MASTER

Multi-echelon Safety Stock Management Approach for Pharmaceutical Companies

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Award date:
2022

Eindhoven University of Technology

Master Thesis

Final Report

Multi-echelon Safety Stock Management Approach for Pharmaceutical Companies

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April 4, 2022

Public Document

Management Summary

This research project studies the field of multi-echelon safety stock management in the context of the pharmaceutical industry. The project focuses on investigating how a multi-echelon safety stock management approach can reduce the safety stock costs and improve the service levels of a life science company. Thus, this approach researched in the context of applying the concept on a case which has been made available by Life Science Company (LSC). LSC is an organization which is globally active in the healthcare and agriculture industry.

The project was initiated by the Global Supply Chain Process & Performance Management Team of Life Science Company. This team is responsible for improving the performance of the pharmaceutical supply chains within the organization. A pharmaceutical supply chain is recognized as being highly complex due to the number of stakeholders and the requirements for the production of products (Lee, 2002; Bhakoo & Chan, 2011). The production process of a product is characterized by the product hierarchy that is present in the end-to-end chain. There are six different product types present in the supply chain of LSC. Each product starts as an Active Pharmaceutical Ingredient (API) which is potentially mixed with an Excipient to produce the Formulation/Bulk Materials from the raw materials. For some products, the Formulation is differentiated to an Intermediate before it is combined with Packaging Materials. The result of this combination is then the so-called Finished Good.

The problem recognized within LSC is that is keeps too much inventory of its products and despite these high inventory costs, the achieved service levels are perceived as low. The identified causes of this problem are on the one hand that LSC has a culture and processes in place where inventory is stored at the end of the supply chain as a Finished Good. On the other hand, it lacks a safety stock strategy for the components of these Finished Goods. The field of multi-echelon safety stock management has been identified as the most promising to provide a solution for the problem of LSC. This approach has proven to lead to an optimal configuration of a supply chain where the safety stock costs are minimized without giving in on service (De Kok et al., 2018). As a result, the following main research question is defined.

Main Research Question

How can a multi-echelon safety stock management approach reduce the inventory costs and improve the service levels of Life Science Company?

The research scope is narrowed to a diverse and representative part of the product portfolio. The inventory of this selection is currently centrally managed according to an inventory control policy. Thus, the stages only consider the local available information on demand and inventory levels. LSC uses Days of Supply (DOS) to express the inventory levels which links the available inventory quantity to the demand forecast. The products are replenished according to a *(R, s, S)* strategy where it is periodically checked whether the inventory level dropped below the DOS level s. This level is yearly determined for each product based on historical demand and the supply chain lead times. Since LSC currently only considers the possibility of storing safety stock at the end of the chain, its current performance is expressed as a single-echelon approach for the final stage in the network.

The literature review showed that two multi-echelon approaches are best aligned with the supply chain characteristics of LSC. These are the Guaranteed Service Model and the Synchronized Base Stock Policy.

Guaranteed Service Model

The Guaranteed Service Model depends on the assumption that service to a stage is guaranteed. Each stages quotes a service time to its linked downstream stage(s) in which it will always supply the demanded materials. The quoted service time makes the lead time deterministic and as a result, the boundaries for demand can be determined. Therefore, the optimal safety stock quantity which a stage has to keep to commit to the quoted service time is finite. The approach assumes

that additional measures are taken when actual demand exceeds the boundaries, such as the outsourcing of production (Graves & Willems, 2003b).

Synchronized Base Stock Policy
The Synchronized Base Stock Policy is based on the combination of a product's Bill of Materials (BOM) and the cumulative lead times of processes throughout its supply chain. Here, the BOM represents the relationships between child- and parent-items and is used to derive an artificial hierarchy for materials. The cumulative lead times determine the releasing of orders in the chain to cover the end-item demand. Therefore, the policy synchronizes the process of timing the order release and the order quantity. The ChainStock software tool by T. de Kok (2008) is used to test the Synchronized Base Stock Policy in a case study.

Results
The supply network of LSC is spanning tree with a convergent structure consisting of six nodes. The basic models are compared in terms of their (proposed) safety stock quantities and costs as summarized in Table 1. The values are because of confidentiality reasons masked by multiplying them with a factor. This factor is only known by the author and the supervisors of this research project. The results show that the Synchronized Base Stock Policy overall outperforms the currently used Single-Echelon approach and the other tested multi-echelon approach, the Guaranteed Service Model.

Table 1: Masked Overview Average Safety Stock Costs per Week per Approach

Product	**Single-Echelon**	**Guaranteed Service Model**	**Synchronized Base Stock Policy**
11873262	€ 42.639	€ 21.958	€ 18.776
11873533	€ 49.241	€ 36.354	€ 25.342
85690604	€ 32.173	€ 48.206	€ 32.694
86189976	€ 12.548	€ 15.908	€ 13.526
86570009	€ 28.047	€ 21.882	€ 20.135
86947552	€ 26.830	€ 26.761	€ 29.902
Total	€ 191.478	€ 171.069	€ 140.375

The multi-echelon approaches show a potential safety stock cost reduction for the product portfolio selection of on average 10.6% for the Guaranteed Service Model and 26.7% for the Synchronized Base Stock Policy. For the individual products in scope, potential safety stock cost reductions reach up to 48.5% and 56.0% under a multi-echelon approach. The safety stock allocation is for all products approximately the same - the stock is placed at either last or the first-to-last and last stage of the network. This is similar to where the organization currently places its safety stock. Therefore, the focus of the organization should be on *how much* safety stock is actually needed, rather than on *where* it is placed.

In addition, a sensitivity analysis and factorial analysis are performed to identify the key-model parameters that drive good performance. The included parameters are *Target Service Level*, *Demand Variability*, *Added Value* and *Lead Time*. The results of the analysis show that the benefits of the Synchronized Base Stock Policy are less impacted by changes of the parameter values of Target Service Level and Demand Variability than the Guaranteed Service Model. The output for the Added Value and Lead Time show a clear distinction in the selection of products. The products that are cross-regionally supplied - with lead times of e.g. more than one week - have experienced a significant increase in transportation costs and to be impacted by low lead time adherence (Rao & Saul, 2021). This provides grounds to propose a redesign of the supply network. Regionally supplied products have due to their short lead times a negligible impact on the safety stock proposal. Therefore, these products are considered as not interesting to gain improvements for LSC. Furthermore, it is safe to say that the multi-echelon approach is beneficial for all products, but it is highlighted that the benefits are greater for products with relatively stable demand.

Discussion & Conclusion

To conclude, both multi-echelon approaches seem to be beneficial for the organization to implement. The proposed safety stock allocations are in line with the company's current approach and literature - placement at the end of the network (Whybark & Yang, 1996). When comparing the two multi-echelon approaches, the Synchronized Base Stock Policy is recognized as being the superior method. The benefits for all products are the least impacted under this approach when the input parameters are changed. Additionally, the reasons provide grounds to propose to research the possibilities of redesigning the supply network for cross-regionally supplied products. The safety stock allocation of this set of products shows to be more impacted by changes in the transportation costs and lead time of shipments. These changes are also recognized as to have happened in the real-world over the past years, making these findings more relevant for other organizations.

The developed models for the Guaranteed Service Model and Synchronized Base Stock Policy can easily be expanded. Both models needs minimal updates and adaption to fit them to a different supply network structures. To further roll out the multi-echelon approach, the organization should focus on improving its master data management and knowledge about the methodology. These factors are identified as crucial for making the expansion of the method a success. Furthermore, it is recommended to improve the demand forecast accuracy since safety stock is used to cover customer demand variability. Thus, the safety stock costs can be further reduced and service levels further improved if the demand forecast is accurate since this enables improving the planning of supply chain processes.

The limitations of the methods are that supply variability is not considered for the safety stock proposals. The variability in supply lead times has become more of a problem for organizations over the past years since logistical processes are under increased pressure due to the pandemic. In addition, the shelf life is also excluded from the safety stock proposals, even though the management of perishability is for some pharmaceutical products of great importance. Finally, the operational characteristics of a supply chain - e.g. on production planning and yield of processes - is left out during the modeling of the network processes. The combination of a multi-echelon safety stock management approach and the dynamics of a manufacturing site seems to be an interesting area to further research for finding additional ways of reducing the safety stock costs and increasing the service levels at pharmaceutical companies.

Preface

The completion of the Master Thesis project marks the end of the Master Program Operations Management & Logistics at Eindhoven University of Technology. Moreover, it represents the end of my student life which I've enjoyed to the fullest for close-to seven years. It has been an amazing journey and I couldn't have done it without the help of others. Therefore, I'd like to take a moment to thank everyone who supported me during all these years.

First of all, I'd like to thank Zümbül Atan for her extensive support, great collaboration and interesting conversations during my earlier internship and master thesis project. Her drive, expertise and passion for supply chain management and multi-echelon inventory management has been a true help. Even though the pandemic led to additional challenges in the project, she has always took the time to supervise me and send me into the right direction. Zümbül, thank you for everything! I'd also like to thank my second assessor Tugce Martagan for her confidence in my research approach and results and her valuable feedback regarding highlighting the industrial application of my project.

In addition, I'd like to thank all my colleagues at the Life Science Company which have been supporting and supervising me throughout the project. Ivan Cupela, with his unlimited attitude to help me whenever I had questions or needed something. Mark Kerkhofs, for our weekly catch-ups which have been helpful, interesting and most of all, much fun. Ernico van Halm, for sharing his opinions and experiences with me about multi-echelon inventory management and supply chain planning within companies. Finally, I'd like to thank my colleagues and friends Alain Geiger & Franziska Trautmann for supporting me during the project, our productive discussions and for the reviewing of the final report.

Lastly, I'd like to thank my friends and family who made my student-life in Eindhoven and my time in Switzerland as great as it has been. Moving to Switzerland during a pandemic was sometimes challenging, but I feel lucky that I had the opportunity to experience how gentle and kind the Swiss people actually are. Leaving Switzerland with a Master Degree and so many new friendships and memories, I can truly say that it has been an amazing 1,5 years. Let's see what else the future has in mind for me!

Lauran Kloosterman
April 2022

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List of Abbreviations

API	Active Pharmaceutical Ingredient
APO	Advanced Planning and Optimization
BOM	Bill Of Materials
CV	Coefficient of Variation
DOS	Days Of Supply
DP	Dynamic Program
EMA	European Medicine Agency
ERP	Enterprise Resource Planning
FDA	Food and Drugs Administration
FH	Frozen Horizon
GSM	Guaranteed Service Model
LSC	Life Science Company
MIME	Multi-Item Multi-Echelon
MPS	Master Production Schedule
MRP	Material Requirements Planning
PSC	Pharmaceutical Supply Chain
SBS	Synchronized Base Stock
SBSP	Synchronized Base Stock Policy
SCOP	Supply Chain Operations Planning
SE	Single Echelon
S&OP	Sales & Operations Planning

1 Introduction

This research project was carried out in collaboration with a Life Science Company (LSC) for the partial fulfillment of the Master of Science Operation Management & Logistics of the Eindhoven University of Technology.

This introduction provides the reader the understanding of the business environment and research area. Firstly, the Problem Context is described in Section 1.1, including the Company Background and the Pharmaceutical Supply Chain Environment. After the Problem Context, the Problem Description is presented in Section 1.2 where the exact Problem Definition and the Research Need are outlined. Consequently, the Research Scope is defined in Section 1.3, including an overview of the Research Questions. Finally, the methodology of the project is presented in the Research Approach in Section 1.4.

1.1 Problem Context

1.1.1 Company Background

LSC is a life science company active in the healthcare and agriculture industry. The company recognizes that a growing and ageing world population requires innovation to maintain and increase sufficient health care and secure the supply of quality food for everyone. Moreover, the increased pressure on nature's ecosystems demands a more responsible and efficient use of natural resources. LSC contributes to this purpose by serving the most basic human needs - health and food.

The company acts according to four strategic levers outlined as their vision. Firstly, LSC aims at developing world-class products by leveraging innovation and cutting-edge research. It does so by engaging third-parties to improve its access to innovation. Secondly, it strives for optimization of the resource allocation of both materials and employees to achieve operational excellence in business. Thirdly, sustainability is recognized as a key-factor within the company. The company wishes to make a positive contribution to the United Nations' Sustainable Development Goals and the climate targets of the Paris Agreement. Consequently, sustainability is considered in the business strategy, operational activities and the compensation system. Fourth and finally, it focuses on continuously developing its business by allocating resources strategically to achieve profitable growth.

The company employed approximately 100.000 people by the end of 2020, divided over more than 80 countries. The healthcare division focuses on development, manufacturing and commercialization of prescriptive and non-prescriptive health products. The agriculture division focuses on seeds, crop protection and non-agriculture pest control. Its products are sold in over 150 countries and its combined revenue exceeded $40 billion in 2020.

1.1.2 Pharmaceutical Supply Chain Environment

The pharmaceutical industry can be characterized as a collection of processes, organizations, and operations associated with the discovery, design, and production of pharmaceutical products (Singh, Kumar, & Kumar, 2016). A Pharmaceutical Supply Chain (PSC) is described as the system for producing, transporting, and consuming drugs (Xie & Breen, 2012). What makes the system unique, but also complex and challenging to manage, is the combination of the many stakeholders (Lee, 2002). More specific, pharmaceutical supply chains are recognized to be more complicated due to the involvement of stakeholders, such as: pharmaceutical producers, wholesalers, distributors, customers, information service providers, and regulatory authorities (Bhakoo & Chan, 2011). Especially the research and development of new drugs and regulatory affairs strongly influence the management of a PSC. The success rate of new drug discovery is low with not even one per 1000 attempts making it to the clinical trials stage (testing on animals and humans) (Laínez, Schaefer, & Reklaitis, 2012). After a new drug discovery and filing the patent, it still takes approximately ten years until the first sales. The drug needs to be tested extensively in clinical trials on safety, efficacy and efficiency before it is approved for the markets by the responsible regulatory authorities, such as the US Food and Drugs Administration (FDA) and the European Medicines Agency (EMA). Conducting these clinical trials is a costly process for a company with total expenses ranging from $200 to $400 million per drug (Shah, 2004).

Companies design their new supply chains when in parallel to this clinical trials for market approval are taking place. Moreover, competitors are possibly also active in the same research field. Consequently, the design of a PSC is subjected to the uncertainty whether or not a product will ever make it to the market. This makes the decision making of how the initial supply chain should be configured a complex and difficult process; which resources should be assigned and how expected customer demand can be best balanced with product supply (Laínez et al., 2012).

Despite ongoing cutting-edge innovation, the pharmaceutical industry is staying behind compared to other industries in terms of advanced supply chain management concepts (Kaminsky & Wang, 2015). A PSC consists in general of five different nodes. The first one is the primary manufacturing, responsible for the production of Active Pharmaceutical Ingredients (APIs). This includes the creation of the drug substance from built up complex molecule structures. The second one is secondary manufacturing where APIs are mixed with Excipients (additional substances to improve functioning of the API). These mixes are further processed, such as compressed to pills, coated and packed in a strip for example. The last three nodes include more general processes: warehouses/distribution centers (3), wholesalers (4) and retailers/hospitals (5) (Shah, 2004). Moreover, there are multiple operational challenges in the supply chain planning process of a PSC. Therefore, the following four aspects of this process are briefly discussed: demand planning, capacity planning, production management and inventory management.

Demand Planning

Supply chain planning starts with considering the uncertainty in customer demand. Therefore, demand forecasts have a great influence on the decision-making process regarding supply chain management. Generally speaking, the quality of demand forecasting within pharmaceutical companies is low. The reason for this is that high margins on sold products never gave the incentive to start putting more money and effort in more accurate demand forecasts. However, this is currently changing as the industry started to recognize its importance as margins are decreasing (Merkuryeva, Valberga, & Smirnov, 2019). A typical characteristic of the pharmaceutical industry is its long planning horizon in terms of demand forecasting. The horizon is usually ranging to a period of twelve- to 24 months. One can understand that demand is relatively unpredictable with such a long horizon and thus, it is bound to fluctuate (Grimson & Pyke, 2007). Furthermore, the demand forecasting depends on the product life cycle stage of a product (Cook, 2016). For a new product, first the initial market size has to be estimated. This calls for using judgmental methods as quantitative data is usually unavailable. For a product which is already for a longer period of time on the market, other factors are present. Examples of factors are the potential market share and the future market growth or decline. Most likely, quantitative data is available which allows for different forecasting techniques to get the most accurate estimation for customer demand (Merkuryeva et al., 2019).

Capacity Planning

The second aspect is planning of production capacity in a PSC. Realizing (additional) production capacity is difficult due to the required construction time, investment and licensing of the manufacturing site (Shah, 2004). Building a new manufacturing facility can cost up to $800 million, but even making the necessary modifications to an existing facility can cost hundreds of millions of dollars. The licensing includes that the respective authorities have to provide a license for producing drugs at a manufacturing site (Kaminsky & Wang, 2015). On an operational level, the primary- and secondary-manufacturing are characterized by low production velocities. The development of the complex molecular structures takes a significant amount of time. In addition, biological production is known for its uncertainties in the process; yields might be unstable and difficult to predict (Kaminsky & Wang, 2015). Therefore, capacity planning is a risky and expensive process within every biological PSC. This emphasizes the importance of the initial demand forecast, such as in which market and how much customer demand can be expected.

Production Management
The third aspect to consider is production management. A factor that has a great influence on this process is the control of product quality. Quality checks of the (non-)finished goods have to be performed after (almost) every processing stage. This is required to ensure the quality and safety of the product for the patients (Shah, 2004). However, the controlling activities bring a disadvantage for the manufacturing process, such as an increase of the lead time (Kaminsky & Wang, 2015). The mentioned characteristics of capacity planning and production management result in considerably long supply chain cycle times. These characteristics reduce the responsiveness of companies to the market dynamics, making e.g. inventory management an important factor in the process (Shah, 2004).

Inventory Management
The fourth and final aspect to consider is inventory management. The approved shelf life of drugs is a characteristic which influences inventory management in PSCs significantly. The complex molecule structures are sensitive for losing their activity over time. The risk of having to write off the product remains, even with modern packaging materials and environmental control measures during the distribution and storage (Shah, 2004). This makes product perishability a critical issue and provides an incentive to keep the inventory of perishable drugs as low as possible. However, some drugs are lifesaving for patients and anything below a service level of 100% is unacceptable. This results in companies keeping enormous amounts of inventory, such that a fill rate of 100% can always be assured. Therefore, inventory management of PSC's is about finding the right balance and requires efficient coordination of all parties in the end-to-end process (Jaberidoost, Nikfar, Abdollahiasl, & Dinarvand, 2013).

1.1.3 Product Hierarchy

The distinction between six product types can be made in the supply chain of LSC. How one product type is related to another one is captured in a product hierarchy tree. The hierarchy contains APIs, Excipients, Formulation (bulk materials), Intermediates, Packaging materials and Finished Goods. The materials flow through the stages of the tree via value-adding and differentiating production processes. The product hierarchy tree is illustrated in Figure 1, followed by a more detailed explanation per type.

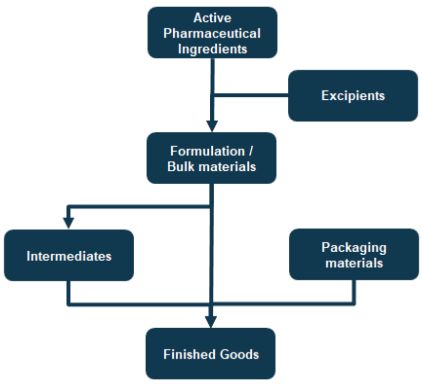


Figure 1: Product Hierarchy

APIs are a substance or mix of substances used for the production of a finished pharmaceutical product. The substance can have different functions, such as enabling pharmaceutical activity or otherwise have direct impact on the diagnosis, cure, mitigation, treatment or prevention of diseases. Other functionalities are the restoration, correction or modification of physiological functions in humans or animals (US Food and Drug Administration, 2015). Therefore, the APIs are seen as the key-ingredient for every product, making them critical for the business. Excipients are substances mixed with the APIs to improve their functionality. An excipient helps to control the gradual release of the active substance to the patient and stabilize the decomposition of the substance. It can trigger physical and chemical reactions between the API and the excipient, such that the effects of the finished goods are affected (Bharate, Bharate, & Bajaj, 2016). Mixing an excipient with an API is only happening in the production of some products, not for all of them.

Formulation includes the bulk material made from the API substance, potentially mixed with the excipients. The bulk material has generally speaking a tablet, liquid or jelly form and determines the storing conditions of the material. In some cases, products first flow from the formulation-stage to the intermediate-stage. Thus, the products in the intermediate stage have another value-adding step in their production process. The step is a form of further differentiation, such as giving the product a particular taste or color.

The packaging materials are used to pack the materials in the formulation or intermediate stage. Examples of packaging materials are tubes, folding boxes and foils. The packaging materials exist in different sizes, based on the pack size of the finished good. Packaging materials are subjected to many design changes. For example, such changes may be triggered by the planning of a marketing campaign for a product when a new design is requested. Another trigger is a regulatory change in the country of sales, such as what information should be on the packaging material for the customer. Finally, the combination of formulation or intermediate materials and the packaging materials results in a finished good.

1.2 Problem Description

The problem recognized by LSC is that the organization keeps too much inventory of its products. Despite these high inventory costs, the achieved service levels are perceived as low. Therefore, a clear problem description is in this section defined. The statement is first validated by checking relevant literature and performing a data analysis. Once it is proven that the problem exists, the research needs for this problem are explained.

1.2.1 Problem Definition

The inventory costs of LSC represent the monetary value of the organization's stock. In general, three different kinds of inventory are distinguished which are base stock, safety stock and pipeline stock. To understand how LSC is performing compared to competitors in the industry, the company participated in a benchmark study executed by an external organization regarding inventory costs. The results of the study showed that LSC keeps much more inventory and thus, it has higher inventory costs than its competitors. The real-world data cannot be disclosed because of confidentiality reasons, but it validates the claim that LSC has high inventory costs.

The service level of LSC represents the delivery performance of the company. Thus, it is the percentage of the ordered quantity that was delivered on time. This Key Performance Indicator (KPI) is measured at a local affiliate-level enabling a more focused delivery performance management and customization of the addressed customer channels by the local entities. The service level for the year 2020 is illustrated below in Figure 2. The target service level differs per country, but is recommended to be 95%. Thus, the graph clearly shows that the target service level per week was less than the target for the year 2020.

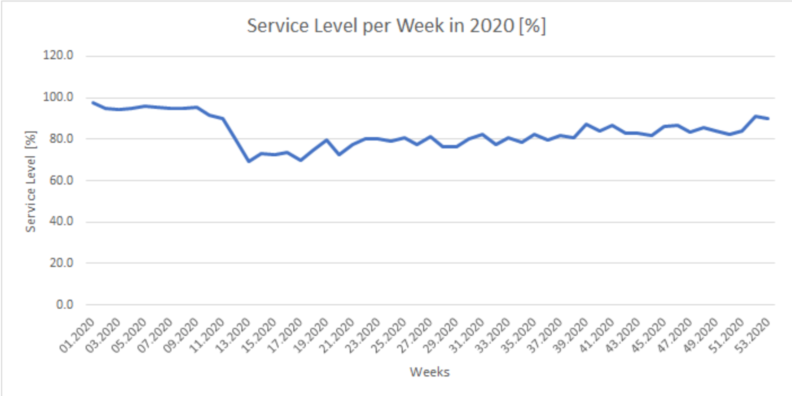


Figure 2: Service Level per Week in 2020

Roughly 50 years ago, keeping inventory as an organization was recognized as a waste of capital and as a result, inventory reduction was in that time a priority for many organizations. The problem is that due to the inevitable variability, keeping inventory is always required to address the customers' needs in time. High service levels have proven to lead to more customer engagement and binding, resulting in higher sales. This led to a change of perspective on keeping inventory and gave organizations the incentive to find the optimal quantities to deal with the trade-off between keeping inventory and serving customers. Nevertheless, inventory is still capital locked up which you cannot use for other purposes (De Kok et al., 2018). Therefore, inventory optimization remains of importance to companies.

