kjt} \in \mathbb{N} \quad \forall k, j, t \quad (5)$$

$$A_{kjt} = x_{kjt} \theta_{kj} \quad \forall k, j, t \quad (6)$$

$$\sum_t A_{kjt} \leq q_{kj} M \quad \forall k, j \quad (7)$$

$$\sum_k \frac{1}{\tau_{kjt}} A_{kjt} \leq \Gamma_{jt}^a - \varphi_{jt}^{total} \quad \forall j, t \quad (8)$$

$$\sum_l S_{kljt} \leq \kappa_j A_{kjt} + I_{kj(t-1)}^+ \quad 1 \leq t \leq T, \quad \forall k, j \quad (9)$$

$$I_{kjt}^+ = I_{kj(t-1)}^+ + \kappa_j A_{kjt} - \sum_l S_{kljt} \quad 1 \leq t \leq T, \quad \forall k, j \quad (10)$$

$$y_{kjnt} \in (0,1) \quad 1 \leq t \leq T, \quad \forall k, j, n, t \quad (11)$$

$$\sum_n y_{kjnt} \leq 1 \quad 1 \leq t \leq T, \quad \forall k, j, t \quad (12)$$

$$A_{kjt} \leq \sum_n y_{kjnt} S_{kjn} \quad 1 \leq t \leq T, \quad \forall k, j, t \quad (13)$$

$$\varphi_{jt}^{total} = \sum_{kn} y_{kjnt} \varphi_{kjn} \quad \forall j, t \quad (14)$$

### Input Parameters:

- 
- $K$  = the set of products, indexed by  $k$
  - $L$  = the set of customers, indexed by  $l$
  - $J$  = the set of production facilities, indexed by  $j$
  - $T$  = the set of periods, indexed by  $t$
  - $N$  = the set of production stages, indexed by  $n$

$D_{klt}$  = the total unit volume of demand of product  $k \in K$  from customer  $l \in L$  at the beginning of period  $t \in T$

$p_k$	=	the price per unit volume of product $k \in K$
$\theta_{kj}$	=	batch size volume of product $k \in K$ in production facility $j \in J$
$K_j$	=	quality rate of production output at facility $j \in J$
$\tau_{kjt}$	=	total unit throughput volume per unit time of production for product $k \in K$ in production facility $j \in J$ in period $t \in T$
$\mu$	=	the upper bound on the utilization level attained at each individual production facility
$\Gamma_{jt}$	=	the total actual capacity (unit time) available for production at facility $j \in J$ in period $t \in T$
$\Gamma_{jt}^a$	=	$\mu \Gamma_{jt}^a$ , i.e. the total actual capacity (unit time) available for production at facility $j \in J$ in period $t \in T$ , given the utilization level upper bound $\mu$
$\tau_{kj}$	=	total unit throughput volume per hour of production of product $k \in K$ in production facility $j \in J$
$\theta_{kj}$	=	production batch size for product $k \in K$ at facility $j \in J$
$M$	=	a sufficiently large generic number
$s_{kjn}$	=	the total capacity volume for production of production $k \in K$ at facility $j \in J$ when producing in production stage $n \in N$
$\phi_{kjn}$	=	the penalty time, or idle time awarded for producing product $k \in K$ at facility $j \in J$ in production stage $n \in N$
$c_{kj}^f$	=	fixed, one-off cost, to enable production for product $k \in K$ in production facility $j \in J$
$c_{kj}^v$	=	total variable production cost per unit output volume for product $k \in K$ in production facility $j \in J$
$c_{kj}^h$	=	holding cost per unit volume for product $k \in K$ in period $t \in T$
$c^b$	=	backorder cost per unit of volume
$c_{il}^d$	=	distribution cost per unit volume from production facility $j \in J$ to customer $l \in L$

### Auxiliary variables:

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$I_{klt}^-$	=	the total unit volume of unfulfilled demand of product $k \in K$ from customer $l \in L$ at the end of period $t \in T$
$I_{klt}^+$	=	the total unit volume of physical inventory of product $k \in K$ at production facility $j \in J$ at the end of period $t \in T$
$A_{kjt}$	=	actual production volume of product $k \in K$ in production facility $j \in J$ for period $t \in T$
$\phi_{jt}^{total}$	=	Total idle time incurred at facility $j \in J$ in period $t \in T$

### Decision variables:

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$S_{kljt}$	=	the total unit volume of demand fulfilled, in unit volume of product $k \in K$ to customer $l \in L$ from production facility $j \in J$ in period $t \in T$
$q_{kj}$	=	binary variable that indicates if product $k \in K$ can be produced at plant $j \in J$ ,
$x_{kjt}$	=	total integer number of batch sizes produced for product $k \in K$ in production facility $j \in J$ in period $t \in T$ .
$y_{kjnt}$	=	variable that indicates if production takes place for product $k \in K$ at facility $j \in J$ in production stage $n \in N$ in period $t \in T$