Two causes of this problem are identified via several interviews with employees of LSC. The first one is that the organization has a culture and processes in place which together lead to storing inventory as a Finished Good at the end of the supply chain. In other words, the organization has never considered inventory management in the perspective of an end-to-end supply chain. Instead, it focused on producing a salable product against the lowest costs possible, resulting in sub-optimal inventory management. The supply chain planning process of LSC is presented in Figure 21 in Appendix B confirms this statement. The graph shows that the complete process is focused on realizing a production order for a finished good. The activity of ordering components - items belonging to every other material type than the Finished Good - is seen as a contributing step in this process. Consequently, the production of finished goods translates into keeping more inventory at the end of the supply chain.

This claim is confirmed by performing a data analysis. Initially, the scope of the analysis is set to one specific manufacturing site which is located in the South of Germany. The reason for picking this site is explained later in Section 1.3.3. The validation is done by reviewing the inventory value per product type versus the location LSC stores its inventory for the ten markets that have the most inventory manufactured at the selected site. The analysis results - shown in Figures 18 and 19 in Appendix A - confirm this statement since the vast majority of the inventory is of the product type 'Finished Good'. In other words, LSC pushes inventory to the end of the supply chain network where its stored as finished goods.

The second one is that LSC lacks a safety stock setting strategy for non-finished goods. The organization only focuses on having enough safety stock on a finished good-level. Consequently, the company never considered the cost efficiency of keeping safety stock more upstream in the supply chain network. De Kok et al. (2018) stated that there is a quantitative relationship between adequate inventory management within a supply chain and the end-item customer service. Therefore, the lack of safety stock setting translates into the situation where inventory is potentially kept at sub-optimal places in the supply chain.

To summarize and conclude, the problem of LSC is that it is not meeting its target service level despite the great amount of inventory it keeps. The problem is caused by having a culture and processes where inventory is stored at the end of the supply chain as a finished good - the most valuable product type. Moreover, the organization lacks a strategy for safety stock setting for components. These statements are validated by literature and data analysis and this confirms the claims that these causes result in high inventory costs and low service levels.

1.2.2 Research Need & Direction

The defined problem requests for a solution to improve the situation at LSC and therefore, a need for research appears. The research direction is set to be the field of multi-echelon safety stock management, such that the project focuses on the area of safety stock management within inventory management. Inventory management itself is recognized as becoming more difficult because supply chains are becoming more complex due to an increasingly number of interacting nodes (Sbai & Berrado, 2018). However, when inventory in a supply chain is managed in an efficient way, it enables achieving a high customer service level. This approach is called multi-echelon safety stock management. It has proven to lead to an optimal configuration of a supply chain where the costs are minimized without giving in on service (Graves & Willems, 2003b; De Kok et al., 2018). Therefore, multi-echelon safety stock management is a promising research direction to solve this problem.

1.3 Research Scope

The research project is further scoped based on the earlier presented information. Firstly, the main- and sub-research questions are defined, such that they are in line with the research need. Subsequently, it is described which product types are considered in the rest of the project. Finally, it is explained how a selection of the product portfolio of LSC is made and which products are in this selection.

1.3.1 Research Questions

The subject of this Master Thesis project is research ways to reduce the inventory costs while improving the service levels of LSC using a multi-echelon safety stock management approach. Therefore, the main research question of the project is defined the following:

How can a multi-echelon safety stock management approach reduce the inventory costs and improve the service levels of the Life Science Company?

The main research question is answered by addressing six sub-questions. The sub-questions are defined the following:

1. What is the current safety stock strategy?

2. What are the safety stock costs and the service levels under the current safety stock strategy?

3. What multi-echelon safety stock management model is suitable for the supply chain of the Life Science Company?

4. What would the safety stock costs and the service levels be with a multi-echelon safety stock management model in place?

5. What are the benefits and disadvantages regarding the safety stock costs and service levels with a multi-echelon safety stock management approach?

6. What is required to further roll out the multi-echelon safety stock management approach in the Life Science Company?

1.3.2 Product Types

The product types considered in the rest of the research project are Excipients, Formulation (Bulk Materials), Intermediates, Packaging Materials and Finished Goods. Thus, this means that only product belonging to the API-product type are left out of scope. The scope for the product types is illustrated in Figure 3.

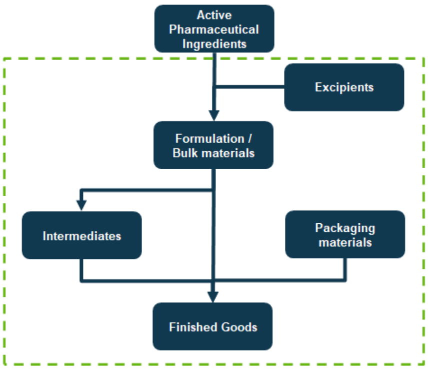


Figure 3: Product Hierarchy Scope

APIs are left out of scope because they are managed separately and individually within LSC. The reason is that these materials are recognized as the key-ingredients and have oftne long lead times to manufacture and release. Therefore, a different safety stock methodology is applied for these materials as much more inventory of them is kept.

Furthermore, Finished Goods are within scope, even though there is already a safety stock strategy for this product type in place. The reason is that the demand for Finished Goods translates into demand for non-Finished Goods and that the strategies have to be aligned to determine the optimal safety stock quantities along the supply chain. Furthermore, it allows the comparison of the performance under the current safety stock management strategy and a multi-echelon approach. This enables determining whether or not a multi-echelon approach is beneficial for the organization.

1.3.3 Selection Product Portfolio

The complete product portfolio of LSC contains too many items to investigate all. Therefore, the portfolio is scoped and a selection of products has been chosen. In the discussion of the results, the project findings are reviewed in terms of the possibilities to generalize the findings to the rest of the portfolio. The selection is made by reviewing the portfolio on a diverse range for parameters for the year 2020. The outcome is a selection of products which seem to provide the most significant improvements for LSC. In addition, these products are selected on how representative they are for a wider range of products of LSC.

Firstly, the scope is narrowed to the manufacturing site of LSC in the South of Germany, leaving out all other LSC manufacturing sites. The decision variable for this decision was the inventory value. The reason is that the eventually selected site must have manufactured a great part of the total inventory value. As a result, this has the potential to reduce inventory costs significantly. The latest available snapshot of the total owned inventory value (taken June 2021) is used to have the most representative picture of the situation. External (non-LSC) manufacturers are not considered as their operational data is unavailable for LSC. Furthermore, all product types except APIs are considered. The manufacturing site in the South of Germany was chosen because of three reasons. The first one is that the site is responsible for a significant amount of the total owned inventory value. The second one is that the site is located within a short distance of the headquarters of LSC, facilitating collaboration and enhancing information exchange. The third one is that the product portfolio of the the site in the South of Germany contains mainly dermatology products which are not subjected to seasonality in demand. Therefore, the latest available snapshot is the most representative for the inventory position at any moment in time. In Figure 19 in Appendix A is the inventory value per manufacturing site illustrated.

Secondly, the scope is narrowed to production line 36 of the site in the South of Germany to decrease the number of products that should be considered. The reason to take line 36 that the product on this line have a high level of representation for the remainder of the product portfolio. In addition, it is taken to keep this research project aligned with another project-stream within the company. Together with the consultancy company *McKinsey & Company*, LSC is currently trying to improve the performance of end-to-end supply chain processes (in different directions than inventory). Production line 36 is used as a pilot for these projects. Therefore, the line is also used as the scope for this project.

There are 57 different finished goods produced on this production line, made with seven different bulk materials. The overview of all finished goods and bulk materials are shown in Tables 10, 11 and 12 in Appendix B. The finished goods that are not produced anymore in 2021 versus 2020 are removed and the remainder of the portfolio is reviewed on the following parameters:

- Product Classification
- Production Frequency in Weeks
- Sales Value [€]
- Sales Quantity
- Case Fill Rate [%]
- Demand Forecast Accuracy in Value [€]
- Demand Forecast Accuracy in Quantity
- Total Owned Inventory Value [€]
- Write Offs Value [€]

Firstly, the threshold value for the sales value is set equal to €750.000 per year, such that decisions are taken on the key products of the site. Next, the planned lead time and standard deviation of demand are identified as factors known to influence safety stock management (De Kok et al., 2018). These factors correspond with the selection parameters *Production Frequency* and the *Demand Forecast Accuracy* respectively. Therefore, these two parameters are used as decision variables for the selection and the others to give a more detailed view on the products. The representative selection is made, such that all production frequencies and the full range of forecast accuracy is represented. The selection of products is shown in Table 2 and contains six finished goods, made from three bulk materials. An overview for all parameter values per finished good can be found in Tables 13 and 14 in Appendix B.

Table 2: Product Portfolio Scope

Bulk Material	**Finished Good**
Mycospor Creme 1%	Canesten Extra 1% CREA 50g DE
	Lotrimin Uno CREA 20gr MX
Canesten Clotrimazole Creme 1%	Canesten External Cream 1% 15g CA
	Canesten Crema 1% 30g MX
	Canesten CREA 15g GT
Canesten Creme 1% (2%B)	Clotrimazol Canesmed 10mg/g CREA 30g ES

The material flow to produce the finished goods is (partially) presented below in Figure 4. The items 1-8 represent the raw materials, items 9 - 11 the bulk materials and the items 12 - 17 the finished goods. Furthermore, every finished good contains two or three unique packaging materials. These aren't shown for the purpose of readability of the graph.

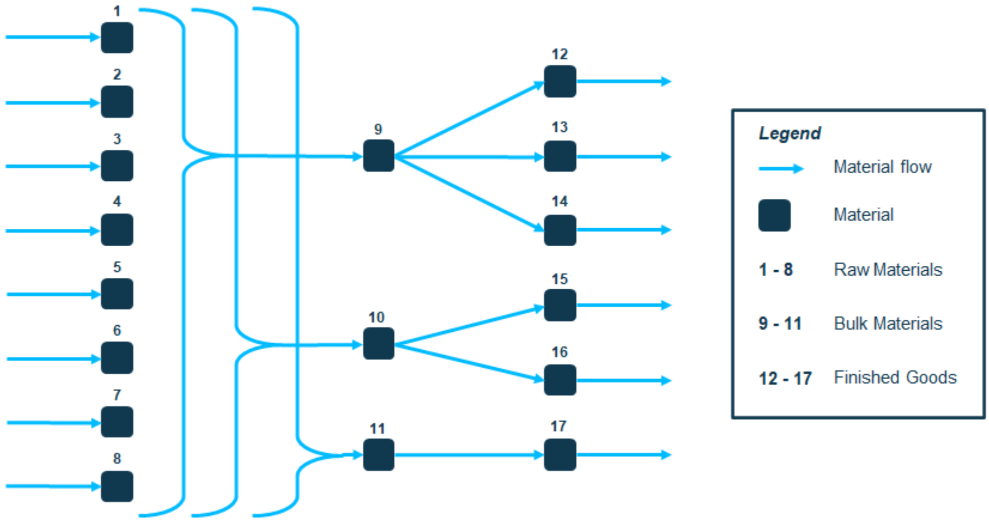


Figure 4: Material Flow for End-Items

Note that the bulk materials (item 9-11) are created from exactly the same set of raw materials (item 1-8), but that the quantities within the BOM differ. Thus, this leads to the production of three different bulk materials (item 9-11). Consequently, these three bulk materials are used in different amounts and/or combined with packaging materials to result in unique finished goods (item 12-17).

1.4 Research Approach

The research approach provides an overview of how the research project is carried out. Firstly, the regulative cycle by Aken, Berends, and Bij (2007) is explained which is used a guide to solve the business problem. Next, the process of collecting the data is described.

1.4.1 Regulative Cycle

The research approach is based on the Problem-solving Cycle by Aken et al. (2007). As shown in Figure 5, the cycle consists of five steps and is triggered by having a *Set of Problems* in a business. The first step is defining the problem based on the set of problems. The second step includes the *Analysis and Diagnosis* of the problem. The problem and its causes are in this step identified and validated. The third step of the cycle is the *Design of the Solution*. Here, a model is introduced and developed based on the results of step two and the literature study. The fourth step of the model includes the *Intervention* in the business. This means that the model is implemented. Finally, the fifth step focuses on *Evaluation* of the intervention to check the performance of the model. Thus, the main research question is answered in this part. Furthermore, based on the evaluation, the limitations of the model are identified, the recommendations for the organization are presented and an overview of interesting future research opportunities is provided.

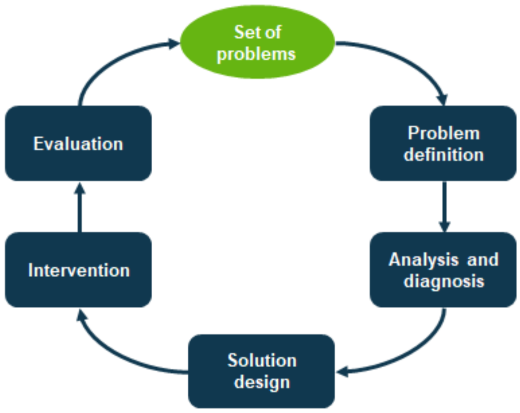


Figure 5: Problem-solving Cycle (van Aken et al., 2007)

1.4.2 Data Collection

The sub-questions are answered with the help of qualitative and quantitative data about the supply chain processes of LSC. The qualitative information is collected via interviewing relevant employees. The interviews are used to improve the understanding of the processes and revealed more practical details about processes not captured in data. By doing so, the full picture of the supply chain and its processes becomes available. The quantitative data is retrieved from the organization's database. The organization stores its financial and operational data centrally in their Enterprise Resource Planning (ERP) system. The maintenance and updating of the data is done by the manufacturing sites, the headquarters and the local affiliates in the countries.

1.5 Report Outline

This section is concluded with a brief summary of what has been presented and an overview of the remainder of this report. Firstly, the project has been introduced by the *Problem Context* and the *Problem Description*. Subsequently, the *Research Scope* including the research questions are defined, followed by the *Research Approach*.

The rest of the report starts with an overview of the key-literature for this project presented in Section 2. Next, the specific analytical models are in more detail in Section 3 described. This is followed by defining the details of the case study in Section 4. The results of the case study are presented in Section 5 and more in-depth discussed in Section 6. Finally, the main- and sub-research questions are answered in Section 7 leading to the final conclusion of the project.

2 Literature Review

The balance of supply and demand requests planning of decisions because demand is often uncertain. The outcome in general comes with misalignment within the supply chain planning process. Organizations try to resolve this issue by keeping inventory for their products. According to a study by De Kok et al. (2018), there is a scientific basis for a quantitative relationship between Multi-Item Multi-Echelon (MIME) inventory systems and the service towards the final customer. Adequate inventory management allows to achieve a customer service which is consistently on the preferred level. Therefore, the available literature of this field is explored and analyzed. Firstly, the concept of MIME Inventory Control is outlined. Next, three approaches within this field - Guaranteed Service, Stochastic Service and Synchronized Base Stock Policy- are discussed in more detail. They are reviewed in terms of their objectives, assumptions and conclusions and assessed on their applicability in a real-world industry.

2.1 Multi-Item Multi-Echelon Inventory Control

The field of MIME Inventory Control has a relationship with the field of Supply Chain Operations Planning (SCOP). The objective of SCOP is *"to coordinate the release of materials and resources in the supply network under consideration, such that customer service constraints are met at minimal cost"* (T. de Kok & Fransoo, 2003). The restrictions on materials and resources are simultaneously considered when coordinating the decisions regarding releasing materials and resources. The coordination of the decisions includes the timing (when to release materials) and the quantity (how much to release)in the supply network. Different activities take place in this network of nodes to transform the input into output. One can distinct three different activities (T. de Kok & Fransoo, 2003):

- Manufacturing activities. These activities include physically transforming the inputs into output.
- Transportation activities. These activities include moving outputs to another location.
- Planning activities. These activities include all required administrative actions to enable the two other activity types.

Manufacturing and transportation activities are seen as transformational activities. These are in general well-defined processes within organizations. Therefore, related aspects of these activities, such as the processing times, process yields and resource requirements are relatively easy to determine. Nevertheless, these activities incorporate the uncertainty of processes which result in a lead time of an order. The lead time is made up from the processing and waiting times around a transformational activity and is known as the concept of *planned lead time* (T. de Kok & Fransoo, 2003).

Inventory control models require assumptions and conditions to result in a feasible solution. The problems are often modeled with mathematical programming and assumptions and conditions are necessary to develop tractable (convenience of obtaining a mathematical solution) models. The difficulty with MIME models is considering the availability of child- and parent-items, especially when items have a high level of commonality with respect to end-items (De Kok et al., 2018).

Another planning and control concept concerned on this topic is the material requirements planning (MRP) logic. This logic is basically a method to determine which quantity of an item is required to produce an end-item and it is often applied in real-world industries. The master production schedule (MPS) translates the release plan for the end-item order into a set of requirements for upstream items in the production process. It does so via the so-called explosion process where the Bill Of Materials (BOM) is the starting point. Together with nominal lead times, safety stocks and lot sizing policies, a scheduled receipts plan for the product is created. The downside of this approach is that the explosion process sometimes leads to infeasible orders (De Kok et al., 2018).

When applying the SCOP constraints to the MRP logic, it is important to understand that the SCOP assumes that demand for items is never backordered. The releasing of items should be managed in such a way that items can only be used in transformational activities when they are actually available. The reason for this is that when demand is backordered, it implies more materials were released than physically available. It seems that the MRP logic does not consider actual item availability when applying the SCOP constraints which is a violation of the constraints. This is a disadvantages for the supply chain planning process for end-items that are developed with many different components. Therefore, MIME inventory control has an advantage over the MRP logic as it does consider the availability of all item-types in a supply chain (T. de Kok & Fransoo, 2003).

2.1.1 Approach Characteristics

MIME inventory systems are supply chain networks with multiple echelons (stocking points) for multiple items. The systems can have a serial, divergent, convergent structure or be a combination of structures. See Figure 6 for an overview of the different network structures. Serial systems (a) have exactly one single predecessor and successor, but these structures barely exist in practice. Divergent systems (b) have a single predecessor and one or more successors. These systems are known as distribution networks. Convergent systems (c) have a maximum of one predecessor and one or less successor(s). These systems are referred to as assembly systems. The other structures (d,e) are a mixture of the ones mentioned and are found most often in practice (Eruguz, Sahin, Jemai, & Dallery, 2016).

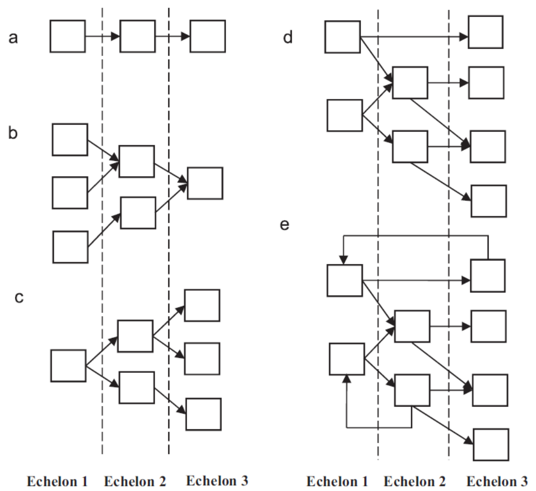


Figure 6: Network structures for multi-echelon models (Eruguz, 2016)

Furthermore, when considering an end-to-end supply network, two concepts play an important role in the planning process. The first one is the allocation of materials, such that the availability restrictions set by the production process are followed. The second one is the synchronization of all the processes, such that orders are released not too early or -late. The general network structures, with their interacting stocking points, make considering the concepts of allocation and synchronization a complex and challenging activity (De Kok et al., 2018). Independent from the structure, one can distinguish three different item types in these supply networks. These are child-, parent- and end-items. The end-items represent the final product of your supply chain processes. A parent-item is an item which is created from one or more items of further upstream stages in the network. The items coming from these stages further upstream are known as child-items. See Figure 6 (b) where e.g. Echelon 3 represents the end-item, Echelon 2 the parent-items and Echelon 1 the child-items (Eruguz et al., 2016).

Furthermore, one can distinguish two types of inventory control policies: installation policies and echelon policies. Installation policies consider only their own inventory position where echelon policies consider not only their own stock, but also the stock of stages more upstream the chain. The inventory position is equal to the inventory on hand at a stage plus the items in the pipeline to that same stage (Axsäter, 2003). See Figure 7 for a graphical explanation of the echelon concept by Van Houtum (2006). Thus, the difference between the two is that with an installation policy, only local available information is used regarding material availability. With an echelon policy, information regarding material availability in the end-to-end network is considered.

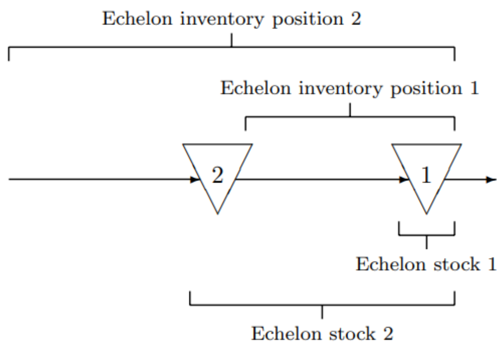


Figure 7: Concept of echelon policy (van Houtum, 2006)

According to De Kok et al. (2018), modeling a MIME inventory control system is complex due to presence of many stochastic variables and the structure of the BOM with respect to all the relationships between items. The systems review the inventory continuously or periodically. The latter of the two is usually cheaper to operate and more practical in case of fast moving items. Before deep-diving into MIME inventory control policies, the concept of echelons is briefly explained first.

2.1.2 Echelon Concept

The echelon concept for general network structures is described by T. de Kok and Fransoo (2003). The network consists of two groups of stages, end stages (E) and non-end stages (I) and includes a safety stock parameter of item i (V_i). The following model is defined:

$O_i(t)$ Cumulative amount of orders outstanding at the start of period t.

Subsequently, the net inventory ($J_i(t)$), the echelon inventory stock ($X_i(t)$) and the echelon inventory position ($Y_i(t)$) computed recursively for item i are defined:

$$X_i(t) = J_i(t), \quad \forall i \in E \tag{1}$$

$$Y_i(t) = X_i(t) + O_i(t), \quad \forall i \in I, E \tag{2}$$

$$X_i(t) = J_i(t) + \sum_{j \in V_i} Y_j(t), \quad \forall i \in I \tag{3}$$

The echelon inventory position represents here the coverage of future demand for any item i for the period until item i becomes available for customers. The interpretation of this is important for the rest of the report. The reason is that the interpretation determines how to synchronize the process of releasing orders in the situation where child-items are used for the production of end-items (T. de Kok & Fransoo, 2003).

Multi-echelon models are in practice often general networks; not purely serial, convergent or divergent. These systems ask for more complex approaches, requiring simplifications and strong assumptions, such that the allocation problem can be solved. The result is on one hand that these models lack rigor, but on the other hand they are successful when applied in practice (Graves & Willems, 2003b). The controlling of these supply chain processes in real world applications keeps being a challenge. Bertrand (2003) stated that flexibility has become the fourth most interesting performance indicator for supply chains after costs, quality and reliability. MIME inventory control models are recognized as providing a form of short-term flexibility in supply chains. More specifically, depending on the control policy, customer demand is met in a particular way. The control policies are based on different assumptions and therefore, different approaches exist. Hence, these approaches are more extensively discussed in the following sections.

2.2 Guaranteed Service Approach

Graves and Willems (2003b) extensively studied the placement of safety stocks along the supply chain and optimal configuration of the chain, such that costs and capital are minimized. They discuss the approach of guaranteed-service models where each stage guarantees the provision of service to the downstream stage. The upstream stage sets a service time to the downstream stage and has to keep sufficient inventory, such that the stage can satisfy the service time commitment. It is assumed that the arriving customer demand is bounded, such that a guaranteed service time can be quoted. As demand is bounded, the inventory on stock is finite as well. The consequence of guaranteeing the service time is that the lead time becomes predictable and deterministic. This allows to develop tractable models for solving safety stock optimization problems.

Note that the approach is based on the assumption that the amount of safety stock is sufficient to meet a part of the bounded demand. The approach is indifferent about what happens if the situation in practice occurs where actual demand exceeds the set demand boundary. In practice this results in the assumption that additional measures are taken to handle such a situation, outside of the general safety stock policy (Graves & Willems, 2003b). This matter is further discussed later in Section 2. First, the general Guaranteed Service approach is presented.

2.2.1 Model Description

Simpson (1958) laid the foundation of the multi-echelon safety stock approach. He developed a model which aimed at optimal allocating safety stock along a serial supply chain. The model assumed that the service times to the downstream stage and by the upstream stage are equal to each other. Therefore, the service time becomes a decision variable - one can determine the optimal safety stock allocation can by finding the optimal service times in the chain.

External customer demand at stage i is met from the inventory (I_i) if greater than zero. In the case there is no inventory available, a backorder for the item is created to supply it when more inventory arrives. The stage commits to fulfilling the order with a specified time, the service time (S_i). The operational time required to fulfill this order, such as obtaining the raw materials from an upstream stage, is represented by the processing time (T_i). The lead time (L_i) is then the upper-time limit for fulfilling the order, which is the sum of the service and processing time.

$$L_i = S_{i-1} + T_i, \quad (i = 1, \ldots, n) \tag{4}$$

The demand at stage i is represented by D_i and has a standard deviation of σ_i. According to the author, it is unnecessary to assume a distribution, and therefore, $\sigma_i(1)$ represents here the deviation of demand over a single unit of time. One can choose a service factor k_i based on the desired service level. Finally, one can compute the amount of safety stock with Equation 5.

$$I_i = k_i \sigma_i(1) \sqrt{L_i - S_i} \tag{5}$$

The bounded demand is equal to the average demand during the lead time minus the service time. Therefore, the order-up-to level represents the expected safety stock level with the service time as the decision variable.

$$D_i\left(L_i, S_i\right) = \mu_i\left(L_i - S_i\right) + k_i \sigma_i \sqrt{L_i - S_i} \tag{6}$$

To ensure the tractability of the model, the author found that following condition should always be satisfied. That is, the outbound service time should be smaller or equal than the inbound service time. Furthermore, the outbound service time should be smaller than the sum of all processing times up to that stage. Otherwise, the situation could occur that an upstream stage cannot guarantee the service to a stage further downstream.

$$S_i \leq S_{i-1} + T_i \leq \sum_{j=1}^{j=i} T_i \tag{7}$$

The function is concave downward where the function's minimum value occurs exactly at a vertex, a corner point of a polygon. This implies that one only has to review a relatively small number of nodes to check which node in the chain provides the service the most efficient as it only had to check the vertices, namely 2^{N-1}. Here is N the number of operations in the serial system - e.g. with three operations, one has to examine only four nodes.

Following the work of Simpson (1958), many models were developed to determine the optimal safety stock allocation in other supply chain structures. Reference is made to the work by Inderfurth (1991) for assembly networks, to Inderfurth and Minner (1998) for distribution networks and to Graves and Willems (1996, 2000) for spanning trees. The work by Graves and Willems (2000) where they developed an optimization algorithm for the strategic allocation of safety stock in supply chain networks is highlighted. More specifically, the algorithm applies to networks modeled as spanning trees and are subjected to uncertain demand. Spanning trees have a structure of general networks and these networks resemble best real-world supply chains (Willems, 2008). To realize a tractable model, three assumptions are made. The first one is that that stages in the network follow a base-stock policy where they review periodically demand from external customers or downstream stages. The second one is that the demand is bounded and the third one is that every upstream stage sets a guaranteed service time to its downstream stages (Graves & Willems, 2000).

A network consists of a set of nodes (N) representing the supply chain stages. The nodes are connected to each other by a set of arcs (A). Together they represent the graph G of the network with $G = (N, A)$. Demand (D) is assumed to be stationary with for every period mean μ and standard deviation σ. Furthermore, demand only arrives at stages at the end of the supply chain. The upper bound of demand is usually a reflection of the non-stock out probability over a specified time period. Let again the lead time (L) be equal to the service time (S) plus the processing time (T). The inventory holding cost at end-stage i per unit (h_i) is there to model the problem. In Equation 14, Problem P represents the optimization problem with the objective to minimize the safety stock holding costs by finding the optimal service times. The problem is subjected to four constraints. Equation 15 ensures that the net replenishment time is non-negative. Equation 16 states that the service time of an upstream stage must be equal or greater than the service time to a downstream stage. Equation 17 with the upper bound for the service time (s_i) assures the guaranteed service time. Equation 18 makes all service times positive integers. As a result, the following model was defined.

$$\mathbf{P} \min \sum_{i=1}^{N} h_i \left\{ D_i(L_i - S_i) - \mu_i(L_i - S_i) \right\} \tag{8}$$

$$\text{s.t. } L_i - S_i \geq 0 \quad \forall i \in N \tag{9}$$

$$L_j \geq S_i + T_j \geq 0 \quad \forall (i, j) \in A \tag{10}$$

$$S_i \leq s_i \quad \forall i \in E \tag{11}$$

$$S_i \geq 0 \text{ and integer} \quad \forall i \in N \tag{12}$$

The problem can be solved with a dynamic programming algorithm for general systems. As preparation, two steps have to be completed. First, the nodes of the spanning tree are labeled in a particular way, such that sub-networks of nodes are created. Second, two functional equations are defined from which one is evaluated based on whether the adjacent node is upstream of downstream. The functions are the minimum holding costs for safety stock under the inbound or outbound service time of the respective sub-network of nodes. After this, executing the last steps of the algorithm will lead to finding the optimal service times for the network. The complexity of the algorithm is bounded to the order of NM^2. Here, N represents the number of nodes in the network and M is the upper limit of the service time, given by $\sum_{i=1}^{N} = T_i$ (Graves & Willems, 2000). Later, an erratum was released by the authors where they corrected a mistake in the dynamic programming algorithm and presented a new function to compute the minimum inventory holding cost for a sub-network (Graves & Willems, 2003a).

2.2.2 Model Extensions

The initial work by Simpson (1958) has led to much more research on the field of the guaranteed service approach. Eruguz et al. (2016) conducted a comprehensive literature review on guaranteed service models and their extensions. The articles are reviewed along three different axis, the considered assumptions, solution methods and industrial applications and results. The model extensions were developed with the aim to better capture the characteristics of real-world supply chains. The most interesting and relevant extensions are selected, summarized and discussed briefly. To structure the summarizing and discussing, the model extensions and their relaxations on assumptions are group in six different pillars. These are *External Demand*, *Lead Times*, *Capacity Constraints*, *Service Times*, *Replenishment Policies* and *Additional Measures*.

External Demand
The general guaranteed service model assumes that arriving demand is stationary and bounded. Graves and Willems (2008) present an extension on their earlier work where they consider demand to be non-stationary. The extension includes that under specific conditions, the optimization problem and its solving algorithm for stationary demand-problems is also applicable to problem with non-stationary demand. The outcome is a strategic and optimal allocation of safety stocks. Furthermore, Inderfurth and Minner (1998) developed an approach where the upper bound is developed with a modified fill-rate service measure. Other approaches also derive a demand upper bound based on relevant service measure, best known as the cycle service level. However, their approach bases the upper bound on the expected unsatisfied demand and the average demand in a specific time period.

Lead Times
One key assumption for guaranteed service approaches is that lead times are known and constant. However, multiple relaxations are developed where instead of deterministic lead times, stochastic lead times are considered. Inderfurth (1993) was the first one to explore this direction. He proposed a model for a multi-echelon safety stock system with a general structure by classifying stages as a demand- and non-demand stage and applying the single-echelon concepts. The downside of this approach is the requirement of two distinct service levels for both demand and lead time. The approach also resulted in higher safety stock quantities kept at the stages and therefore, the approach was improved by Minner (2012). With a concave objective function, he assumed a serial system and defined an approach with only a single service level, such that the model's complexity decreases. Finally, Humair, Ruark, Tomlin, and Willems (2013) proposed another approach for multi-echelon supply chains with a general structure and stochastic lead times. They express the shortfall - the difference between the cumulative replenishments and shipments - which is a stochastic variable due to random demand. When the shortfall is greater than the base stock level at a node, there is a stock-out situation. Therefore, the required safety stock level for a stage can then be determined if the shortfall is positive. This positive part can be approximated with the normal distribution. However, they also incorporated the option where stock arrives early because the inbound service time is smaller than the outbound service time. The result is that a stage keeps additional inventory, on top of their regular safety stock. The authors included this in the objective function by considering both the costs for safety and early arrival stock. In specific situations, this might lead to the undesirable situation where the objective function becomes non-concave and non-differentiable.

Capacity Constraints
The first generation of guaranteed service models assumed infinite capacity for processing or storing products at stages. However, this might not be the case in a real-world supply chain. It seems that there has been less research on relaxing this assumption. Sitompul, Aghezzaf, Dullaert, and Landeghem (2008) was one of the first to try to relax the assumption. The result was only approximate and the findings are based on a limited set of simulations. Furthermore, Schoenmeyr (2008) tried in the same year to overcome this assumption. He proposed a so-called censored order policy where stages have the possibility to reduce the order size if the required size is bigger than the capacity of that stage. However, the numerical experiments conducted showed that the policy is not always optimal for MIME models of the Guaranteed Service Approach.

Service Times
The original guaranteed service model states that service times are constant. This assumption has advantages and disadvantages for the quality of the solutions. The advantage is that it makes the model less complex, increases computational speed and leads to a consistent allocation of the safety stocks (Neale & Willems, 2009). The disadvantage is that in case demand is non-stationary, the solution can be sub-optimal (Graves & Willems, 2008). Thus, a general improvement of the model would be if one would consider individual customers and determine their specific service times (Graves & Willems, 2000). Other model extensions in this area, such as the ones by Minner (2012) for distribution systems and the even further extended model formulation by Grahl, Minner, and Dittmar (2016) for general acyclic systems are considered as irrelevant. The increase in model complexity results in a significantly longer computational time which leads to an out of proportion improvement in terms of inventory costs. Therefore, these models are less applicable in practice and are not further discussed.

Replenishment Policies
The replenishment policy of a stage in a guaranteed service model is assumed to review stock periodically and follow a constant base stock policy. The most interesting extension in this area is the model proposed by Bossert and Willems (2007). They distinguished different replenishment policies based on the specific stage in the supply network. The policies include a constant and adaptive base stock policy and a set of constant targets for safety stocks. Furthermore, they integrated the specific review period and the lead time of every stage with each other. This allows the model to capture the inventory dynamics better and results in a significant reduction of the inventory levels. Subsequently, it leads a decrease of the inventory costs.

Additional Measures
Models of the guaranteed service approach are in general indifferent about what additional measure include in the case where demand exceeds the set upper-demand bound. The measures can be classified as either improvements of the process at the stage or utilizing external resources. The former includes actions such as the making use of over-time or increase production speed and is available for the bounded-part as well as the exceed of the demand (Chen & Li, 2015). The latter includes e.g. the outsourcing of activities and is only available for demand that falls within the pre-specified demand boundaries (Eruguz, Jemai, Sahin, & Dallery, 2013). However, the impact of these additional measures is not clearly demonstrated. Therefore, extensions of this sub-field are not further discussed.

Furthermore, a number of solution approaches are discussed based on what kind of supply network they consider and how their objective function looks. Simpson (1958) showed that his approach for serial systems includes an optimal solution property with solutions only on the extreme points. In practice this means that the allocation assigns no or sufficient safety stock to a stage, such that it becomes decoupled from the stage downstream. This all-or-nothing property for every stage can also be generalized to distribution networks (Inderfurth, 1991). In another article, Inderfurth and Minner (1998) formulated an optimization problem and they derived the optimal solution properties for serial, assembly and distribution networks. Two other researched structures are general cyclic and acyclic networks. The optimal solutions properties for these network structures are presented by Minner (2001, 2012). He also made a distinction in this work in the case either a distribution- or assembly system structure is dominant in a general acyclic network. The decision space of the problem can be minimized by choosing a forward- or backward-recursion dynamic programming algorithm depending on the case, such that the amount of state variables is limited (Minner, 2012). A different approach for acyclic network structures was used by Magnanti, Shen, Shu, Simchi-Levi, and Teo (2006) where they stated that such problems can be formulated as a sequence of mixed integer programming problems. The consequence of this formulation is that the approach requires a significant amount of computational effort. This is seen as a significant disadvantage for applying the method in a real-world supply chain.

2.3 Stochastic Service Approach

Graves and Willems (2003b) also refer to another approach, the so-called Stochastic Service Approach. The difference with the Guaranteed Service approach is that the Stochastic Service approach incorporates stochastic instead of the deterministic lead times. The approach assumes that inventory is the only way to satisfy customer demand and it is capable of dealing with variability in the supply of materials. The core of this approach is that the system responds the same to arriving demand, independent of the specific demand condition. The demand condition means that there is sufficient inventory on hand or a total stock-out situation. The demand itself is assumed to be stationary and when its observed, a replenishment order is placed at a supplier. Furthermore, the stages are assumed to follow a base-stock policy and have unconstrained capacity.

The approach is best described as follows. All stages in the supply network keep safety stocks according to set service level target, based on the stock-out probability in any period. The upstream stages in the network quote a replenishment time in which they deliver materials from stock to a single downstream stage. However, the upstream stages sometime experience issues with their material suppliers, such that the order by the downstream stage gets delayed. The length of the delay is unpredictable and therefore, the replenishment time becomes stochastic, independent from the processing time. The challenge in the stochastic service approach is how to characterize this stochastic replenishment time, such that the optimal service stock levels for stages can be determined. The groundwork for the stochastic service approach was laid by Clark and Scarf (1960). They developed a framework to determine the optimal purchasing quantity for every echelon in a centrally controlled serial system. By making a number of plausible assumptions to simplify the problem, a recursive computation can be applied on the network which results in an optimal allocation of inventory.

Lee and Billington (1993) experienced that the latest developments in globally-operating businesses resulted in more decentralized control in supply chains. Thus, information about material flows is not centrally available in these networks because of the geographical distance between nodes. Inventory is stored at nodes in the chain, but it is unclear what their exact impact is on the costs and service level. Therefore, the authors developed a model to analyze the problem of how to allocate the inventory in supply chains with decentralized control and to show the related costs and service performance. The supply chain is modeled as a general structured network of nodes where every single node follows a base-stock policy or has a service level target as input. To show the related costs and service performance, a tractable base-stock calculation is presented. The calculation is propagated to stages further upstream, making it a multi-echelon approach. The used base-policy is a function of the replenishment time, including the processing time, unforeseen downtime and random delays. Finally, the authors demonstrated a successful application of their model to a real-world supply chain where they reduce the inventory costs, but meet the desired service level.

Glasserman and Tayur (1995) also considered a supply chain with a decentralized control system and a general network structure. However, they looked at the case where production capacity has a lower- and upper-bound which requires the modification of the base-stock policy. The order size after each period has to be equal or greater than the lower-bound of the production capacity, such that the inventory position rises to the preferred base-stock level. Like Clark and Scarf (1960), first expressions for stage inventories, pipeline inventories and production levels are presented.

Subsequently, they used simulation to develop estimations for the derivatives of the cost function for keeping inventory according to the specific base-stock levels. The derivatives are estimated by using an Infinitesimal Perturbation Analysis. Finally, the cost function's gradient is reviewed to identify the optimal base stock policy and inventory allocation. Glasserman and Tayur applied their model as a verification to a real-world supply chain and managed to find the optimal base-stock levels for the respective system.

Another stochastic service approach was developed by Ettl, Feigin, Lin, and Yao (2000). This work is recognized as a state-of-the-art contribution to the research field of multi-echelon inventory management. The model assumes that individual stages are uncapacitated and operate a continuous reviewed base-stock policy, also known as a $(S-1, S)$ policy. The authors make a distinction here between the nominal lead time and the actual lead time. The nominal lead time is the time quoted by a stage. The actual lead time is derived from the performance measures and also considers the probability of a stock-out at an upstream stage. The stochastic replenishment time is characterized by developing an approximating upper-bound for the expected delay by a supplier using queuing theory (M|M|∞ queue). The delays are assigned a weight which is based on the stock out probability of suppliers. Subsequently, the weights are combined with the nominal lead times to obtain the actual lead times of stages. For a more extensive, mathematical explanation of the model, the article itself is referred to. The intention of the model is on the one hand to provide managers the opportunity to analyze the supply chain performance under a specified base-stock policy. On the other hand, the model is capable of finding the optimal balance between inventory levels and service-level targets. Therefore, based on the intention, one can either find the optimal base-stock levels or simulate performance measures given a specific base-stock policy.

2.4 Synchronized Base Stock Policy

The concept of the Synchronized Base Stock (SBS) policy has similar characteristics as the other multi-echelon safety stock management approaches. However, in comparison to the other approaches, the unique aspect of the SBS policy is that it synchronizes the process of timing the order release and the order quantity. Thus, it uses different assumption regarding the controlling the supply chain processes. The general model includes the BOM, nominal lead times and stochastic demand. The concept uses two of these characteristics as a starting point, the BOM of (end-)items and the cumulative lead times. The BOM translates in the mapping of the items' relationships and required order quantities. The cumulative lead times determine the decision-making processes regarding releasing orders over time to cover the end-item demand (de Kok et al., 2018). Furthermore, the policy is restricted to uncapacitated systems as no models exists in literature for the combination of capacitated systems and stochastic demand (T. de Kok & Fransoo, 2003).

The groundwork for the SBS policy is laid by Rosling (1989) with the development of a base stock policy for pure assembly systems. A decade later, the work is extended to divergent supply chain systems by applying the balance assumption. This assumption includes that at the end of every period, the policy allocates a nonnegative quantity of inventory to every stage, such that all stages face the equal stock out probability (Diks & de Kok, 1998). Consequently, the authors have proven the Generalized Newsboy Equations Theorem and proposed a base-stock policy for optimal allocation. The policy is theoretically capable of computing optimal base-stock levels and determining the optimal inventory allocation. However, the optimal allocation functions are non-linear which results in intractable models. Diks and de Kok (1999) continued their own work by assuming the optimal allocation functions to be linear and managed to derive a generalized form of the theorem. The results of the analysis show that the generalized form generates close-to-optimal policies for divergent systems.

An approach was proposed by De Kok and Visschers (1999) to develop a class of policies for supply chains with a more general supply network structure. This class is based on the rule that the allocation of item quantities has to happen before the synchronization of the decision making process, such as the timing or order release. The system assumes independent and identical distributed exogenous demand for an end-item and an artificial hierarchy is derived from the BOM and planned lead times to synchronize the order releasing decisions over time. The general assembly network structure is transformed into a set of pure divergent or serial systems. The Generalized Newsboy Equations presented by Diks and de Kok (1999) can be applied on the set of sub-systems. This allows one to determine what order-up-to level at a stage is required to meet the target service level constraints. In the case a component is used in multiple different end-items, the required quantities of the different sub-systems are just summed up. Therefore, the result is a close-to-optimal base-stock policy for a multi-item multi-echelon system.

The performance of the synchronized base stock policy was compared with the linear programming approaches on a rolling schedule by T. de Kok and Fransoo (2003). The results showed that SBS policies are superior and result in significant lower average inventory costs on a long-time horizon. More specifically, linear programming approaches tend to store too much inventory at upstream stages because of the minimizing character of the objective function - it aims to avoid the high cumulative costs of end-items. Another aspect in which SBS policies are different compared to other approaches is that they allow to set different service level targets for individual end-items. Furthermore, they highlight the fact that SBS policies are relatively simple in terms of computations. Therefore, the concept of synchronized base stock policies is suitable for applications in real-world industrial supply network systems with many different nodes. An example of an application is the work by De Kok et al. (2005) where it is described how the concept is introduced at Philips Semiconductors to improve the planning of operations.

2.5 Literary Alignment

The literature study aimed to provide an overview of the available literature relevant for the problem of LSC. To conclude the review, a brief summary of the different approaches is presented, followed by the selection of two methods. These methods are used to execute a case study with LSC's data. Finally, overview is closed by the identification of the gaps in literature.

2.5.1 Summary of Approaches

Three different MIME approaches are discussed in Sections 2.2, 2.3 and 2.4. These are the Guaranteed Service Approach, the Stochastic Service Approach and the Synchronized Base Stock Approach. The Guaranteed Service Approach depends on the assumption that demand is bounded and that a stage guarantees it can supply materials to a stage downstream of it. This implies that the service time is deterministic and predictable. Moreover, this provides the possibility to develop tractable models for solving safety stock optimization problems. At a later stage, the general models have been extended to capture more characteristics of the real-world supply chain. The model extensions and their relaxations on assumptions are grouped in six different directions. These are *External Demand*, *Lead Times*, *Capacity Constraints*, *Service Times*, *Replenishment Policies* and *Additional Measures*. The success of these extensions in terms of application and results is variable. Some extensions seem to be promising for application, where for other extensions the proposed models are intractable or the computational time too long.

The second approach discussed is the Stochastic Service Approach. This approach differs from the Guaranteed Service Approach in the way that it incorporates stochastic instead of deterministic lead times. Thus, it is capable of dealing with the variability in supply. Compared to the Guaranteed Service Approach, less models exist in this field. Moreover, the models that exist are in general perceived as more difficult to solve due to their stochastic components. Nevertheless, there are examples of the models being applied to real-world supply chains and lead to a reduction of inventory costs and meeting the desired service level.

The third and last approach to highlight is the Synchronized Base Stock policy. The concept of the SBS policy is based on the BOM of an end-item and the cumulative lead times of processes throughout the whole supply chain. The BOM represents the relationships between items - how much of an item is required. The cumulative lead times determine the decision-making process regarding releasing orders in the chain to cover the end-item demand. The fact that the SBS policy synchronizes the process of timing the order release and the order quantity makes this approach unique compared to the other two approaches. The developed models result all in tractable, close-to-optimal base-stock policies for MIME systems. Moreover, the SBS policies are perceived as relatively simple in terms of the required computational effort. This makes models of this approach interesting for real-world applications.

2.5.2 Approach Selection

The supply chain of the LSC is designed as a Multi-Item, Multi-Echelon network. The supply chain environment is the pharmaceutical industry, bringing additional challenges and complexities to the design and configuration of the network, such as long lead times and challenging production circumstances. Based on the results of the literature analysis, the *Guaranteed Service Approach* and *Synchronized Base Stock policy* are recognized as the most suitable approaches for the LSC's supply chain.

The reasons for choosing these approaches are known to be applicable on real-world supply chains, to lead to inventory costs reductions and to manage to meet the target service level. In terms of financial impact, the applications indicate potential safety stock cost reductions ranging from 25% to 50% (Graves & Willems, 2003b). Moreover, the work by Graves and Willems (2000) provides an algorithm how the *Guaranteed Service Approach* can be applied to real-world supply chain. This is the same case for the articles by Diks and de Kok (1999) and De Kok and Visschers (1999) about the *Synchronized Base Stock Approach*. An example of an application of this approach is provided in the article by De Kok et al. (2005). To conclude, the examples where the concepts are applied lead to the expectation that these two multi-echelon approaches are able to reduce the inventory costs and improve the service levels.

2.5.3 Gap in Literature

From the literature analysis results, a clear gap in literature can be recognized. The gap is that there is an evident lack of real-world applications of MIME inventory control models. Both the *Guaranteed Service Approach* and the *Synchronized Base Stock policy* have proven to be valuable for businesses as they are capable of reducing the inventory costs and improving service levels. Moreover, they make supply chains more flexible and resilient, serving the latest trend in the field of supply chain management (Bertrand, 2003). With the emerging market of online sales via omni-channel organized supply chain, this call for flexibility only becomes stronger (de Kok et al., 2018).

The field of MIME inventory control claims to have a wide range of applications to real-world supply chains. However, from all studies in the research area conducted, less than 5% of all papers can be classified as an actual field study in terms of the methodology. The most likely reason for this is the complexity of these models. From the field studies, the majority is about a supply network consisting only two echelons (de Kok et al., 2018). This conclusion can also be drawn from the work by T. de Kok and Fransoo (2003). They state that there is a lack of empirical validated managerial insights from MIME inventory control applications to real-world supply chains.

In addition to the lack of applications, the review of the field studies shows that it is unclear what makes an application successful. MIME control models require many input parameters to apply them, such as the planned lead time of a process or the standard deviation of demand for an item. The supply chain operations planning is depending on the parameter values like these. To improve the understanding of this matter, consider the following example of planned lead time and lead time adherence. The planned lead time for a process is five days, but the lead time adherence is low and the process takes in reality often more than ten days to complete. This has a major influence on the performance of a company's MIME inventory control system because it could cause stock-out situations due to delayed availability of the required materials. Therefore, it would be interesting to identify what the drivers for good MIME inventory control system performance are.

It is currently still unclear what the specific drivers are, but there an opportunity is recognized to fill this gap in literature - at least for the pharmaceutical industry. Therefore, it is safe to say that the gap in existing literature has been identified. To summarize, the gap includes on the one hand the lack of real-world applications of MIME inventory control systems. This gap is addressed by performing a case study with a real organization to apply the methodology. On the other hand, the gap is the lack of knowing what drives a good MIME inventory control system performance. To address this gap, the model and findings of the case study are challenged and extensively discussed on how generic and transportable they are. Hence, these insights proof that it is worthwhile to conduct this research project.

3 Analytical Models

3.1 Guaranteed Service Model

The supply chain is modeled as a network of nodes or stages N which are linked to each other via arcs A. Every stage in the network is capable of holding inventory and operates according a periodic review base stock replenishment policy. A stage represents a process in the supply chain, such as the sourcing of raw materials or the assembly of an item. The processing time T of a stage is independent of the order size and assumed to be known and deterministic and includes the waiting, processing and transporting time at that stage. The model is based on the assumption that a stage guarantees to deliver each order to a connected stage downstream within the quoted service time. As a result of lead times being deterministic, it is possible to determine the bounds for customer demand. In this setting, every stage becomes a decision node with the quoted service time as a decision variable. The purpose is to find the optimal value for the service time per stage, such that the total safety stock costs are minimized.

3.1.1 Lead Time Coverage

The amount of safety stock placed at a stage is driven by the lead time gap. This works as follows. A stage has to wait with its processing activities until it obtained all required materials from an upstream stage. The time that elapsed is the inbound service time SI_i. The replenishment time of a stage i is then equal to $\tau = SI_i + T_i$. The same stage i quotes an outbound service time S_i to a linked stage downstream. Thus, the net replenishment time is equal to the replenishment time minus the outbound service time, e.g. $SI_i + T_i - S_i$. This is illustrated for a single-echelon concept in Figure 8.

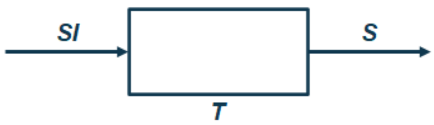


Figure 8: Guaranteed Service Model Single-Echelon Concept (Snyder & Shen, 2019)

The net replenishment time is the lead time gap in the supply chain process. This gap should be covered with safety stocks to protect the supply chain against variability in customer demand. To avoid the early arrival of unnecessary inventory, the net replenishment time must be non-negative ($SI_i + T_i - S_i \geq 0$).

3.1.2 Bounded Customer Demand

Customer demand can only occur at stages that have no successors. These stages are termed demand nodes or demand stages. The demand for end-items is assumed to be stationary with average demand μ per period τ and standard deviation σ.

$$D(\tau) = \mu\tau + k\sigma\sqrt{\tau} \tag{13}$$

In this setting, k reflects the safety factor how the variation in demand is covered. In other words, the demand variation per period τ is assumed to not be greater than $k\sigma\sqrt{\tau}$ as mean demand is equal to $\mu\tau$. In case actual demand exceeds the demand bound, it is assumed that additional measures outside the model are taken to deal with this. These measures can for example be the outsourcing of production of produce during overtime.

3.1.3 Basic Model Description

The basic model is based on a supply network with the form of graph G where $G = (N, A)$. The maximum replenishment time M_i at stage i is equal to the longest potential path leading to it. This is the case when every stage before i quotes its maximum outbound service time. Furthermore, the holding costs per unit are represented by h_i. As a result, optimization problem **P** is defined to find the optimal service times:

$$\mathbf{P} \min \sum_{i=1}^{N} h_i \left\{ D_i(SI_i + T_i - S_i) - \mu_i(SI_i + T_i - S_i) \right\} \tag{14}$$

$$\text{s.t. } SI_i + T_i - S_i \geq 0 \quad \forall i \in N \tag{15}$$

$$SI_i - S_j \geq 0 \quad \forall (i,j) \in A \tag{16}$$

$$S_i, SI_i \leq s_i \quad \forall i \in E \tag{17}$$

$$S_i \geq 0 \text{ and integer} \quad \forall i \in N \tag{18}$$

In words, the equations mean the following:

- Equation 14 expresses Problem **P** which represents the optimization problem with the objective to minimize the safety stock holding costs by finding the optimal service times. The problem is subjected to four constraints defined as Equations 15 - 18 where:
- Equation 15 ensures that the net replenishment time is non-negative.
- Equation 16 states that the service time of an upstream stage j must be equal or greater than the inbound service time of a downstream stage i.
- Equation 17 assures the guaranteed service time with upper bound s_i for the time.
- Equation 18 makes all service times positive integers.

3.1.4 Solution Method

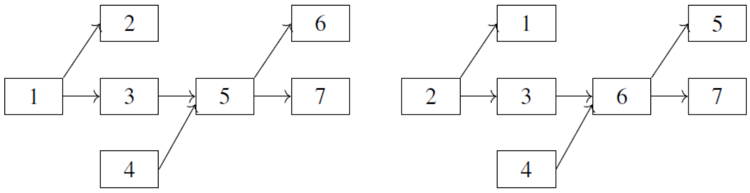
The problem of how to allocate safety stocks is solved by computing all possible combinations of the service- and processing-times and the related local costs for the stage itself and connected stages upstream and downstream. From all options, the allocation with the lowest overall cost for the defined supply chain determines where to place the safety stocks. To solve the problem for tree systems, a Dynamic Programming (DP) approach is used. This approach has due to the tree network structure two key-steps. The first one covers determining the order of stages for solving the DP. The second one includes how to deal with the complexity in computing the costs of a specific decision since one stage may have multiple related stages up and/or downstream which are affected by the decision.

The structure of DP recursion is determined by applying a relabel algorithm. The algorithm ensures that each stage except the final stage N has exactly one neighboring stage with a higher label.

Relabel Algorithm

1. Initialize with an unlabeled set of nodes $\{1, ..., N\}$
2. $LS = \emptyset$, $US = \{1, ..., N\}$
3. For $k = 1, ..., N$:
4. Pick $i \in US$ such that i is adjacent to at most one other node in US
5. Label node i with index k
6. Remove node i from US and insert at LS
7. Stop when set US is empty

An example of how the relabel algorithm works is shown in Figure 9.



(a) Original network.

(b) Relabeled network.

Figure 9: Example Relabel Algorithm (Snyder & Shen, 2019)

The functional equations are used to evaluate the costs of decisions taken at a stage. The order in which the costs are computed depends on the label given to a stage by the relabel algorithm. Therefore, we determine first for a given stage k in the range of $k = 1, ..., N-1$ which stage with a higher index is adjacent to k. This stage is represented by p_k. The decision at k does not only influence the costs at the stage itself, but also the linked stages with lower labels. Let these nodes be represented by sub-network N_k where $N_k = 1, 2, ..., k$ and which can be found with Equation 19.

$$N_k = \{k\} \cup \bigcup_{\substack{(i,k)\in A \\ k,k}} N_i \cup \bigcup_{\substack{(k,j)\in A \\ j<k}} N_j \tag{19}$$

The second step to solve the problem is to define the functional equations. The equation exist in two forms, $f_k(S)$ and $g_k(SI)$. Which one of the two functions is computed, depends on whether p_k is upstream or downstream of stage k. For stages where p_k is downstream of k, the decision is made for the outbound service time S with functional equation $f_k(S)$.

$$f_k(S) = \min_{SI} \{c_k(S, SI)\} \tag{20}$$

$$s.t. \max(0, S - T_k) \leq SI \leq M_k - T_k \tag{21}$$

Here, SI must be integer and M_k as the maximum replenishment time at stage k. For stages where p_k is upstream of k, the decision is made for the inbound service time SI with functional equation $g_k(SI)$.

$$g_k(SI) = \min_{S} \{C_k(S, SI)\} \tag{22}$$

$$s.t. 0 \leq S \leq SI + T_k \tag{23}$$

Again, SI must be an integer. Furthermore, if k is a demand stage, then S is set equal to s_k. Consequently, having defined the functional equations, the cost function is presented.

The expected holding costs for a sub-network N_k is a function of both S and SI. The function $C_k(S, SI)$ contains three terms where the first one denotes the local expected holding costs at stage k. The second term represents the holding costs of the stages in N_k upstream as a function of inbound service time SI. The third term corresponds to the holding costs of stages in N_k downstream and is a function of outbound service time S.

$$\begin{aligned} C_k(S, SI) = & h_k z_\alpha \sigma_k \sqrt{SI + T_k - S} \\ & + \sum_{\substack{(i,k)\in A \\ k<k}} \min_{0 \leq x \leq SI} \{f_i(x)\} \\ & + \sum_{\substack{(k,j)\in A \\ j<k}} \min_{S \leq y \leq M_j - T_j} \{g_j(y)\} \end{aligned} \tag{24}$$

The original cost function by Graves and Willems (2000) slightly differed from the one above. The authors initially falsely assumed that $f_k(S)$ is non-increasing in S and that $g_k(SI)$ is non-decreasing in SI. This was later corrected via the releasing of an erratum (Graves & Willems, 2003a; Humair & Willems, 2011).

The DP is solved with an algorithm for spanning trees. The minimization of the functional equations is done with enumeration which includes computing all possible combinations for S and SI. The optimal solution is then found by applying a standard backtracking procedure. The result is the optimal set of service times for the whole supply network which leads to the lowest costs.

Dynamic Programming Algorithm

```
for k := 1, ..., N − 1
    if p_k is downstream of k
        for S = 0, 1, ..., M_k
            Compute f_k(S)
    if p_k is upstream of k
        for SI = 0, 1, ..., M_k − T_k
            Compute g_k(SI)
for k := N
    for SI = 0, 1, ..., M_k − T_k
        Compute g_k(SI)
Minimize g_N(SI) to find SI*
```

The optimal objective function value SI^* enables to find all other optimal values for S^* and SI^* in the network. The final step is then to plug in the set of optimal values in Equation 25 to determine the amount of safety stock required at stage i.

$$z_\alpha \sigma_i \sqrt{SI_i + T_i - S_i} \tag{25}$$

The respective expected holding costs of the safety stock at stage i is then computed with Equation 26.

$$h_i z_\alpha \sigma_i \sqrt{SI_i + T_i - S_i} \tag{26}$$

To summarize, the expected holding costs at each stage for sub-network N_k are computed as a function of the decision variable S or SI. Which state variable is used, depends on the direction of the arc between two nodes. The functional equation $f_k(S)$ or $g_k(SI)$ is then repeatedly computed and evaluated until the dynamic program reaches the final stage N. At this stage, the expected holding costs for the entire supply chain network are computed as a function of SI. Finally, the inbound service time for stage N is optimized to find the optimal set of service times for the network. This set of values serves then as input to compute per stage how much safety stocks are required and what the respective expected holding costs are.

3.1.5 Reflection GS Model

The explanation of the Guaranteed Service Model is concluded with a brief reflection on the method. The first comment is regarding the assumption that lead times are known and deterministic. This assumption forms the foundation of the model, but is questionable in the setting of a real-world supply chain. As stated in De Kok et al. (2018), dealing with variability in the supply chain is inevitable. Thus, lead times are in reality always stochastic. On the contrary, if the actual service level achieved for supplying internal stages and customers is close to 100%, the safety stock proposal should be accurate enough to work in the real-world setting.

Furthermore, the deterministic lead times allow to set bounds for customer demands. This assumption is seen as controversial when considering literature on stochastic-demand inventory management models (Graves & Willems, 2000). In addition, if actual demand exceeds the demand bound, the placed safety stock will be insufficient. The model is indifferent about what happens then, but most likely managers will have to take extraordinary measures to meet the excess. However, situations in the real-world exist where demand for end-items is bounded in a natural way. For example, when a stage forms a bottleneck for the supply chain, the capacity constraint forms a demand bound. Finally, the authors of the method also recognize the strength of this assumption. They state that the purpose of the assumption is to provide guidance to managers to find the optimal tactical position of safety stocks in the supply chain. Therefore, their aim is to make the challenge of material and safety stock coordination throughout a supply chain easier (Graves & Willems, 2000).

Finally, the reflection is concluded with the remark that an important characteristic for being an inventory control policy suitable for the real-world supply chain is how to handle in material shortage situations. The Guaranteed Service Model is indifferent about allocating materials in case insufficient materials are available for all successor-items (De Kok et al., 2018). Furthermore, the likelihood of a company adhering to the quoted outbound service time $S > 0$ is questionable. More specifically, whether or not a company will wait with shipping an order if all materials are already available (Peeters, de Kok, Martagan, & Atan, 2020).

3.2 Synchronized Base Stock Model

In the real-world, lead times are stochastic which is in contrary of the deterministic lead time assumption in the GSM. Thus, for stochastic models is keeping safety stock the only option to deal with the supply chain uncertainty (Klosterhalfen & Minner, 2010). In this setting, arriving customer demand is served directly from the available inventory within the replenishment time. However, when a stock-out situation appears, the serving of demand is delayed with a varying amount of time. This stochastic delay turns the replenishment time into a stochastic variable, independent from whether the processing time is deterministic. The Synchronized Base Stock Policy incorporates these stochastic lead times with the probability for a stock-out situation as an input parameter. The policy was proposed in T. de Kok and Fransoo (2003) and forms the basic model of the ChainStock software tool (T. de Kok, 2008).

3.2.1 Basic Model Description

The groundwork of SBS was laid by the initial development of an optimal policy for pure assembly systems (Rosling, 1989). Later, De Kok and Visschers (1999) extended this policy to solve material coordination problems for MIME systems which led to the definition of the SBS policy. The difference between the model described by De Kok and Visschers (1999) and the one by Rosling (1989) is that the former is able to deal with items that have multiple successors, the latter not. The foundation of the SBS policy is based on two key-characteristics of MIME systems, the introduction of an artificial hierarchy and considering the cumulative lead times. The creation of an artificial release hierarchy is based on the design of the general supply network. The design itself is derived from mapping the BOM relationships between materials. The consideration of cumulative lead times determines the order release decision for items. Finally, the combination of the BOM mapping and cumulative lead times for orders leads to the definition of state variables which guides the item order releases.

The explanation of the model is based on the presentation of the policy in T. de Kok and Fransoo (2003). Before going into detail, an overview of a number of initial variables is provided in Table 3.

Table 3: Variables Synchronized Base Stock Policy

Variable	**Meaning**
i	Item i
j	Item j produced from i
V_j	Set of successors of item i
I	Set of intermediate items
E	Set of end-items

The first step of the model formulation is defining the cumulative lead time L_i^c of an item.

$$\begin{aligned} L_i^c &= L_i, \quad i \in E \\ L_i^c &= L_i + \max_{j \in V_i} L_j, \quad i \in I \end{aligned} \tag{27}$$

Next, the root node s is defined by identifying the first node of a supply network to produce a specific end-item. The identification of the root nodes is the trigger for the appearance of multiple divergent systems. Each time an order for a component must be released to produce an end-item, the root node is identified. In case this item has not been identified earlier because it is for example part of another end-item, the root node becomes another divergent tree of decision nodes for order releases. Thus, by assuming that cumulative lead times are unique, s is different for every end-item.

$$s = \arg\left(\max_i L_i^c\right) \tag{28}$$

In addition, the following restriction should be met to verify a node is the root node. That is, the cumulative lead time of the root node should be longer than the cumulative lead time of any other item.

$$L_s^c \geq L_i^c, \quad i \in I \cup E \tag{29}$$

To structure the order releases, a hierarchical procedure is introduced for end-items in E_s. The hierarchy is derived from the cumulative lead times L_i^c in the network and leads to the definition of item set $\hat{C}_i$. This set is used to structure the order releases for components related to end-items in E_s.

$$\hat{C}_i = \left\{ j \mid L_j^c > L_i^c, E_j \cap E_i \neq \phi \right\} \tag{30}$$

This definition only holds if the restriction is met which states that all components have to be common to end-items in E_i if they are ordered earlier than item i and used in the same end-items as i. See the restriction below.

$$E_j \cap E_i = E_i, \quad \forall j \in \hat{C}_i \tag{31}$$

In case the restriction is not met, there is still a way to apply the rest of the principles the method. A set of elements of E_i is taken and a selection of subsets of $\hat{C}_i$ with one-to-one relations. If the restriction holds for each one-to-one related pair of subsets, the rest of the principles can still be applied to it. Finally, it is defined that set of items $\hat{C}_i$ is equal to (a part of) E_j.

$$E\left(\hat{C}_i\right) = \bigcap_{j \in \hat{C}_i} E_j \tag{32}$$

From this point it is possible to determine the order release quantities for items. The first item is ordered according to the hierarchy from the BOM and logically, this is the item coming from root node s. The ordering happens at the start of an arbitrary period t and is done according to a pure base stock policy, such as the one below. Here, r_s is the release quantity at the root node, S_s the inventory position for future demand for E_i and $Y_s(t)$ the inventory position at time t.

$$r_s(t) = S_s - Y_s(t) \tag{33}$$

After the ordering of items at the root note, the intermediate items i are considered. The most straightforward is to order according a base stock policy. Thus, a quantity of item i is ordered to bring the echelon inventory position up to base stock level S_i, such that future demand for the end-item can be supplied. However, decisions regarding the end-item coverage have potentially already been taken earlierinto account for items $j \in \hat{C}_i$. Therefore, the state variable $Z_{\hat{C}_i}(t)$ is introduced which represents this demand coverage. More specifically, it shows the demand coverage over period $t, t+l, ..., t+L_i^c$ for end-items for items in $E(\hat{C}_i)$.

The reason that decisions are potentially already taken, depends on whether $Z_{\hat{C}_i}(t)$ is completely dedicated to cover future demand for end-items in E_i. Assuming it is fully dedicated, so $E_i =$

$E(\hat{C}_i)$, the target coverage is equal to S_i. Thus, the order release quantity is determined according to Equation 34 below.

$$r_i(t) = \max\left(0, \min\left(S_i, Z_{\hat{C}_i}(t)\right) - Y_i(t)\right) \tag{34}$$

The order release quantity of item i is the maximum of the range 0. The difference between target coverage S_i where $Z_{\hat{C}_i}(t)$ is fully dedicated to item i and the inventory position of item i at time t.

However, the other option is that $E_i \neq E(\hat{C}_i)$ which implies that $Z_{\hat{C}_i}(t)$ is shared by more end-items than in E_i. This creates the complex situation that the order quantity of item i has to cover demand for multiple end-items. In other words, components that are part of $\hat{C}_i$ are ordered while there might not yet be a need to order the other items part of the subset, so $E(\hat{C}_i) \setminus E_i$.

To deal with this situation, an artificial base stock level $S_{E(\hat{C}_i)\setminus E_i}$ is introduced for end-items in $E(\hat{C}_i) \setminus E_i$. The artificial base stock level allows to define the target for future demand coverage $Z_{\hat{C}_i}(t)$ for all items in $E(\hat{C}_i)$. That is, the target coverage equals $S_i + S_{E(\hat{C}_i)\setminus E_i}$.

Finally, the order release policy for item i is defined the following for when the situation occurs that $Z_{\hat{C}_i}(t)$ drops below the target level.

$$r_i(t) = \max\left(0, S_i - q_i\left(S_i + S_{E(\hat{C}_i)\setminus E_i} - Z_{\hat{C}_i}(t)\right)^+ - Y_i(t)\right) \tag{35}$$

Here, q_i represents the part of the deficit which belongs to end-items in E_i. Furthermore, the equation has the same structure as Equation 34. Note that when $q_i = 0$ and $S_i + S_{E(\hat{C}_i)\setminus E_i} = 0$, the situation occurs that an item is not shared by more than one end-item(s).

With the creation of an artificial order-up-to levels, the situation appears where every level relates to a decision node. The height of the level is determined by the unique combinations of sets of items $E(\hat{C}_i)$ and sets of end-items E_i. More specifically, both sets of items are associated with multiple (artificial) order-up-to levels, thus creating multiple decision nodes. When there is an excess in coverage so $Z_{\hat{C}_i}(t) > S_i + S_{E(\hat{C}_i)\setminus E_i}$, it is assumed that this excess is kept and considered for the coverage of future demand for the period after $t + L_i^c$.

To summarize, the SBS policy is based on the combination deriving an artificial release hierarchy from the BOM relationships between materials and their (cumulative) lead times. Firstly, the cumulative lead times are introduced, followed by determining the root node of the network. Next, the set of components is defined which should be considered for a related set of end-items. This set of components represents the hierarchy and determines the order release decisions for an item. To ensure a sufficient coverage of future demand for items, a state variable is introduced which purpose it is to realize the target level for coverage. Finally, based on whether the state variable is fully dedicated to cover future demand of end-items, two equations are presented to guide the releasing of order quantities of components.

3.2.2 Reflection SBS Model

The section regarding the explanation of the SBS policy is concluded with a brief reflection on it. The policy was proposed as an extension of the optimal policy for pure assembly systems (Rosling, 1989; De Kok & Visschers, 1999; T. de Kok & Fransoo, 2003). The extension enabled the application of the methodology also to MIME inventory systems with the structure of a spanning tree. Another well-known work on the concept of synchronized base stock policies is the one by Diks and de Kok (1999). The concept of synchronized base stock policies is here applied to networks with a divergent structure. This requires that allocation rules should be considered in the case of shortages of materials, with multiple options available in literature (A. de Kok, 1990; van der Heijden, 1997; Diks & de Kok, 1998, 1999).

Moreover, it is important to note that SBS policy generates close-to-optimal solutions. This is caused by the situation where future coverage $Z_{\hat{C}_i}(t)$ is allocated in an early stage to item i before having the real need to do so (T. de Kok & Fransoo, 2003). Finally, the last comment is regarding the processing time parameter the ChainStock software tool uses as input (T. de Kok, 2008). That is, ChainStock assumes planned lead times to be deterministic and allows to use the average historical processing time when a company is unable of determining the planned lead time, even though it might have data regarding stochastic processing times available. Possibly, this results in underestimating the required quantity of safety stock (Peeters et al., 2020). For the case study, this is not further taken into account.

4 Case Study

The Guaranteed Service Model (GSM) and Synchronized Base Stock Policy (SBSP) are studied in the setting of a real-world supply chain. The aim is to research whether and/or how a multi-echelon safety stock management approach can reduce of the inventory costs and improve the service levels of LSC. Therefore, additional background information regarding the case is provided in this section. Firstly, the supply chain of LSC and its characteristics are described. This is followed by an overview of the model assumptions and their argumentation and how the methods are adapted to fit the case study. Subsequently, the parameters of the ChainStock software tool are described (T. de Kok, 2008). Finally, the different model scenarios for both approaches are presented.

4.1 Supply Chain of Life Science Company

Three different aspects of the supply chain of LSC are discussed to allow and enable a fair comparison between the currently used approach, the GSM and the SBSP. The aspects are the replenishment strategy, the currently in place inventory control policy and the design of the supply network.

4.1.1 Replenishment Process

The replenishment of materials happens according to the concept of Sales & Operations Planning (S&OP), visualized in Figure 20 in Appendix B. The concept of S&OP aims for the creation of a single integrated set of company plans regarding balancing supply and demand as well as connecting the Sales, Operations and Central Managing entity to each other (Thomé, Scavarda, Fernandez, & Scavarda, 2012). The standard S&OP cycle includes five steps: demand forecasting, demand and supply planning, supply allocation, implementation of the operating plan and performance measurement. The detailed process can slightly differ from the standard based on a company's unique characteristics (Grimson & Pyke, 2007). The standard S&OP cycle is illustrated in Figure 10.

Figure 10: Standard S&OP Cycle (Grimson, 2007)

The S&OP cycle of LSC is nearly identical to the standard process. The steps are executed by the following functions: the local forecast/supply manager, the customer supply manager, the supply performance manager and the manufacturing site's pipeline manager. An illustration showing the supply chain planning process can be found in the form of Figure 21 in Appendix B.

The monthly cycle starts with the creation of a demand forecast at a local affiliate. A local affiliate is an office of LSC in the country of sales. The demand forecast is created by the local country forecast/supply manager using statistical forecasting methods. The initial forecast forms the baseline of the demand and building blocks are added to it or removed. For example, new product launches and products at the end of their life cycle are considered. In parallel, local planned promotions are acknowledged and the demand forecast is fine-tuned by checking local markets for the latest demand signals.

The output is a preliminary demand forecast that is reviewed. This review is the responsibility of the local forecast/supply manager and performed with information from the customer supply manager. Next, the demand forecasts are reconciled based on input from local finance, marketing and product supply teams. The reconciliation can trigger some minimal changes before the forecast is confirmed. Finally, it is uploaded by the local country forecast/supply manager to the SAP Advanced Planning and Optimization (APO) system.

The customer supply manager collects information about the customers during three sets of calls, via the weekly so-called 'drumbeat calls', the monthly supply review meeting and the monthly S&OP meeting. The weekly drumbeat calls are held to check the supply situation for the country's full product portfolio versus the demand signal. Subsequently, during the monthly supply review meeting, the supply situation for the respective country is checked on a higher level. That is, the situation is reviewed for every individual brand. Next, during the monthly S&OP meeting, the supply situation is reviewed on an even higher and broader level since the demand-supply balance is reviewed, such that a final consensus is reached. The discussions about customer demand serve as input for the review of the initial demand forecast. After reconciliation and finalizing of the forecast, a month has passed by. Therefore, the customer supply manager checks then again the latest demand signal provided by the country. In the case that the new demand signal creates problems for the supply chain, the country supply manager gets in contact with the finance, marketing and product supply teams to address these problems and solve them.

The supply performance manager considers for every product the demand forecast the local expired stocks, the local stock-outs and the local safety stock levels. The forecast is modified based on the results of these checks. Subsequently, the net required demand for every product is calculated by the SAP APO system. Next, the supply performance manager checks whether there are any regulatory changes for the products in the forecast. In parallel, maintenance, shutdowns or other factors influencing the production capacity are considered and if required, orders are prioritized. In case of any limitations with one or multiple orders, the supply performance manager reaches out to the local affiliate to resolve and/or prioritize them. In the case that alignment is achieved, the set of production orders is finalized. Subsequently, it is shown in the SAP APO system as so-called 'planned production orders'.

The set of planned production orders serves as input to create a rough cut production capacity plan for the manufacturing site. In the case of constraints on the plan, they are reviewed and the supply performance manager checks how manufacturing can be optimized. When there are no constraints, the set of production orders is handed over to the pipeline manager of the manufacturing site.

The pipeline manager receives a proposal for a production schedule from the SAP APO system. The proposal shows the sequence for orders to be manufactured. It is based on the volume and the related master data of the product in the system, such as the throughput rate and set up time. The pipeline manager reviews the proposal by the system and creates out of this a detailed production capacity plan and detailed production schedule.

Next, the required APIs, Excipients and Packaging Materials are ordered for the production of the Formulations, Intermediates and Finished Goods. The pipeline manager reschedules an order in case the lead time for the components is too long. However, if there are no lead time issues present, the materials are ordered and received. Finally, the product is produced and the process ends.

4.1.2 Inventory Control Policy

The inventory of LSC is centrally managed according to an inventory control policy. This means that the management of safety stock is optimized while considering the end-to-end supply chain network. Thus, the safety stock parameter settings of the individual stages are following an overall approach to minimize the costs in the full. In addition, LSC practices an installation policy to control the inventory. This means that every individual stage only considers its own inventory position which is equal to the sum of the on-hand and pipeline inventory of this single stage. Thus, the stages only consider the local demand and available information about inventory on-hand and in the pipeline and not global information on stock levels. (Axsäter, 2015).

The installation policy is in contrast with the Guaranteed Service Model and Synchronized Base Stock Policy. Both these methods apply the so-called echelon policy, meaning that they use available supply chain data of the total network. In other words, they also consider the stock levels and demand at related stages up- and downstream of its own place in the chain. The echelon-policies are in general superior to installation policy and therefore, they are proposed to further investigate (Axsäter & Rosling, 1993).

In the context of LSC, it was discussed earlier in Section 1.2 that LSC only keeps safety stock for Finished Goods. It stores the products as safety stock at the final stage of the supply network. The safety stock is centrally controlled within the organization by the supply chain department in the headquarters. This department manages how much inventory should be and is kept by the respective stages. LSC manages safety stocks currently according to a single-echelon concept. That is, because it only considers the on-hand and in-transit safety stock of the final stage. Therefore, the following explanation of the replenishment strategy is scoped to this final stage.

To describe the replenishment strategy in place at LSC for Finished Goods, the notation by Silver, Pyke, Peterson, et al. (1998) is used. LSC uses a so-called *(R, s, S)* strategy which differentiates from other strategies on its parameters. The first differentiation is the review period, denoted by the letter R. The inventory position is periodically reviewed with a review period being equal to one working-week. The second differentiation is the replenishment quantity. This quantity is variable at LSC, meaning that every quantity can be ordered. The inventory position is replenished up to a fixed order-up-to level, denoted by the capital letter S. The order-up-to level differs for every product at LSC because dynamic order-up-to levels are used. Instead of a quantity, the organization uses Days Of Supply (DOS). The DOS is the estimated number of days you can supply your customer's demand with your current inventory position based on the most recent demand forecast. The third differentiation is the moment of placing a replenishment order. The decision when to place a replenishment order depends on the reorder level, denoted by the small letter s. An order is placed when the inventory position drops below a particular quantity or number of DOS s. When the order is received, the inventory position rises up to the order-up-to level S.

The required safety stock quantity that a local affiliate should keep is centrally in the organization - at the headquarters - determined. Thus, the headquarters is responsible for the safety stock setting within LSC. The local affiliates usually follow the safety stock proposal, but can challenge it if there are factors present that the computation does not consider. The safety stock quantity is computed with Equation 36.

$$SS = k * \sqrt{\sigma_D^2 * LT + D^2 * \sigma_{LT}^2} \tag{36}$$

In Equation 36, the variable SS corresponds to the calculated safety stock quantity. The safety stock quantity can be converted to DOS by combining the quantity with the demand forecast. The variable k denotes the Alpha-Service-Factor. The service factor differs per product and depends on the assigned product classification. A product is classified as an A-, B-, C- or D-product and consequently, a target service level is assigned. The service-factor is derived from this target service level. Furthermore, D^2 represents the actual sales over the past twelve months and σ_D^2 the variance of the demand forecast error over the past twelve months. Finally, the LT denotes the replenishment lead time and, σ_{LT}^2 the variance of the replenishment lead time.

4.1.3 Supply Network Design

The scope of the research project has earlier been narrowed in Section 1.3 to a part of the product portfolio which is produced at production line 36 of the manufacturing site in the South of Germany. Therefore, the design of the supply network is presented together with its most important characteristics. The network consists of six nodes representing supply chain processes and which are functioning as potential stocking points. The numbers of the nodes correspond to the following supply chain processes of LSC.

1. Procurement and Quality Control of incoming Raw Materials
2. Processing Raw Materials to Formulation/Bulk Materials
3. Procurement and Quality Control of incoming Packaging Materials
4. Processing of Bulk Materials and Packaging Materials to Finished Goods
5. Quality Control of Finished Goods
6. Transport of Finished Goods from manufacturing site to local affiliate

The supply chain network is illustrated in Figure 11 below. The applicability of the method to other network structures is briefly discussed in Section 6.4.

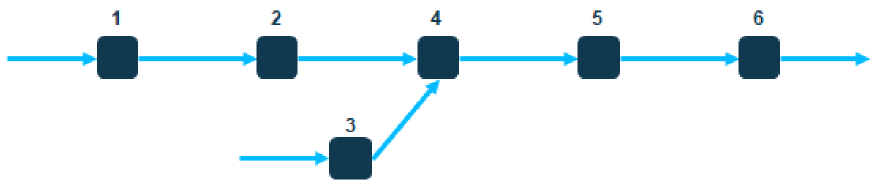


Figure 11: Supply Network Design

Furthermore, the parameters that determine where to place the safety stock are the added value per stage and the respective (cumulative) lead times per stage. The added value per stage is in terms of percentages roughly the same for every Finished Good and therefore, the average is illustrated as an indication in Figure 12. The product specific graphs can be found in Appendix D as Figures 22a - 24b.

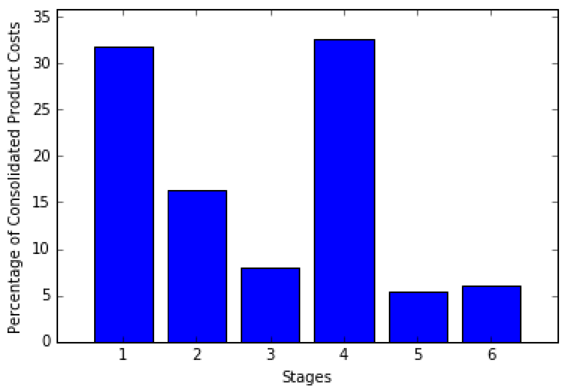


Figure 12: Mean Added Value per Stage

The six Finished Goods are based on three different Bulk Materials, created from eight Raw Materials as shown earlier in Figure 4. To give a general indication of the lead time distribution over the stages, the mean planned lead time per stage as a percentage of the total cumulative lead time is shown below in Figure 13. The planned lead time per stage is relatively similar for each product since the networks are similar. The product specific graphs can be found in Appendix D with the true values in Figures 25a - 27b and the relative percentages in Figures 28a - 30b. The lead time variability per stage is reflected in the analysis of the single-echelon supply chain performance, presented in Section 5.1.

It is important to note in Figures 11 and 13 the effect on determining what the upper-bound of the replenishment time is. The summed up lead time of stages 1 and 2 - which are in series - is longer than the lead time of stage 3. In words, the Procurement and Quality Control of incoming Raw Materials (1) and Processing Raw Materials to Formulation/Bulk Materials (2) require more time than the Procurement and Quality Control of incoming Packaging Materials (3). These two parts of the supply network come together at the Processing of Bulk Materials and Packaging Materials to Finished Goods (4). Therefore, the lead time which is used for the upper bound within the GSM is the cumulative lead time of stages 1 and 2.

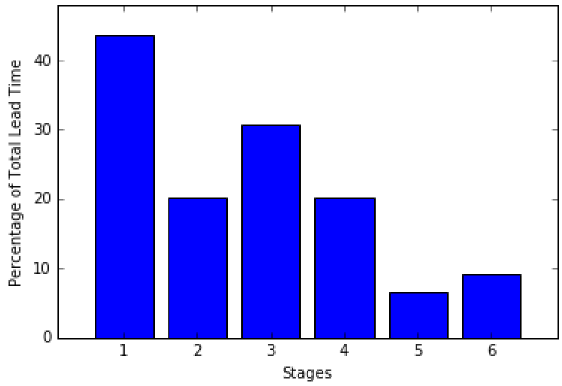


Figure 13: Mean Lead Time per Stage

To conclude, the supply network consists of six different nodes with the center of gravity in terms of added value and lead time at the beginning of the network. Relatively seen for all products, the most expensive processes are the Procurement and Quality Control of incoming Raw Materials and Processing of Bulk Materials and Packaging Materials to Finished Goods. In addition, the Procurement and Quality Control of Raw Materials and of Packaging Materials take the most time. However, as the cumulative lead time of step 1 and 2 is higher than of step 3, the former is used as upper-bound in the GSM.

4.2 Model Assumptions

The GSM and SBSP require some initial assumptions to result in models which can be solved. Thus, four additional assumptions are presented and discussed which are necessary for fitting the models to LSC's supply chain.

The first one is regarding the processing times of the stages 2 and 4 of the supply network, corresponding to the processing of materials to Bulk Materials and Finished Goods. It is assumed that both processes take 42 days/six weeks to be completed which is equal to the so-called Frozen Horizon (FH) of LSC. The FH is the period of time for which the production schedule is filled and fixed with orders that will be produced. It implies that once the production of an order is confirmed and a new order is received which should be produced as soon as possible, it takes six weeks before it can be produced. This is recognized as waiting time and therefore, it is part of the processing time of a stage. The implication of this assumption is that the overall lead time gets significantly longer, leading to a higher required amount of safety stock. The relaxation of this assumption, by for example using only the processing times, will lead to different results since the overall lead time reduces.

The second assumption is about the yield ratio of the supply chain processes. Especially the yield of biopharmaceutical production processes is known to be unstable and can vary much (Boulaksil, Fransoo, & van Halm, 2009; Shah, 2004). Nevertheless, it is assumed - after verification with the employees of the manufacturing site in scope - that the yield of all processes is equal to 100%. The reason is that the production of processes at LSC for the products in the portfolio selection are known to be very stable. That is, the processes cannot be classified as e.g. biopharmaceutical. The rejection of a batch for this product group is such an exception that it is a negligible factor in the supply chain operations planning of LSC. Thus, the assumption is perceived as reasonable in the setting of the case study and does not impact the intended results. The assumption can be relaxed by for example using a different yield ratio when applying the model to a different product group and/or supply network. The implementation of a yield ratio in the models is easily done by adding the ratio as a factor in determining how customer demand has to be supplied. The required implementation time of this action is negligible for both researched mulit-echelon approaches.

The third assumption is regarding using the target service level as an input parameter for both the GSM and SBSP. The target service level is assumed to be equal to 95%, even though the models make use of a different type of service level. The GSM uses the Type-II service level or fill rate as an input parameter which is the delivery percentage of the requested quantity. Thus, this input parameter considers the volume of an order - e.g. the requested quantity is 100 pieces and 95 are delivered, resulting in a service level of 95%. In contrary of the GSM, the SBSP uses the Type-I service level or non-stock out probability as an input parameter - e.g. if there are during 100 cycles 5 stock-out situations, the service level is 95%, independent from the volume of the stock-out. The consequence is that the comparison between the two methods is not completely fair. However, the impact is assumed to be minimal, such that the results still provide valuable insights. The relaxation of the assumption - increasing or decreasing the target service level - results in either higher or lower proposed safety stock quantities. The target service level cannot be left open as its a required input parameter for both approaches.

The fourth and last assumption made is about the distribution of demand. It is for both models assumed that demand is normally distributed with μ and σ per period. This assumption is in line with similar examples of applications and therefore, it is seen as reasonable to use for the case study (Graves & Willems, 2000, 2003b; Peeters et al., 2020). The relaxation of this assumption would result into an undefined demand distribution with different values for μ and σ. Consequently, the output of both the GSM and SBSP will change as well.

4.3 Adaption of Models

The GSM and SBSP are both well-known algorithms and lead to well-known solutions. The methods required negligible adaptions to fit the models to the the supply chain of LSC, especially because of the data structure. The data that served as input for the GSM was converted in some cases to fit the computations of the model. An example is the conversion of data per day to data per week. The concept and its equations remained the same to fit the case study details. This is recognized as a simplification of modeling the real-world. It implies that the model is not adapted to the operational characteristics of manufacturing - e.g. production batch sizes and minimum order quantities. Leaving this adaption out did not influence the intended results, but it is nevertheless more extensively discussed in the Section 6.

As well as for the GSM, the input data of the SBSP is in some cases converted to fit the model's computations. An example is the change of the data format of the BOM, such that it fit the data input requirements of the ChainStock software tool (T. de Kok, 2008). The method did not require any other significant adaptions to fit the supply chain of LSC or the software tool. Therefore, the method remained the same since the software tool was used, meaning as well that the intended solution have not been influenced.

4.4 Parameters ChainStock

The ChainStock software tool requires an input data set with a set of parameters (T. de Kok, 2008). The data set includes an overview of all possible combinations of items and locations in the supply network, the statistics of customer demand and the BOM relationships between materials. These data sets are created by retrieving the required data from LSC's systems and combining them via a script in the programming language *Python*. The overview of all parameters and their descriptions can be found in Table 4.

Table 4: Synchronized Base Stock Policy Input Parameters

Parameter	Description
Item	Identification code of a material.
Location	Stage of supply network.
Expected Lead Time	Planned lead time of a process.
Added Value	Costs of process, thus the value added to the product, derived from the consolidated product costs of each Finished Good.
Yield Ratio	Yield of process, set equal to one as no scrapping of materials is assumed.
Review Period	Length of review period, set equal to one days.
Historic Average Stock	Average historical quantity of stock kept in 2020.
Order Quantity	Average requested quantity for any material type, derived from order records of 2020.
Expected Demand	Average requested quantity for Finished Goods, derived from actual sales in 2020.
Standard Deviation Demand	Standard deviation of demand for Finished Goods, derived from actual sales in 2020.
Customer Lead Time	Planned lead time to service customers from demand node, set equal to zero days.
Target Service Level	Alpha, set equal to 95%.
Quantity	Conversion rate, derived from the BOM relationships.

4.5 Model Scenarios

The first two model runs are the basic Guaranteed Service Model and Synchronized Base Stock Policy with the ChainStock software tool. The additional model scenarios are defined for performing the sensitivity analysis. The aim of this analysis is to identify drivers of good multi-echelon safety stock model performance. More specifically, by defining and running a set of scenarios, the idea is to see how the proposed safety stock quantity and its related costs are influenced having different input parameters. The sensitivity analysis focuses on four different input parameters which are recognized to influence the proposed safety stock quantity and/or related costs. These input parameters are:

- Target Service Level
- Standard Deviation in Demand for Finished Goods
- Added Value per Stage
- Lead Time of a Stage

There is a distinction made between the number of running scenarios for the GSM and SBSP. The reason for this is that running a scenario for the SBSP requires significantly more time and effort compared to the GSM. Therefore, running exactly the same number of scenarios is not an option. In Table 5, the overview of all model scenarios per parameter is presented. The explanation for each set of scenarios per parameter is given together with the result in Section 5 to relate the implication to the real-world.

Table 5: Model Scenarios

1. Basic Models
A. Guaranteed Service Model
B. Synchronized Base Stock Policy
2. Sensitivity Analysis on Target Service Level
A. GSM for 95% to 99% in steps of 0.5%
B. SBSP for 97% and 99%
3. Sensitivity Analysis on Standard Deviation of Customer Demand
A. GSM for 50% to 150% in steps of 25%
B. SBSP for 50% and 150%
4. Sensitivity Analysis on Added Value
A. GSM for 50% to 300% in steps of 50%
B. SBSP for 50%, 200% and 300%
5. Sensitivity Analysis on Lead Time per Stage
A. GSM for 50% to 200% in steps of 25%
B. SBSP for 50% and 200%

5 Results

In this section, the results of the project are presented in three parts. Firstly, the current supply chain performance under a single-echelon approach is illustrated and discussed in Section 5.1. Secondly, the results for the case study with the Guaranteed Service Model and Synchronized Base Stock Policy are depicted in Section 5.2. Thirdly, the results of the sensitivity analysis for both approaches are shown in Section 5.3. Fourthly and finally, the section is concluded with a compact factorial analysis in Section 5.4 to verify the findings of the previous section.

5.1 Single-Echelon Supply Chain Performance

The supply chain performance under the currently in place single-echelon (SE) concept is reviewed in four different directions for the year 2020. The directions are the Safety Stock Quantities & Costs, Customer Demand, Planned & Actual Lead Time for processes and the Service Level. The implications of the results are briefly discussed for the product portfolio selection. In case the results have significant implications, these are highlighted and further considered.

5.1.1 Safety Stock Quantities & Costs

The safety stock quantity per week which was kept by the local affiliate for each product is presented in Figures 31a to 33b in Appendix E. In general it is observed that the available quantity for each product is considerably fluctuating, but only within certain boundaries and without any total stock-out situations. The fluctuations in safety stocks available indicate that there is a replenishment strategy in place with the stock quantity reducing and increasing over time within these boundaries. No general patterns applying to all products are recognized, but when investigating the individual products, it is possible to recognize patterns in the reduction and replenishment of safety stocks.

Logically, the cost of safety stock follows the pattern of safety stock quantities held, since the stock is valued at the consolidated cost price of the product. As a result, the graphs look precisely identical, except for the different axis and therefore, there is no further elaboration on the safety stock costs specifically.

5.1.2 Customer Demand

The review of customer demand for products demands a more individual explanation as clear differences between products are observed. The requested quantity for each product per week is illustrated in Figures 34a to 36b in Appendix E. The demand per week of product 86947552 is only shown for a half year because of an omission in the master data - although the product was also sold for the remainder of the year, these data were unavailable in the systems.

Table 6 shows per product the Mean Demand and Standard Deviation of Demand per week. Furthermore, it shows the respective Coefficient of Variation (CV) which is the standard deviation divided by the mean. The latter is the key statistic as some products show relatively stable sales for 2020 (e.g. 86947552) while others have much more variation (e.g. 85690604).

Table 6: Statistics Customer Demand

Product	Mean Demand	Standard Deviation of Demand	Coefficient of Variation
11873262	9392	6363	0.68
11873533	11470	7236	0.63
85690604	13269	9688	0.73
86189976	6520	4668	0.72
86570009	6206	3202	0.52
86947552	25471	8676	0.34

In general, a $CV < 1$ is considered as low-variation, implying that the overall sales quantities are relatively stable (Hopp & Spearman, 2011). Nevertheless, it is worth to consider the products individually and highlight and reflect on the implications of these numbers on the (proposed) safety stock. The product 86947552 has significantly higher demand than the other products, but its sales are much more stable with a CV of 0.34. Therefore, it is expected that for this product less safety stock is required than for the other products. Another interesting conclusion is the fact that the four products which are cross-regional supplied - 11873262, 11873533, 85690604 and 86189976 - have more fluctuating customer demand. Hence, the combination of having longer lead times and relatively unstable sales indicate that a significantly higher level of safety stock is required for these products.

5.1.3 Planned & Actual Lead Time

The comparison of the planned and actual lead times provides an indication of the likelihood any lead time-related problems appear. The planned lead times are already presented and reviewed in Section 4.1. Thus, the focus in this part lies on checking the adherence of these planned lead times. This is done only for the last process of the supply network, the transportation of the Finished Goods. For the other processes, there is either no data available or the lead times are based on an assumption, such as for the production lead time of Bulk Materials and Finished Goods as discussed in Section 4.2. The results per product, showing the deviation of the actual lead times of the process, are depicted in Figures 37a - 39b in Appendix E.

First of all is from the results derived that a great variety between the number of transport records exists. Within the selected product portfolio is one product which only shipped once in 2020 (e.g. 86189976), where two others products were shipped fifteen times in that same year (e.g. 11873533 and 86570009). Logically, this translates into having two different situations for safety stock setting. When products are shipped more than once a month, less safety stock is required than when product are shipped once a year because there exist more opportunities to replenish the product. Nevertheless, the lead time adherence is perceived as low when reviewing the deviations of shipments Figure 37a to 39b in Appendix E which still demands consideration of the impact on safety stock. The adherence results are divided into three parts:

- Positive deviation, meaning the actual lead time was longer than the planned one. This is the case in 28% of the reviewed transports, with small delays of approximately 15% of the planned time (e.g. product 86189976 in Figure 38b) reaching to 300% (product 86947552 in Figure 39b). The delays imply the presence of variability within the transportation process. Thus, this supply variability impacts the required amount of safety stock and expected to increase this number.

- No deviation, meaning the actual lead time was equal to the planned one, applied to 32% of the shipments (e.g. products 86570009 and 86947552 in Figures 39a and 39b. The majority of the 'no deviation' came from products destined for the German market. The planned lead time is in this case equal to one day, not allowing much room for deviations since for example, the product does not pass through any border controls.

- Negative deviation, meaning the actual lead time of the shipment was shorter than the planned time. This occurred for 40% of the shipments, but comes with a side note regarding transportation modes. Many of these shipments were not just a little bit faster, but more than 50% of the planned time faster. This implies that the standard transportation mode for cross-regional supply - read: cross-ocean supply - was changed to air since it is impossible for a container ship to cross the Atlantic within one week. It is well-known that air freight is much more expensive and therefore, the number of much faster transports indicates that an expensive air transport was required to bring the products to the market in time. Therefore, it is another sign of the presence of supply variability within the supply network. Moreover, these shipments should be recognized as a positive deviation of the lead time which validates the statement that the lead time adherence is perceived as low.

To conclude, the lead times within the supply chain influence the proposed safety stock quantity since longer lead times allow a greater aggregated variability of customer demand in the chain. Moreover, these lead times can vary which affects the determination of the required safety stock quantity. The results of the lead time adherence analysis show that especially products with a relatively high planned lead time - e.g. multiple weeks for cross-regional supply - have often delays for their shipments. Therefore, it is important to be aware of this in the setting of proposing safety stock.

5.1.4 Service Level

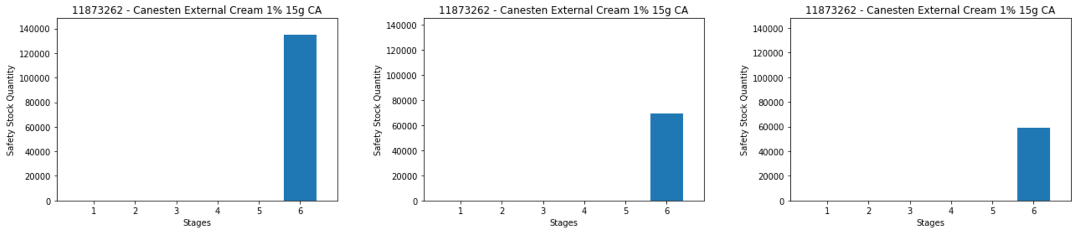
The service level was for the product portfolio selection for 95% of the considered weeks equal or higher than the target service level of 95% as shown in Appendix E in Figures 40a to 42b. There are a few small deviations noticed where the level was below 100%, but most likely these can be explained by minor supply issues. However, it is worth to highlight the case of product 11873262 since a serious drop in the service level was recognized shown in Figure 40a. The level has been (close to) 0% for multiple weeks, indicating there has been a serious supply issue. This indication is further explained by a peak in sales before the service level dropping is to 0% illustrated in Figure 34a and by a decrease in safety stock availability during this period depicted in Figure 31a. Hence, it can be concluded that the service level for the products in the product portfolio selection was in general sufficient, but not perfect. The implication of the historically achieved service levels on the safety stocks is that it can be concluded that there was in the past in general (more than) enough safety stock to achieve these high service levels.

5.2 Model Comparison Safety Stock Quantities & Costs

The main research question focuses on whether a reduction of the inventory costs is feasible when a multi-echelon safety stock approach is implemented. Therefore, the (proposed) safety stock quantities and costs under the single-echelon (SE) and multi-echelon approaches are compared. For the SE safety stock quantity, the mean quantity of 2020 located at the final stage of the network is used. For the GSM and SBSP, the proposed safety stock quantities by the models are used.

In the results under a multi-echelon approach, two types of safety stock allocations are distinguished. For the purpose of explaining, the allocation types are denoted as Type-A and Type-B. Thus, the results per approach are presented for two products (e.g. 11873262 and 11873533) to show the differences. The different allocation types are illustrated in this section in Figures 14a to 14c (Product 11873262) and Figures 15a to 15c (Product 11873533). The results of the other products can be found in Figures 43a to 46c in Appendix F. From the total of six products in the portfolio selection, four have a Type-A allocation and two a Type-B allocation. The cause behind the two different allocation types is later briefly discussed.

The allocation Type-A, illustrated in Figures 14a to 14c, shows the same results as the single-echelon approach, which means all safety stock is being placed at the end of the network. The proposed quantities under the multi-echelon safety stock management approach are lower than LSC's current stock levels. This implies that to reduce safety stock costs, LSC should not necessarily look at *where* it keeps safety stock, but rather at *how much* safety stock is kept.

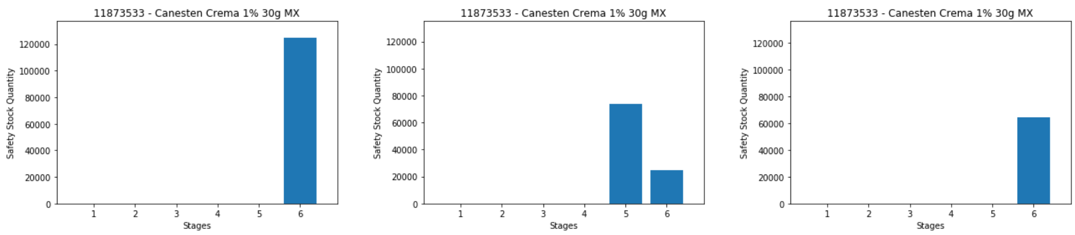


(a) SE Safety Stock Quantity (b) GSM Safety Stock Quantity (c) SBSP Safety Stock Quantity

Figure 14: Type-A Proposed Safety Stock Quantity Allocation

The Type-B allocation proposed for the two other products is to keep safety stock at the last two stages. Stage five represents the Quality Control of Finished Goods, stage six is the Transportation of the Finished Good to a country. The Type-B allocation and the comparison of the different approaches is shown in Figures 15a, 15b and 15c. This allocation is apparently under the GSM the most cost-efficient option for these products. The reason for placing the stocks at these stages is that the relatively high transportation costs for these products make it less attractable to ship and store them in the country of sales.

The similarity of the two products with a Type-B safety stock allocation is that both their country of sales is Mexico. This is an indication that LSC should manage its safety stock differently than how the organization is currently doing it. Instead of storing at the final node of the network, it should store the stock in the warehouse next to the manufacturing site after completing step five. Taking into account the planned transportation time of approximately four weeks (step six), the decision to ship the stock has to be made four weeks in advance of the point in time where the stock will actually be needed. Therefore, this form of safety stock allocation is depending on accurate estimates when the safety stock is needed and on a stable transportation process. The retrieved insights for these products are more extensively discussed later in this Section and in Section 6.



(a) SE Safety Stock Quantity (b) GSM Safety Stock Quantity (c) SBSP Safety Stock Quantity

Figure 15: Type-B Proposed Safety Stock Quantity Allocation

Besides the (proposed) safety stock quantities, the average safety stock costs per week under each approach are reviewed and compared. The costs are computed by multiplying the proposed safety stock quantity at a stage with the cumulative value of the product at this stage. An overview of the average safety stock costs per week under each approach for the product portfolio selection is shown in Table 7. The values are because of confidentiality reasons masked by multiplying them with a factor. This factor is only known by the author and the supervisors of this research project.

Table 7: Masked Overview Average Safety Stock Costs per Week per Approach

Product	**Single-Echelon**	**Guaranteed Service Model**	**Synchronized Base Stock Policy**
11873262	€ 42.639	€ 21.958	€ 18.776
11873533	€ 49.241	€ 36.354	€ 25.342
85690604	€ 32.173	€ 48.206	€ 32.694
86189976	€ 12.548	€ 15.908	€ 13.526
86570009	€ 28.047	€ 21.882	€ 20.135
86947552	€ 26.830	€ 26.761	€ 29.902
Total	€ 191.478	€ 171.069	€ 140.375

The results for the product portfolio selection in Table **??** show that both the multi-echelon approaches outperform the single-echelon approach. Comparing the two multi-echelon approaches, the total safety stock costs are the lowest under the proposed safety stock allocation by the SBSP.

It is surprising that the single-echelon approach has the lowest costs for the products 85690604 and 86189976. This is explained by the fact that the average weekly safety stock costs for the year 2020 are used. It was shown earlier in Section 5.1.1 that the available safety stock quantity and costs are subjected to considerable fluctuations. The safety stock quantity per week shows for both products a positive trend in the quantity on stock as illustrated in Figures 32a and 32b in Appendix E. Therefore, the average safety stock quantity/costs of these products is recognized as an underestimation of the costs under the single-echelon approach. In case the safety stock quantity available in the last week of 2020 was used instead of the average, the SBSP would lead to the lowest costs of all approaches.

To conclude, the results of the comparison show that the multi-echelon safety stock approach outperforms the single-echelon approach in terms of costs for the full product portfolio selection. More specifically, the SBSP leads to the lowest safety stock costs which is received as a little surprising. Therefore, this matter is further discussed in Section 6. The proposed safety stock quantities under the multi-echelon approaches show a potential safety stock costs reduction of on average 10.6% for the GSM and 26.7% for the SBSP. For the individual products, the potential cost reduction reaches up to 48.5% and 56.0% under the GSM and SBSP multi-echelon approaches.

Furthermore, the results indicate that often (four out of six times) the placement of safety stock at the end of the chain (allocation Type-A) is the most cost-efficient solution. Therefore, it is safe to say that LSC should focus on options to reduce the amount of safety stock it keeps, rather than focusing on trying to store safety stock more upstream based on the opinion that this approach is increasingly cost-efficient. The impact of these findings are more extensively discussed at the beginning of Section 6.

5.3 Sensitivity Analysis

The second part of this section includes the results of the sensitivity analysis. The analysis was performed to identify the drivers for good multi-echelon safety stock approach performance and executed for four input parameters: *Target Service Level*, *Added Value per Stage*, *Standard Deviation in Demand for Finished Goods* and *Lead Time of a Stage*. The scenarios for each approach have been defined earlier in Section 4.5 to recognize the impact of the parameter on the proposed safety stock allocation. Moreover, it provides the opportunity to define key-focus points for other pharmaceutical companies that consider using a multi-echelon approach for their safety stock management.

5.3.1 Service Level Adherence

The first parameter which is reviewed is the service level adherence. The service level constraint only applies to the final stage of the network for both the GSM and SBPS because the research scope is to improve the service level towards customers. The proposed safety stock quantities by the multi-echelon approaches are based on achieving the target service level. Logically, this means for the safety stock allocation that the higher the target, the more safety stock is required to achieve this target. For the analysis of all selected products, the (marginal) costs of the safety stock allocation are reviewed versus an increasing service level target. This is illustrated for the GSM in Figure 16.

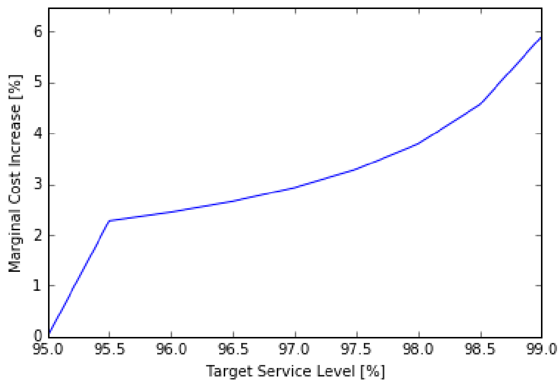


Figure 16: GSM Marginal Cost Increase by Increasing Target Service Level

The results under the GSM in Figure 16 clearly show that the first additional 0.5% of the target service level is less costly than the last 0.5% as the incline of the line is increasing. The fact that the first step has a marginal costs of only 2.3% and the last step of 5.9% indicates that organizations will have to make a trade-off between the target service level and the safety stock costs. The impact is for every product of the same size due to the changing safety factor. The results for the individual products are illustrated in Appendix G in Tables 15 and 16

The effect of the increasing target service level on the proposed safety stock quantity under the SBSP approach is similar as presented in Appendix G in Figures 17 and 18. Even though the analysis is performed with greater increments, it is recognized that the marginal costs of increasing the target are become bigger. Nevertheless, the marginal costs increase under the SBSP is less than under the GSM. The target service level increase under the GSM from 95% to 97% results in 10.7% higher safety stock costs where the SBSP shows an increase of only 9.1%.

To conclude, the findings provide organizations the opportunity to improve the safety stock management of their products. The described insights enable to review how the costs can be minimized and service level maximized. The marginal cost increase for increasing the target service level becomes higher for every increment. Thus, the benefits of the multi-echelon approaches are clearly impacted by the increasing costs. The effect is the same for all products, but it seems to be stronger under the GSM than under the SBSP. In other words, it is safe to say that the benefits of the SBSP seem to be less impacted by the changing service level target than the of the GSM. Therefore, the SBSP is the most promising approach for all products in the context of an increasing target service level.

5.3.2 Demand Variability

The safety stocks are used to deal with the variability in customer demand. Thus, the greater the fluctuations in the demand, the more safety stock is required to ensure customer service. The standard deviation of historical customer demand is used as an input parameter for the multi-echelon safety stock approaches. The key for supply chain planning, so forward-looking, is knowing accurately what the variability in customer demand is. This allows to manage the supply chain accordingly. Therefore, the standard deviation of customer demand is varied to see the effect on the safety stock quantities and costs.

The results for the analysis for the GSM show a linear relationship between the demand variability and the proposed safety stock quantity and costs. The overview of all results for this parameter under the GSM approach can be found in Appendix G in Tables 19 and 20. The relationship applies to all selected products, independent from the variability in demand. Logically, the lesson which is derived firstly is that less variability means that less safety stock is required. However, the result secondly highlights the importance of having an accurate demand forecast. The impact of the standard deviation on the required quantity of safety stock is significant. Thus, having an inaccurate demand forecast emphasizes the effect of variability in demand. This situation makes the supply chain planning much more complex, resulting in e.g. having too much safety stock or having a stock-out situation.

The set of model scenarios for the SBSP is smaller than for the GSM, but it is noticed that the SBSP responds different to the changing parameter. All results for this part of the analysis can be found in Appendix G in Tables 21 and 22. On the one hand, the GSM showed a positive linear relationship between the standard deviation of demand and the proposed safety stock quantity and costs. On the other hand, the SBSP does not show this relationship. Instead, the safety stock quantities and costs increase more when the standard deviation is changed from 50% to 100% than for the increase from 100% to 150%. Unfortunately, the lack of additional model runs prevents to draw further conclusions. Therefore, it is not further elaborated in this study on what this causes. However, the same principle applies to the SBSP as to the GSM - fluctuations in demand show to strongly influence the proposed safety stock quantity. Therefore, the importance of accurately estimating the customer demand and so its variability is once more emphasized.

The products are not analyzed nor grouped on the size of their demand variability. The tested scenarios for the standard deviation of customer demand are relative to the products' sales. The scenarios show the impact of the proposed safety stock quantity and costs. However, grouping of products makes no sense as it depends on a product's initial demand variability and the size of the product portfolio selection is too small to draw general rules from the results. Nevertheless, the tested scenarios allow to review the impact on the benefits of both multi-echelon approaches. Under the GSM, all products are in the same way impacted by changing the demand variability since there is a linear relationship between the level of variability and safety stock costs. Under the SBSP, the impact of the variability seems to be lower when the variability increases. More scenarios have to be tested to confirm this claim. Still, it indicates that the SBSP is the more beneficial multi-echelon approach in the context of changing and/or increasing customer variability.

Furthermore, the allocation of the stock in the network is an important factor whether the multi-echelon approach is beneficial to implement. In the setting of having products with high variability which are stored further upstream in the network, the time to the market is longer. This brings additional complexity to the supply chain planning and safety stock management in the form of lead time variability and the perishability of products. Therefore, products with relative stable customer demand are more likely to benefit from a multi-echelon approach, independent from whether their safety stocks are completely downstream or upstream placed.

The benefits of multi-echelon approach for products with more customer demand variability are more impacted. The reason is that the management of all stocking points and the supply chain process is more complex with higher end-item variability. Thus, this asks for a more thorough supply chain design and implementation of the concept for the group of products with higher demand variability. The placement of the safety stocks closer to the market will reduce the impact of the high demand variability on the benefits of the multi-echelon approaches. Finally, one should be aware of the complexities and challenges for products with high end-item variability and the safety stock being allocated upstream. The benefits of the multi-echelon approach are significantly impacted in this setting. Hence, the single-echelon approach might be better here since the supply chain planning can be simplified.

To summarize, safety stock is used to cover variability in customer demand and as a result, the proposed safety stock quantity is influenced by this variability. The results clearly show that higher customer demand variability leads to significantly more costly safety stock allocations. It is difficult to influence customer demand so correctly estimating the magnitude of the variability can lead to more accurate safety stock management. More specifically, it can result in either a reduction of safety stock costs or an improvement of the service level since the supply chain planning can become more accurate. Therefore, accurately forecasting customer demand is of key-importance for an organization when applying a multi-echelon safety stock management approach.

In addition, it seems that the benefits of the GSM are more impacted by higher customer demand variability than the benefits of the SBSP. More scenarios of the SBSP have to be tested to confirm this statement, but the results indicate that the SBSP is the better able to deal with demand variability. An additional perspective is that the combination of the demand variability and where the safety stock in the supply network is placed complicates the supply chain planning and safety stock management. This increased complexity impacts the benefits of the multi-echelon approaches for the different products. The results of the analysis show that products with relatively stable sales are more likely to benefit from the multi-echelon approach - independent from where in the network the stock is placed. The benefits for products with higher demand variability are more impacted. However, by placing the safety stock further downstream, the implementation of the multi-echelon approach can still be beneficial for these products. Finally, for products with unstable sales and safety stock being allocated upstream, the single-echelon approach might be better to apply. These dynamics impact the benefits of the multi-echelon approach significantly, such that a simplified form of safety stock management could lead to better supply chain performance.

5.3.3 Added Value

The added value per stage is an input parameter for the multi-echelon approaches. In this context, it is used as a decision variable because it determines how costly and therefore, how likely it is to place safety stock at a certain stage in a supply network. The added value of the last stage of the network is changed, such that the effect on the safety stock proposals by the basic GSM and SBSP becomes clear. By increasing the costs of transportation, it is checked when exactly the multi-echelon approaches propose to allocate safety stock further upstream in the supply network. This question is highly relevant in the light of current events where freight costs have increased in the real-world with over 700% percent over the last two years (Rao & Saul, 2021). The overview of results for all model runs can be found in Appendix G in Tables 23, 24, 25 and 26.

The results for the GSM are divided into two groups. The first group contains two products that have lead times shorter than one week and the shipment costs are relatively low because the transport is done by per truck. The results show that there is no tipping point for these products within the range of 300% of the original price of the transport.

The second group responds to the increase of transportation costs by proposing safety stock further upstream. That means at the manufacturing site where the product is produced, rather than the local warehouse in the respective country. However, there is always proposed to keep some safety stock in the country to ensure customer service. This result applies to the four products whose common factor is a lead time of more than one week. The place of the exact tipping point differs per product: for one case already between 100% and 150% of the original price and for another one between 150% and 200%. This might seem inaccurate, but in the light of the 700% increase in freight costs, it already provides important new insights.

The results for the SBSP show something unexpected at first sight. That is, the safety stock quantities and costs decrease when the transportation costs are increased. This is caused by the way the output of the ChainStock software tool is interpreted. The output includes for every item-stage combination a proposed safety stock quantity and an estimate of what the service level for this combination would be. The basic SBSP uses a non-stock out probability of 95% as the target service level and therefore, only the item-stage combinations are considered with an estimated service level equal or higher than this target. The other combinations are excluded from interpretation since it makes from a supply chain management perspective no sense to keep safety stock at a certain stage if the estimated service level at the stage is low, e.g. 25%. In the real-world, such safety stock allocations would trigger too many discussions within an organization about why there is often insufficient stock of an item available upstream in a network. Thus, it makes it impossible to adequately manage the supply chain.

The target service level of 95% is only achieved for item-stage combinations where the stage is the final node of the supply network. Therefore, the results are interpreted as that the SBSP reduces the safety stock kept at the final node of the network when the transportation costs increase. This is as well in line with expectations and how the GSM responds to a cost increase at this stage. When reviewing the output more in-depth for all item-stage combinations for the first-to-last stage of the network, it is noticed that the proposed safety quantity increases here. Moreover, the estimated service level increases as well, but remains below the threshold of the target to be considered. Therefore, the retrieved insight is that the safety stock allocation changes for the increasing transportation costs.

To conclude, the findings regarding how the multi-echelon models respond to the change of the transportation costs have a great impact on the safety stock allocation. The difference between the two multi-echelon approaches is that on the one hand, the SBSP approach indicates incremental reductions of the proposed safety stock at the final stage. On the other and, the GSM shows more a tipping-point from where it changes the allocation substantially. From this tipping point, a considerable quantity of safety stock is then allocated more upstream. Furthermore, the results imply that for the considered supply network and under cost developments in the real-world, allocation of safety stock further upstream can be more cost-efficient than keeping it at the final node of the network.

Finally, it is safe to say that the multi-echelon approaches seem to be beneficial for any product with a relatively longer lead time - e.g. more than one week. The results show that the significant increase of transportation costs over the past two years makes it more cost-efficient to store these products further upstream (Rao & Saul, 2021). The higher the added value of this supply chain process becomes, the more it impacts the safety stock management. As a result, the more holistic multi-echelon approach becomes increasingly beneficial for organizations to implement. The implications of these findings and for which product types they are interesting are more extensively discussed in Section 6.

5.3.4 Lead Time Adherence

The effect of the lead time is analyzed by changing the transportation time. Thus, the processing time of the last stage in the network. LSC transports its products from the manufacturing site in scope to every country of the world. The lead time of this step in the supply chain is highly variable as shown earlier in Section 5.1.3. Especially in the context of having a pandemic in the real-world, logistical processes are under pressure and transportation times fluctuate. Therefore, the transportation time was changed for a set of model scenarios to check its influence on the safety stock proposal in terms of quantities and costs. An overview with all results for the model runs can be found in Appendix G in Tables 27, 28, 29 and 30.

The results for the GSM show that the longer lead times of more than a week have a linear relationship with the proposed safety stock quantity and costs. In other words, the longer it takes to transport a product, the higher the proposed quantity is. It does not cause a shift in the safety stock allocation - e.g. placing it further upstream. This is a logical result as the basic models already place safety stock at the final node of the network. The increasing lead time for transportation means that replenishments take longer to arrive, increasing the probability that safety stock is used. Thus, the stock is allocated to the stage close(st) to the market. Furthermore, shortening the lead times with 50% for the products in scope also does not lead to an allocation with safety stock placed more upstream.

The analysis results for the products with a lead time less than one week are considered as not interesting for this project. The reason is that the impact of low lead time adherence is negligible for the safety stock allocation. Also, products with a lead time of less than one week need a considerable transportation delay before it impact the safety stock management. According to conversations with employees of LSC, a delay of this magnitude is rare which is also in line with the analysis of the lead time adherence in Section 5.1.3. Hence, this situation is not further investigated nor discussed.

The results of the lead time analysis for the SBSP are similar to the results for the GSM. For cross-regional supply, again a positive relationship between the lead time and the proposed safety stock quantity and costs is identified. The proposed safety stock quantities and costs for products that are regionally supplied change like under the GSM with a negligible amount. Therefore, the effect of varying lead times on the safety stock allocation under the SBSP is not further discussed.

To conclude, the results of the sensitivity analysis on the lead time show that there is a positive relationship for the GSM and SBSP between the lead time length and the proposed safety stock costs. The increase of lead time clearly influences the safety stock allocation in terms of proposed quantity, but not in terms of where the stock should be placed. In other words, the placement of safety stock remains for each product at the final stage of the network.

Nevertheless, the results of the lead time analysis show that a distinction can be made between two sets of products. These are the products which are regionally and cross-regionally supplied, similar to the previous discussed parameter in Section 5.3.3. The safety stock allocation for regionally supplied products is negligible influenced by the increasing lead time. The lead time being relatively short prevents having a real impact on the benefits of the multi-echelon approaches. However, the combination of long(er) lead times for cross-regional supplied products and low lead time adherence is highlighted. This combination clearly impacts the benefits of the multi-echelon approaches since it increases the safety stock costs. Especially, with the presence of the pandemic, this finding is of importance for LSC and other organizations in context of safety stock management. Therefore, this finding is further on elaborated in Section 6.

5.4 Factorial Analysis

The results of the sensitivity analysis are used to perform a factorial analysis on the input parameters for both concepts. Two scenarios are defined to check what their combined impact is on the proposed safety stock allocation and the benefits of the multi-echelon approaches. The scenarios are derived from the review of the individual input parameters. The output of the factorial analysis is placed next to the supply chain performance under the single-echelon approach to put it in perspective. The proposed safety stock allocation per approach for each product can be found in Appendix H as Figures 47a - 58c.

First Scenario

The first scenario is defined as an extreme supply chain case. It includes a target service level of 99% and a high demand variability of 150% of the original variability. The added value is set equal to 300% of the original transportation costs. The transportation/lead time to the final stage is modeled as 200% of the original time. The reason for this scenario definition is to see how multi-echelon approaches in this setting allocate the safety stock and how the benefits of the methods are impacted by it.

The safety stock allocations are illustrated in Figures 47a - 52c which can be found in Appendix H. The results under the GSM show a clear distinction between the safety stock proposals. In line with the results of the sensitivity analysis in Section 5.3, there is a group of products with a lead time less than a week and a group with a lead time of more than one week. For the former, the GSM proposes to keep all safety stock still at the last stage, such that it is the closest to the market. For the latter, the model recommends to place the safety stock further upstream. Even though more safety stock is required due to the longer to-the-market time, it is apparently more cost-efficient to initially avoid the high shipping costs.

The SBSP proposes the same allocation for all products as the basic model - placing the stock at the final stage of the network. However, considering the raw data shows that actually as well the SBSP pushed safety stock upstream to avoid the high transportation costs. This is not illustrated in the graphs since the estimated service level is still below the threshold of the target service level to be considered. See Section 5.3.3 for a more detailed explanation on why this is not represented in the graphs. This finding is in light with the retrieved insights in Section 5.3, even though there is a conflict of objectives. On the one hand, the high target service level, high customer variability and long lead time lead to placing safety stock closer to the market. On the other hand, the high costs of shipping push safety stock further upstream. Therefore, there is clearly an opportunity to reduce the safety stock costs and improve the service levels for products which are cross-regionally supplied.

The proposed safety stock quantities by the multi-echelon models are approximately the same or higher than under the single-echelon approach. Consequently, the same applies to the safety stock costs of the multi-echelon approach proposals. The costs per approach is for each product shown in Table 8. The values are because of confidentiality reasons masked by multiplying them with a factor. This factor is only known by the author and the supervisors of this research project. The order of the total costs per approach for the selected products is the same as for the basic model comparison. That is, the SBSP is superior compared to the GSM. It is derived from of Table 8 that the safety stock costs proposed by the multi-echelon approaches are higher than the original setting of the single-echelon approach. This is in line with expectations since scenario 1 is an extreme case of the supply chain dynamics. Furthermore, there are differences recognized between the individual products and approaches. For all products except one - the difference is 1.5% - the SBSP is still better able to deal with the extreme supply chain dynamics. Therefore, it is concluded that the SBSP is beneficial for all products to reduce the safety stocks and improve the service levels.

Table 8: Factorial Analysis Scenario 1 - Masked Overview Average Safety Stock Costs per Week per Approach

Product	Single-Echelon	Guaranteed Service Model	Synchronized Base Stock Policy
11873262	€ 42.639	€ 62.582	€ 37.836
11873533	€ 49.241	€ 56.101	€ 48.195
85690604	€ 32.173	€ 77.675	€ 64.787
86189976	€ 12.548	€ 30.441	€ 27.826
86570009	€ 28.047	€ 30.782	€ 30.333
86947552	€ 26.830	€ 35.869	€ 41.213
Total	€ 191.478	€ 293.451	€ 250.189

Second Scenario
To verify the impact of the first scenario, the second scenario is defined as the opposite. Thus, this scenario includes a service level of 95%, a low demand variability of 50% compared to the original variability, an added value in the form of 50% of the original transportation costs and 50% of the original transportation/lead time to the final stage.

The output of this scenario shows that the safety stock proposals by the multi-echelon approaches all have the same allocation in terms of where the safety stock is placed. The GSM and the SBSP both propose to place all stock at the last stage of the network. Furthermore, the proposed quantities are for each product lower than under the single-echelon approach. This is illustrated in Figures 53a - 58c which can be found in Appendix H. Consequently, the safety stock costs are as well significant lower under the multi-echelon approaches. The average safety stock costs per week per approach for each product is shown in Table 9. The values are because of confidentiality reasons masked by multiplying them with a factor. This factor is only known by the author and the supervisors of this research project. The defined scenario logically leads to these results, such that they are all in line with the initial expectations.

Table 9: Factorial Analysis Scenario 2 - Masked Overview Average Safety Stock Costs per Week per Approach

Product	**Single-Echelon**	**Guaranteed Service Model**	**Synchronized Base Stock Policy**
11873262	€ 42.639	€ 10.164	€ 11.819
11873533	€ 49.241	€ 14.129	€ 17.175
85690604	€ 32.173	€ 18.732	€ 21.407
86189976	€ 12.548	€ 7.409	€ 8.254
86570009	€ 28.047	€ 11.003	€ 14.759
86947552	€ 26.830	€ 12.966	€ 23.348
Total	€ 191.478	€ 74.403	€ 96.762

Furthermore, the results in terms of costs as shown in Table 9 surprisingly show that the total costs of the safety stock proposals under the GSM are less than under the SBSP. The most likely reason for this is that the demand bound of the GSM is lower since sales are modeled as being more stable. This, in combination with the target service level of 95%, shorter lead times and lower transportation costs, leads to an underestimation of the required safety stock. Furthermore, the multi-echelon safety stock proposals are as intended the opposite of the Scenario 1. The costs are much lower and the safety stock is allocated at different stages in the network.

To summarize and conclude, based on the results of the sensitivity analysis in Section 5.3 and of the factorial analysis, there is reason to think that - when having the same circumstances as under the single-echelon approach - the multi-echelon approaches are beneficial for all products. The impact of the varying parameters show that it can still be beneficial for organization to apply a multi-echelon approach. It is highlighted that especially for product which are cross-regionally supplied, an opportunity seems to exist. Furthermore, when comparing the multi-echelon approaches, the SBSP is the superior method. It is better able to deal with the extreme supply chain dynamics as modeled in Scenario 1 and to predict the adequate safety stock levels in Scenario 2. These findings are further discussed in Section 6.

6 Discussion

The results and their implications have been presented in the previous section. The findings are more extensively discussed in this section in terms of their implication in the real-world and their relevance. Firstly, the safety stock proposals by the multi-echelon approaches are reviewed on their content. Secondly, the findings of the sensitivity analysis are translated to a set of focus points for pharmaceutical companies, which determines the success of a multi-echelon safety stock model. Thirdly, the requirements to roll the concept out within LSC's supply chain are discussed. Fourthly, the findings for LSC are evaluated on their potential to be generalized to other companies. Fifth, a company recommendation for LSC is presented where it is explained what its next steps should be. Sixth and finally, the limitations of the project and ideas for future research projects are outlined.

6.1 Strategic Safety Stock Placement

The strategic safety stock challenge includes determining the best place in the supply chain to store your stock (Snyder & Shen, 2019). The results showed in Section 5 included a comparison between the currently in place single-echelon approach and two multi-echelon approaches, the Guaranteed Service Model and the Synchronized Base Stock Policy. The findings are to some extent surprisingly as the multi-echelon models propose to allocate the safety stock at the same node as the single-echelon approach, located at the end of the supply network. The end of the network means that an end-item is completely produced, transported to the respective country of sales and stored there in a warehouse, until customer demand arrives. As a result, the question arises why the multi-echelon approaches propose to store safety stock in the final stage of the network. The purpose of the approaches is to reduce inventory costs and since a finished good is more expensive than its components, the result of keeping finished goods feels counter-intuitive. Therefore, this topic is discussed in the first place.

6.1.1 Placement at Final Stage

The network of LSC is modeled as a set of six processes. All can function as a potential stocking point in the supply chain. The network is according to the input received from LSC representative for the real-life supply chain so no significant simplifications have been made. Nevertheless, the number of considered stages is relatively low compared to other application examples (Graves & Willems, 2003b; De Kok et al., 2005). The supply chain characteristics of LSC discussed in Section 4.1 showed that the most expensive processes for producing the end-item are in the beginning of the network and the lead times of those stages are relatively long. In addition, the organization has currently an inventory control policy in place with a review period equal to a month and the target service level is set equal to a fill rate of 95%. The multi-echelon approach has the aim of serving customer demand against minimal costs by coordinating your material and resource availability within the supply chain (T. de Kok & Fransoo, 2003). Therefore, the approaches respond to these network characteristics in a way such that it will always meet its target service level. The models propose safety stocks at the final stage of the network to protect the customer against the long internal lead times and expensive processes at the beginning of the network.

The counter-argument is that the cumulative value of a component is cheaper than of a finished good. This way, keeping components as safety stock could theoretically lead to the minimization of the safety stocks costs. However, this argument lacks the consideration of the effect of the lead time. For storing safety stock further upstream as components, any additional lead time should be covered with safety stock. Thus, many more components than finished goods should be kept, making it a non-optimal solution in terms of safety stock costs.

This statement is also supported by the results presented in Section 5. The safety stock for each product with a transportation lead time of more than one week in the product portfolio selection, as shown in Section 5.2, is allocated at the last stage of the network. The length of the lead times result in the situation that so much safety stock for components would be required, it is not efficient. In addition, the results of the sensitivity analysis described in Section 5.3 show that approaches update the safety stock proposal if the lead time increases or transportation costs become higher. The multi-echelon models search for the most-efficient way to allocate safety stocks and when for example the transportation costs become responsible for a great(er) part of the consolidated product costs, the safety stock is allocated at an earlier stage.

Furthermore, the assumption of having a customer lead time equal to zero means that some safety stock at the last stage of the network is required to cover the customer demand variability. The effect of this for the network of LSC could be interesting to further investigated in future research. It could be checked how realistic the assumption is and what would happen if the lead time is increased. However, the conclusion is that the placement of safety stock at the final stage might seem counter-intuitive to some, but the allocation is proven to be the most optimal.

6.1.2 Allocated Safety Stock Quantity

Even though the safety stock allocations are similar in terms of nodes as shown in Section 5.2, the quantity under a single-echelon approach is notably higher than under a multi-echelon approach. There are two potential reasons for this result. Firstly, the LSC currently uses Equation 36 which was discussed in Section 4.1.2 to determine the required amount of safety stock. This function includes the variance of the demand forecast error as it is used to determine how much safety stock is required in the future. The demand forecast error is measured per product and the average error for the full product portfolio of LSC is above 40%. More specifically, the forecast error for the majority of the selected part of the portfolio is approximately the same as shown in Appendix B in Table 13. This influences and increases the process of determining the required safety stock because the stock should cover the variability. In other words, it is an indication that LSC is structurally keeping too much safety stock.

Secondly, the employees of LSC described that there are a culture and processes in place where the local affiliates in countries dictate the discussion on how much inventory is required. The local affiliates have a financial incentive to always have sufficient safety stock, such that they can maximize their revenue. If it turns out at the end that there was too much safety stock, the local affiliate has no (financial) responsibility for this excess. Instead, the costs of writing off the surplus is the responsibility of the supply chain department of LSC. Therefore, the final statement of the previous paragraph is repeated and emphasized since there is an indication that LSC structurally keeps too much safety stock.

On the other hand, the holistic approach of the multi-echelon safety stock management concept has proven to lead to reducing inventory costs while achieving its service level. It manages this since it is better able to deal with the conflicting objectives within the concept - maximizing the overall fill rate against minimizing the safety stock costs (Ekanayake, Joshi, & Thekdi, 2016). Therefore, the output of the multi-echelon approaches being lower than the single-echelon costs is in line with the initial expectations.

6.1.3 Multi-Echelon Safety Stock Allocations

At the same time, the results of the multi-echelon model comparison in terms of costs, shown in Table **??**, are initially received as quite surprising by LSC. The results for LSC imply that the safety stock costs under the GSM are higher than under the SBSP. This conflicts with the findings by Graves and Willems (2003b) and Klosterhalfen and Minner (2010) which stated that the GSM in general proposes lower safety stocks than a stochastic approach due to the assumption of bounded demand. This assumption means that in case demand exceeds the bound, additional measures, such as longer production hours or outsourcing are taken to take care of the exceed. The model excludes this part of the demand in its safety stock proposal which leads to a lower suggested required quantity.

However, De Kok et al. (2018) proofed for the examples used in the work by Graves and Willems (2003b) that the SBSP outperforms the GSM and results in lower safety stock costs. There are multiple reasons identified why the SBSP results in lower safety stock costs than the GSM and the two most important ones are further discussed. Firstly, the ChainStock software tool that is used to model the SBSP also makes use of deterministic lead times as input which most likely leads to underestimating the required safety stock (T. de Kok, 2008; Peeters et al., 2020).

Secondly, for the GSM is a different MIME-situation modeled than for the SBSP. On the one hand, the GSM is individually applied on the identical network for six end-items which are created out of similar set of components. Thus, every time the optimal allocation within the supply network is computed for the individual end-item and its components. On the other hand, the SBSP is applied on the full set of end-items and components. This enables the SBSP to aggregate the standard deviation for components demand when the standard deviation for end-items is propagated further upstream. This leads to overall less demand variability within the network, yielding the output of proposing a lower required safety stock quantity to cover this variability. Therefore, it is safe to say that the results are consistent with the findings by De Kok et al. (2018). The fact that the SBSP leads to lower safety stock costs than the GSM is another confirmation that the SBSP is the superior concept.

To summarize and conclude, the strategic safety stock placement is discussed in three parts. Firstly, it is explained that the allocation of safety stock at the final stage of the network is most optimal and is in line with earlier findings. Next, the single-echelon and multi-echelon approaches are compared in terms of their results. The multi-echelon approaches yield the minimization of safety stock costs and maximization of the service level. This means these approaches lead to reduction of inventory costs and achieving or increasing the service level compared to the single-echelon approach. Finally, the multi-echelon approaches are compared with each other and it is discussed whether the proposed safety stocks are in line with the expectations. This leads to the conclusion that the SBSP is superior compared to the GSM.

6.2 Identification of Key-Model Parameters

The sensitivity analysis presented in Section 5.3 clearly showed that the parameters have a different influence on the performance of the methods. Subsequently, the findings of the analysis have been verified by a factorial analysis as described in Section 5.4. Therefore, the impact of the individual parameters is once more discussed and put in perspective. Also, it is examined for which products groups the multi-echelon approach is beneficial. This leads to the final conclusion regarding what the key-model parameters for pharmaceutical companies are that consider a multi-echelon approach.

6.2.1 Parameter Review

Service Level Adherence
The first parameter to review is the target service level. For the GSM, the model indicated that with the increase of target, every additional percentage-step has a higher marginal cost. This is likewise for the SBSP, but the marginal cost increase is less substantial for this method. In general, this finding is not spectacular, but it is definitely a relevant topic for companies and their the trade-off between safety stock costs and service. The objectives of minimizing the safety stock costs and maximizing the service are conflicting. Thus, organizations should consider what for them the optimal balance between the two aspects is or in other words, be aware that increasing the target service level comes at a cost. The benefits of the multi-echelon approaches are for all products impacted by the increasing target service level. Nevertheless, the SBSP seems to be for all products the superior method since it better able to deal with the changes in the target service level.

Demand Variability
The second parameter is the demand variability which showed to be of great importance in the setting of required safety stock. The output of the analysis for the GSM showed that there is a

positive linear relationship between the safety stock costs and the demand variability. The SBSP showed this positive relationship as well, but it is for this method not exactly linear. Either way, the output leads to the finding that the solution to minimize the demand variability and so the safety stock (costs) is two-sided. The first step is to establish a S&OP cycle between the local affiliates (sales), the headquarters (central entity) and the manufacturing sites (operations). This creates the alignment within the organization on what the demand for each product is and how the customers should be supplied. Demand variability is evident, but the alignment on the variability leads to better awareness and a more stable the supply chain. The final result of this initial alignment is that there is less safety stock required to achieve the target service level.

The second step is to increase the demand forecast accuracy, such that LSC knows more accurate how to plan the supply. Even the current single-echelon approach performance could hypothetically be improve this way. The current approach uses a forecast error of approximately 40% for its safety stock setting as mentioned in the previous section. Thus, by more accurately estimating the customer demand, the variability is better recognized and possibly reduced, leading to a reduction of the safety stock quantities and costs.

The benefits of the multi-echelon approaches are impacted by higher customer demand variability, but are nevertheless present. The results showed that the approaches are most beneficial for products with stable demand, independent on where in the network the stock is placed. The reason is that the stable demand allows more accurate supply chain planning. The multi-echelon approach is still beneficial for products with more demand variability, but the safety stock management will be more challenging. The complexity in the management can be reduced by allocating the safety stock further downstream since this simplifies the supply chain planning. Finally, for products with high demand variability and an safety stock allocation upstream in the network, it is worth to consider using a single-echelon approach. This allows more simple supply chain planning which leads to more stable supply chain performance and thus, lower safety stock costs.

Added Value
The third parameter to discuss is the added value per stage. The sensitivity analysis for the GSM on the transportation costs showed that for the products within the selection, storing the goods one stage earlier will be of interest as soon as the costs increase with a particular amount. For the products where the transportation costs are already relatively high, the GSM does not respond in its safety stock allocation to the increase of the costs. The quantity remains the same and allocated to two stages, with a little bit of stock on the last node and more on the first-to-last node.

The safety stock allocation under the SBSP reflects that it tries to avoid the higher transportation costs at final stage by proposing to keep more safety stock upstream. The results do not reflect this because item-stage combinations are only considered if the threshold of a 95% service level is matched which is not the case here. Nevertheless, the finding that safety stocks should be kept one stage earlier - before the shipment to the country - when the transportation costs increase is highly relevant and of interest for companies. The pandemic has triggered an increase of the freight costs, but most likely companies did not (yet) adjust their safety stock management strategies to this new reality. Therefore, the implications for safety stock management and opportunities to improve are briefly discussed in the next sub-section.

Lead Time Adherence
The fourth and final parameter to review is the lead time of a stage. The results of the analysis for the GSM showed that there is a positive linear relationship between the lead time length and the proposed safety stock costs. The combination for products with relatively long transportation times - cross-regional supplied - and lower lead time adherence indicate that LSC should consider the importance of this relationship. For the products with a lead time less than a week and which are transported (usually) by truck, the analysis showed that the effect of different lead times is negligible. These results are similar under the SBSP and therefore, they are not repeated nor further discussed. It is safe to say that the influence of the lead time on the safety stock allocation is significantly higher for products with relatively long transportation time (approximately more than one week) since their lead time adherence is in general lower. This indicates that LSC should

either consider this variability in its safety stock management approach or improve its lead time adherence to reduce this effect.

To summarize for all parameters, the sensitivity analysis is performed on the four input parameters to find the drivers of good multi-echelon safety stock management model performance. The analysis results show that the marginal costs of increasing the target service level become higher with every increment. Thus, this requires for all products a well-considered decision on how to balance the conflicting objectives of minimizing safety stock costs and maximizing service levels. Furthermore, the variability in customer demand showed to have a great influence on the safety stock costs. This variability can be reduced by organizations by establishing a high quality S&OP cycle and improving the demand forecast accuracy.

In addition, the finding of how the model responds to the increase of transportation costs is recognized as highly relevant in the light of current events. Freight costs have significantly increased during the pandemic, leading to the question whether redesigning supply networks for cross-regional supply is a way to further improve the safety stock management. Finally, the lead time has clearly an effect on the setting of safety stocks, but the results indicated that it is only an interesting factor when the lead time is longer than approximately one week. The lead time adherence makes in this case a significant difference. The opposite applies for products destined for countries that are supplied by truck and have lead time less than one week since it has been found that the safety stock costs are hardly affected by changes.

The benefits of the multi-echelon approaches are impacted by changes in the input parameters as shown in the sensitivity analysis in Section 5.3 and factorial analysis in Section 5.4. Nevertheless, the approaches seem both beneficial for all products - especially when the SBSP approach is applied since it is superior compared to the GSM. There is a distinction made between regionally and cross-regionally supplied products since the results show that the multi-echelon approach provides opportunities to further improve the safety stock management.

6.2.2 Network Redesign for Cross-Regional Supply

Whybark and Yang (1996) stated that organizations which serve its customers from inventory, it is best to place the inventory close(r) to the customer, especially when the target service level is high. The results of the multi-echelon allocation and the sensitivity analysis showed that the safety stock is placed at the last node of the network, but moved upstream if transportation costs increase for cross-regional supply.

In addition, the combination of the high costs and long lead times for processes at the beginning of network force the basic models to place safety stock towards the end. In other words, the processing of Bulk and Packaging Materials into Finished Goods takes too much time and is too expensive to create the conditions where it is interesting for keeping components as safety stock. Consequently, this could change when the packing process lead time becomes shorter and the process itself cheaper.

Therefore, it is proposed to investigate the benefits of redesigning the network for cross-regional supply. It is inevitable that to supply a country in another region, transportation over the ocean is required. The current situation is that the end-item is centrally produced at LSC's manufacturing site located in Germany from which every country in the world is supplied with Finished Goods. However, by transporting Bulk Material to regional packing hubs, these components are brought closer to the market at an earlier stage in the supply chain. The packing of products in for example Guatemala is considerably cheaper than in Germany. Furthermore, on the one hand, the lead time at the end of the chain is reduced since the shipping time from the regional hub to the rest of the region will be shorter than the current transportation time of the last stage of the network. On the other hand, the lead time adherence for shipments closer to the market most likely improves. Therefore, the conditions might be created to further minimize the safety stock costs for products that are currently cross-regional supplied.

6.3 Method Expansion Requirements

The initial scope of the project has been kept intentionally narrow since the concept of multi-echelon safety stock management becomes very complex for large networks and product portfolios. The GSM and SBSP have been applied to one supply network of six stages for six different end-items and presented to be able to result in a reduction of the safety stock costs while achieving or improving its service level. However, LSC has a much greater product portfolio and therefore, it is discussed what is required to further roll out the concept.

The first requirement is understanding the methodology of the multi-echelon safety stock management approach. The purpose is to find the optimal allocation for safety stocks in a supply network. The concept feels initially counter-intuitive to many people as it often proposes to keep the more expensive finished goods than the cheaper components. When supply chain planners do not understand that this is the most cost-efficient allocation, they will reject or change the proposed safety stock quantity by the model. Thus, there is no point of introducing the concept if its output is not trusted nor followed.

The second requirement is having accurate master data for every product. The more products to which the concept is applied, the more master data is required. The experience during the research project was that the data which was assumed to be available and easy to collect was in reality much harder to find. More specifically, the following master data took multiple months to collect:

- Bill of Materials
- Planned & Actual Lead Time of Raw Material Supply
- Planned & Actual Lead Time of Packaging Material Supply
- Planned & Actual Lead Time of Transporting Finished Goods

Furthermore, the collected data had often a static format, such as being a manual extract from the LSC's ERP system. That significantly increased the effort to collect the data and reduces its flexibility towards the future, such as when the BOM of a product changes. On a positive note, LSC already recognized the importance master data before the project started and it is currently putting time, money and effort in projects with the aim of improving the master data availability and quality.

The third expansion requirement is regarding identifying the supply network of a product. Logically, each different product(-family) and production line has a supply network with a unique form. Currently, there is no option within LSC to identify the network in a digital way, meaning that for an expansion, each network has to be modelled manually. During the research project, a visit to the manufacturing site to see the process in real-life was the key-step that led to the final model of the supply network. The reason is that each production line and/or manufacturing site has its own dynamics and restrictions which makes the modelling of the network based on data significantly more difficult. Therefore, to roll out the concept further to other manufacturing lines or sites, the participation and contribution of employees working at the site is of vital importance for modelling a supply network.

6.3.1 Model Run Time

Finally, the two multi-echelon approaches are also compared on the required time to run the models. For the GSM, it is a matter of seconds to solve the dynamic program and find an optimal safety stock allocation in the network for a single scenario. The sensitivity analysis with more than a thousand different scenarios per product requires multiple minutes per product to produce all output. For the SBSP, the situation is approximately the same, but slightly faster than the GSM. The expectation is that the required time to solve a single scenario for both approaches will gradually increase when expanding the scope of the model to a bigger network and/or more products. However, based on the current model performance, the increased required computational time should remain within reasonable boundaries. Therefore, the run time of both multi-echelon approaches are not expected to be an important factor in further rolling out the concept within LSC.

6.4 Generalization of Findings

The findings of the project are perceived as relevant for every pharmaceutical company and can easily be generalized. The pharmaceutical industry has some unique characteristics in terms of its supply chain (network) design and performance. Thus, it is first briefly discussed how applicable the findings are to other network structures. In addition, the industry's unique characteristics have been discussed at the beginning of this report in Section 1.1.2 in terms of four supply chain management sub-fields: *Demand Planning*, *Capacity Planning*, *Production Management* and *Inventory Management*. The multi-echelon safety stock management approach touches all of the four sub-fields within the general concept of supply chain management. Therefore, the findings are also briefly discussed in the context of each sub-field.

Other Supply Network Designs
The supply network of LSC has the structure of a spanning tree containing six nodes. Both the GSM and SBSP are applied to this structure, but the models can also be easily applied to different network structures. The GSM is able to solve the strategic safety stock placement problem for systems with a serial, assembly, distribution or general (spanning tree) structure (Snyder & Shen, 2019; Graves & Willems, 2000). The model only requires two changes to deal with another structure. The first one is that the new number of nodes of the network and their mutual relationships must be incorporated. The second one is that the data sets including the processing times need to be assigned to the corresponding stages. The algorithm of the GSM is then again able of finding the optimal solution for this different network structure.

The SBSP is as well able to find the optimal safety stock allocation for systems which have a serial, assembly, distribution or general structure. The difference with the GSM is that the SBSP is capable of dealing with any general network structure, not only spanning trees (T. de Kok & Fransoo, 2003). The required changes for the model to adapt to the new structure are the same as for the GSM. The new number of nodes has to be incorporated and the data sets with processing times should be assigned to the corresponding nodes. The complexity of the changes and how long the implementation of another network structure takes, depends on how many nodes the new network contains. Based on the findings, it is safe to say that for network sizes similar or slightly bigger than the of LSC, the complexity is low and the implementation time for both models is a matter of hours.

Demand Planning
The subject of demand planning showed to have great influence on safety stock management. However, the size of the importance is in general in conflict with the quality of the demand forecasting (Merkuryeva et al., 2019). The horizon ranges usually up to 12- to 24-months so this it is understandable that demand is bound to fluctuate on such long horizons (Grimson & Pyke, 2007). The results for the case study of LSC showed that the company currently uses a forecast error of 40% to predict their safety stocks under a single-echelon approach. A multi-echelon approach would outperform the current performance, but the approach could significantly be improved if the demand forecasting becomes more accurate. Therefore, this finding is because of its impact on the safety stock allocation relevant for any company that considers to start with multi-echelon safety stock management.

Capacity Planning
For capacity planning, it was mentioned earlier that realizing (additional) production capacity is difficult and expensive. In addition, the production is known for its unstable yields, making capacity planning a challenging process (Shah, 2004; Kaminsky & Wang, 2015). The latter is not considered within the case study since the yield is assumed to be equal to 100%. However, the

capacity planning is strongly dependent on the demand forecast and its accuracy on the noise within the demand signal. Therefore, the importance of accurate demand forecast is once more emphasized.

Production Management
The discussion of the sub-field of production management showed that the cycle times for pharmaceutical products are relative long. Excluding the procurement of APIs, the total lead time for the product portfolio selection is approximately 30 weeks - more than half of a year. These characteristics reduce the responsiveness to the market dynamics (Shah, 2004). Therefore, multi-echelon models often allocate safety stock close to the market to ensure achieving a high service level (Whybark & Yang, 1996). The finding for the case study of LSC is another confirmation of this statement which allows it to generalize this recommendation.

In addition, the results of the sensitivity analysis gave reason to further investigate the benefits of redesigning a supply network in the case of cross-regional supply. The combination of long lead times, low lead time adherence, high transportation costs and lower labor costs in these regional packing hubs showed to be a set of interesting conditions within the supply chain. Altogether, it provides reasons to think that redesigning the network could lead to a further minimization of the safety stock costs. These conditions are not only applying to LSC and therefore, this topic is relevant for every global life science company.

Inventory Management
Finally, the key-finding of this research project is that a multi-echelon safety stock management approach is capable of reducing the safety stock costs while achieving or improving its (target) service level. This finding is in line with other applications of the methodology, but so is the reason why there is a lack of real-world applications. The approach is complex and feels to many people counter-intuitive which results in the reality that organizations choose for another way to manage their safety stock. Therefore, there are several recommendations for LSC provided in the next sub-section.

6.5 Company Recommendation

The company recommendations are ordered on their importance to give clear guidance to LSC on what its next steps should be to start with multi-echelon safety stock management. The first action the organization is recommended to undertake is improving its demand forecast accuracy. Independent from whether they use the currently in place single-echelon approach or start using a multi-echelon model, the costs of safety stock depend on the customer demand variability. Consequently, accurately estimating the customer demand leads to a reduction of the safety stock costs or improvement of the service level. The culture and processes where countries currently dictate the discussion on how much safety stock they want is related to this. The local affiliate creates the demand forecast and has a financial incentive to always have sufficient stock to maximize its revenue, but this leads to having too much safety stock. Therefore, this matter should should continuously be challenged.

The second step is that LSC should improve its master data quality. It became clear that the multi-echelon safety stock management approach is highly dependent on the quality of the master data. In other words, the models require data for its many input parameters and if the quality is insufficient, the proposed safety stock quantities will be inaccurate. Also, the application on a large scale requires the sufficient availability of master data to become a success. Hence, this recommendation is listed second for the LSC.

The third recommendation is to reconsider the current set up of the supply network. The real-world supply chain dynamics with long lead times, low lead time adherence and high transportation costs strongly influence the management of safety stock. The supply network design where some products are supplied cross-regionally seem sub-optimal with these new dynamics. Therefore, it is recommended to LSC to further investigate the benefits and disadvantages of changing the supply network to one with for example regional packaging hubs.

The fourth and final recommendation is that LSC should invest in knowledge too make the further roll out of the multi-echelon safety stock management approach a success. The approach is capable of reducing the safety stock costs and achieving or improving the (target) service level, but the method is complex and feels to some people counter-intuitive. As a result, supply chain managers will for example adjust or reject the safety stock allocations by the model. Therefore, it is important that the appropriate knowledge is present within the organization if LSC aims for implementing this methodology.

6.6 Limitations

The limitations of the research project which influenced the quality of the results are discussed in this section. The first limitation is that the comparison between the GSM and SBSP is not completely fair. Even though both situations are considered as MIME-problems, the models run in a different way. For the GSM, the algorithm determines for each individual end-item and its components how much safety stock is required and what the optimal allocation within the network is. However, the SBSP performs simultaneously the safety stock allocation for all end-items and their (shared) components which have the same supply network design. This allows the SBSP to aggregate standard deviation for components that is propagated from the demand-stage upstream, resulting in a lower standard deviation on average. As a result of having less variability in the chain upstream, the SBSP can propose lower safety stock quantities to cover up the variability of customer demand.

The second limitation is that the supply variability is not considered in the models. It is assumed that when components are ordered, suppliers deliver the exact ordered quantity. However, this is not always the case in the real-world and therefore, the material availability is unstable. During the research project, there have been multiple examples of situations within LSC where suppliers prioritized other customers of their products over LSC. Also, sometimes are suppliers simply unable to supply the ordered materials due to effects of the global pandemic. Thus, by excluding this supply variability, the models underestimate the required amount of safety stocks.

The third and final limitations is that the shelf life of products is not considered. In the case that models recommend to keep Finished Goods as safety stock for products with high demand uncertainty, there will be more safety stock kept. However, the combination of perishability of products and high demand uncertainty lead to significant obsolesces risks. In the event of having less demand than expected, products expire which means have to be written-off and destroyed because they cannot be sold anymore. The costs of destroying products make multiple percentages of the cost of goods sold and therefore, they influence the costs of safety stocks.

6.7 Future Research

Finally, three directions for future research projects are proposed. The first one has already been discussed and includes researching the benefits of redesigning the supply network for products which have cross-regional supply. The pandemic has increased freight costs significantly and in addition, the lead time adherence on cross-regional shipment is relatively low. This makes it potentially more attractive for LSC to pack products in regional hubs, such that the components are brought closer to the market in an earlier stage and the production costs can be reduced as the labor here most likely costs less.

The second proposed research directions is further investigating the operational impact of the multi-echelon approach. It would be interesting to compare the model output with the production runs that are planned. The proposed quantity might be efficient in terms of how much safety stock to keep, but not when it has to be produced. When the proposed quantity would only be half of what is actually required for a production run, the achieved cost-efficiency is canceled out by the increase in production costs. Moreover, the yield of production processes in assumed to be 100% while in reality it is lower for pharmaceutical production. Therefore, alignment between the multi-echelon safety stock and the operational dynamics and requirements of a manufacturing site could further contribute to minimizing the safety stock costs.

The third proposed research direction is the further investigation of multi-echelon safety stock management within the pharmaceutical industry. The case study results showed that the approach is well-capable of dealing with the conflicting objectives of safety stock costs minimization and service level maximization. However, the concept touches many functions within the supply chain and therefore, the application has a significant impact on the supply chain management. This project has tried to fill a part of the gap for the pharmaceutical industry, but there are many less or more complex products and supply networks. Therefore, further investigating this subject would provide pharmaceutical companies more opportunities to learn how the methodology can be successfully applied in practice.

7 Alignment & Conclusion

In this final section, the Master Thesis project is concluded. The section consists of two parts, where the first part includes an alignment on the research project. In the alignment, the answers to all sub-questions are once more briefly discussed. In the second part, the final conclusion of the project is presented by answering the main-research question.

7.1 Research Alignment

The six defined sub-questions and their answers are the following:

1. What is the current safety stock strategy?
The inventory of LSC is currently centrally managed according to an inventory control policy. Thus, the management is optimized via applying an holistic view on the supply chain. In addition, the company practices an installation policy which is in contrast with the proposed echelon policies. Since the organization only stores safety stock at the end of the network, the inventory control of LSC can also be explained as applying a single-echelon approach. It applies a *R, s, S* replenishment strategy to the this stage as described in Sections 1.2 and 4.1. The required safety stock quantity per product is computed with Equation 36 and it is once more shown here below.

$$SS = k * \sqrt{\sigma_D^2 * LT + D^2 * \sigma_{LT}^2} \tag{37}$$

In the equation, variable SS corresponds to the calculated safety stock quantity. The safety stock quantity can be converted to DOS by combining the quantity with the demand forecast. The variable k denotes the Alpha-Service-Factor. The service factor differs per product and depends on the assigned product classification. A product is classified as an A-, B-, C- or D-product and consequently, a target service level is assigned. The service-factor is derived from this target service level. Furthermore, D^2 represents the actual sales over the past twelve months and σ_D^2 the variance of the demand forecast error over the past twelve months. Finally, the LT denotes the replenishment lead time and, σ_{LT}^2 the variance of the replenishment lead time.

2. What are the safety stock costs and the service levels under the current safety stock strategy?
The safety stock costs and achieved service levels are reviewed in Section 5.1 for each product within the product portfolio selection. An overview of the safety stock costs for each product under the single-echelon approach is illustrated in Section 5.2. The safety stock quantity kept per week for each product is depicted in the Figures 31a to 33b in Appendix E. The quantities clearly fluctuate which indicates that the safety stock has been used and replenished according to the current safety stock strategy.

In general, the service level was for the product portfolio selection for 95% of the considered weeks equal or higher than the target service level of 95% as shown in Appendix E in Figures 40a to 42b. There was an exception for one product where the case fill rate was approximately 0% for multiple consecutive weeks. This was also recognized within the kept amount of safety stock since the quantity decreased during this period.

3. What multi-echelon safety stock management model is suitable for the supply chain of the Life Science Company?
This sub-question has been answered by analyzing the available literature on multi-echelon safety stock management in Section 2. The conclusion of the section was that Guaranteed Service Model by Graves and Willems (2003b) and the Synchronized Base Stock Policy by De Kok and Visschers (1999) seemed to be most promising for application on a real-world supply chain such as the one of LSC. Moreover, they are well-capable of dealing with the conflicting objectives of minimizing inventory costs and maximizing the service level. In terms of financial impact, applications indicate potential safety stock cost reductions ranging from 25% to 50% (Graves & Willems, 2003b). More specifically, the work by Graves and Willems (2000) provides an algorithm how the Guaranteed Service Approach can be applied to a real-world supply chain. The applies for the articles by

Diks and de Kok (1999) and De Kok and Visschers (1999) about the Synchronized Base Stock Policy. An example of an application of this approach is provided in the article by De Kok et al. (2005).

The difference between the two models is that on the one hand, the Guaranteed Service Model assumes that demand is bounded. In addition, the model is based on the assumption that a stage quotes a service time to an adjacent stage in which it guarantees to supply materials. This leads to a model with deterministic and predictable service time which is capable of optimizing the safety stock allocation throughout a supply chain. On the other hand, the Synchronized Base Stock Policy is based on BOM of an end-item and the cumulative lead times within the supply chain. The BOM represents the relationships between items, such as how much of an item is required. The cumulative lead time determines the decision-making process regarding releasing orders in the chain to cover the end-item demand. Consequently, the policy synchronizes the process of timing the order releases and the order quantity which distinguishes this approach from the Guaranteed Service Model.

4. What would the safety stock costs and the service levels be with a multi-echelon safety stock management model in place?
The multi-echelon safety stock management models both propose significantly lower safety stock quantities than the single-echelon approach while achieving the target service level of 95%. The (proposed) safety stock quantities are compared in Section 5.2 and show that average cost reduction for the GSM is 10.6% and for the SBSP 26.7%. Therefore, it is concluded that from the two applied multi-echelon safety stock management approaches, the SBSP is the superior one.

5. What are the benefits and disadvantages regarding the safety stock costs and service levels with a multi-echelon safety stock management approach?
There are multiple benefits of the multi-echelon safety stock management approach for the safety stock costs and service levels discussed in Section 6. The most important one is that the approach is proposing to keep less safety stocks which leads to a reduction of the safety stock costs while achieving or improving the (target) service level. Furthermore, it is explained in Sections 5.3, 5.4 and 6.2 for which products the multi-echelon approaches are most beneficial

The greatest disadvantage of the method is that significantly more master data is required to apply the concept on a large scale and that the correctness of the data strongly influences how successful the application is. Furthermore, the method feels to some people counter-intuitive which could lead to changing or rejecting the safety stock allocation. This decreases the probability of successfully apply the multi-echelon safety stock approach within the organization.

6. What is required to further roll out the multi-echelon safety stock management approach in the Life Science Company?
This sub-question has been answered in Section 6.3 and 6.5 by defining requirements and giving recommendations to LSC. Firstly, the organization should improve its demand forecasting accuracy as basically safety stock is used to cover variability in customer demand. The improvement of the forecast accuracy allows the company to better manage its safety stocks, leading either to a reduction of the costs or an improvement of the service levels. Secondly, to roll out the approach further within LSC, it is required to invest in knowledge, such that each employee completely understands the method. Thirdly, the availability and quality of the master of each product which is managed according to the multi-echelon approach has to be improved. The reason is that the concept depends significantly on the availability and quality of the master data. The fourth and final requirement is to find an efficient solution for identifying the supply network of each product. This step currently requires currently much time and effort which makes it more challenging to roll out the approach on a large scale within LSC.

7.2 Conclusion

The final conclusion of the project is given by answering the main research question defined at the beginning of the research project. The research question was defined the following:

How can a multi-echelon safety stock management approach reduce the inventory costs and improve the service levels of the Life Science Company?

The results of the project showed that the multi-echelon approach is better capable of dealing with the conflicting objectives of minimizing the safety stock costs and maximizing the service level. More specifically, the safety stock allocation under the Synchronized Base Stock Policy for the product portfolio selection indicated potential cost reductions of on average 26.7%. This makes the method superior compared to the single-echelon approach which is currently used by LSC and the Guaranteed Service Model. The multi-echelon approaches both propose in general to allocate (most of) the safety stock at the final stage of the modeled supply network. However, the results of the sensitivity analysis showed that the combination of long lead times, low lead time adherence and high production and transportation costs make redesigning the supply network seem to be an interesting option to further minimize the safety stock costs.

Furthermore, the results of the model comparison and the sensitivity analysis lead to the identification of key-model parameters. This results in the recommendation of focusing on improving the demand forecasting accuracy, increasing the master data quality, investing more in knowledge and finding an efficient way of identifying the supply network of each product. All these recommendations should improve the safety stock management and make the application on a larger scale successful within LSC.

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A Appendix A - Inventory Review

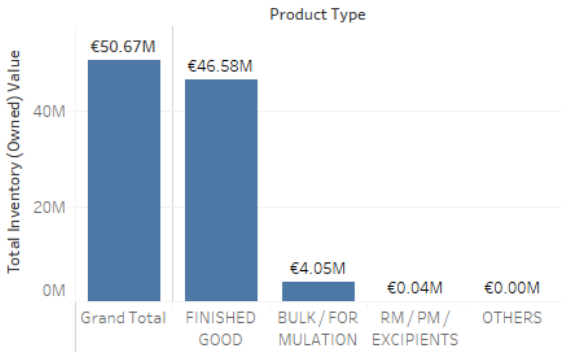


Figure 17: Inventory Value per Product Type

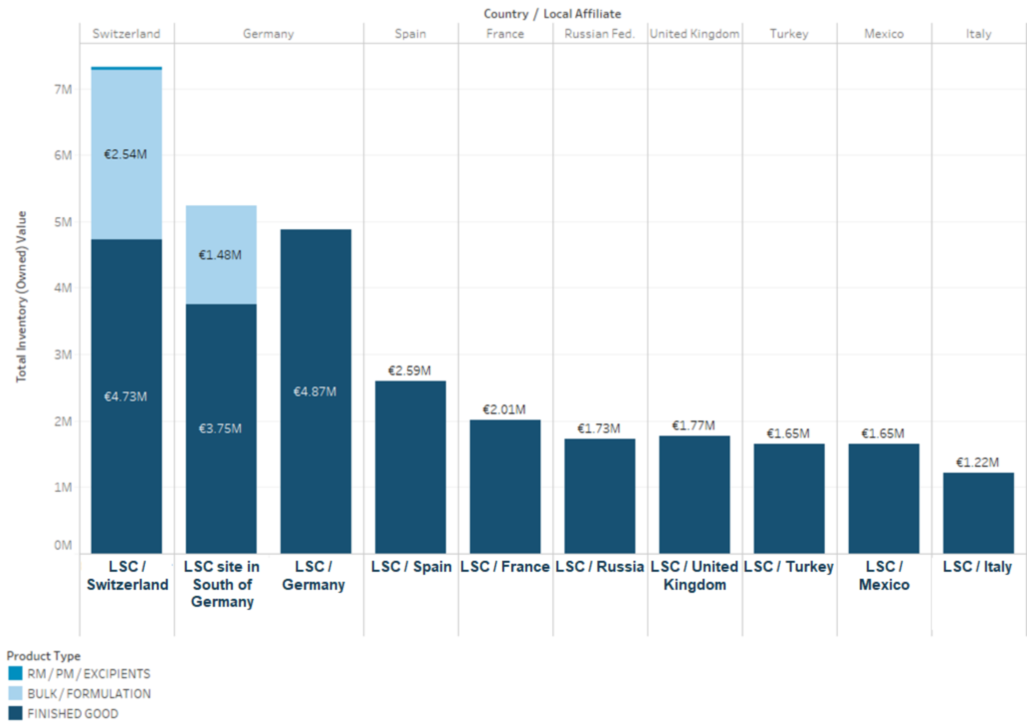


Figure 18: Storage Location of Product Types

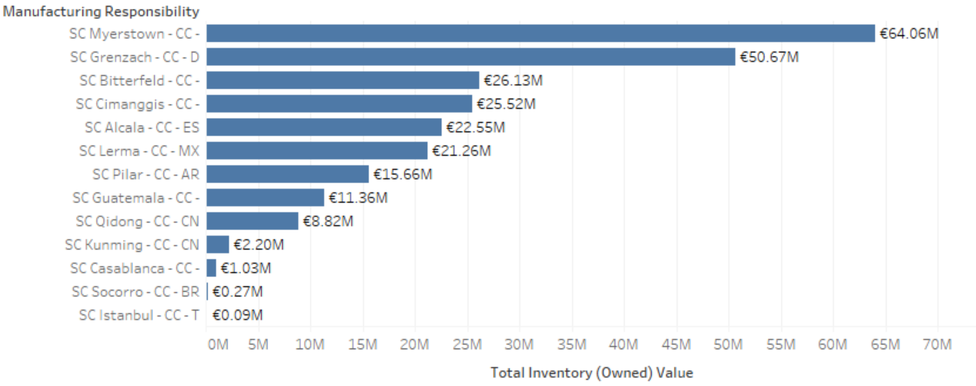


Figure 19: Inventory Value per Manufacturing Site

B Appendix B - Product Portfolio Selection

Table 10: Full Product Portfolio Line 36 - 1

SKU	Material Description
11873226	Canesten Crema 1% 20g CL
11873230	EMPECID cre x20g AR
11873231	Baycuten Crema Pomo 15g CL
11873238	Canesten Crema 1% 20g UY
11873239	Baycuten Crema 40g BR
11873257	Canesten Topical cream 1% 15g CA
11873258	Canesten Topical cream 1% 30g CA
11873262	Canesten External Cream 1% 15g CA
11873263	Canesten Crema 1% 20g BR
11873533	Canesten Crema 1% 30g MX
11873536	Canesten Dual Crema 1% 10g MX
11873583	Canesten 1 Day Tab/Cream Combipak CA
81221006	CAN Urea 10g PT
81493855	CANESTEN CREMA TOPICA 1% X 50GR IMP
81493863	CANESTEN CREMA TOPICA X 20GR IMP
81545774	CANESTEN ULTRA CREMA X 15GR IMP CO
82228721	CANESTEN CR 1% x 20 GR PE
82485554	CAN Urea 10g GB
84026719	CAN Urea 10g IE
84142352	Canesten Cream 1% 10g tube Kern
84175005	CAN Urea 10g GR
84374342	CAN Urea 10g FI
84656666	CAN Urea 10g AUS
84845337	CAN Urea 10g MA
85139150	Canespor Cream 1% 15g GT
85690604	Lotrimin Uno CREA 20gr MX
86189976	Canesten 1% CREA 15g GT
86570009	Canesten Extra 1% CREA 50g DE
86621371	Canesten Gyn 2% CREA 15g CA
86634570	Canesten Clotrimazol 1% CREA 30g AT
86824663	Canesten Skin 1% CREA 30g NL
86844583	Canesten Clotrimazole 1%CREA TUBE 30g HU
86865130	Canesten Gyn 2% CREA 15g CA - Bulk tube
86907550	Canesten DA 1% CREA TUBE 30g GB
86907577	Canesten 1% CREA TUBE 50g GB
86913550	Canesten 1% CREA TUBE 50g DE
86915030	Canesten 1% CREA TUBE 30 MD/RO
86940957	Canesten 1% CREA TUBE 50g IE
86947552	Clotrimazol Canesmed 10mg/g CREA 30g ES

Table 11: Full Product Portfolio Line 36 - 2

SKU	Material Description
86947595	Canesmycospor 1% CREA TUBE 20g ES
86947692	Canespie Clotrimazol 10mg/g CREA 30g ES
86948869	Canesten 10mg/g CREA TUBE 30g ES
86949180	Mycohydralin 1% CREA TUBE 20g FR
86988712	Canesten OnceDailyBifon 1%CREA 30g AU/NZ
87056198	Canesten 1% CREA TUBE 20g CH
87056201	Canesten 1% CREA TUBE 50g CH
87090469	SEM Tube Canesten 500mg OVU 1+1% CREA SI
87155471	SEM Tube Canesten 500mg OVU+1% CR 20 NO
87155501	SEM Tube Canesten 500mg + 1% CREA SE/NO
87235416	Canesten 1% CREA TUF 50g SK
87235432	Canesten 1% CREA TUF 50g CZ
87378187	SEM Can Extra Nail Set Oint 10g DE
87437159	SEM Canespor Denne OINT 10g Nail Set CZ
87468232	CAN Bifonazole 20g (FS inkl. Tube) AUS
87502554	CAN Canespor Onychoset 10 PL
87390330	Canesten 1% CREA TUF 20g IL
88049179	SEM Canesmycospor Onicoset ES

Table 12: Bulk Materials of Product Portfolio Line 36

SKU	Bulk Description
10104553	Canesten Clotrimazole Creme 1%
10104551	Baycuten N Creme
11874759	Urea Salbe (OniCombo)
81520801	Mycospor Creme 1% (new API)
10104552	Canesten Creme 2%
80644671	Canesten Creme 1% (2% B) (1600980)
85878743	Canesten Derm Urea Ointment

Table 13: Selection product portfolio decision variables

Bulk Material	Finished Good	Production Frequency	Forecast Error	Std. Dev. of Forecast Error
Mycospor Creme 1%	Canesten Extra 1% CREA 50g DE	16	26.7%	21.2%
	Lotrimin Uno CREA 20gr MX	12	61.5%	63.7%
Canesten Clotrimazole Creme 1%	Canesten External Cream 1% 15g CA	16	37.6%	17.4%
	Canesten Crema 1% 30g MX	8	18.1%	15.3%
	Canesten 1% CREA 15g GT	52	41.1%	53.2%
Canesten Creme 1% (2% B)	Clotrimazol Canesmed 10mg/g CREA 30g ES	4	5.3%	5.7%

Table 14: Selection product portfolio additional parameters

Bulk material	**Finished good**	**Product Classification**	**Sales Value**	**Sales Qty.**	**Total Owned Inventory Value**	**CFR**	**Write-offs value**
Mycospor Creme 1%	Canesten Extra 1% CREA 50g DE	2	€ 3,002,471.29	319,552	€ 824,174.00	98.3%	€ 2.48
	Lotrimin Uno CREA 20gr MX	2	€ 1,195,430.60	657,024	€ 1,964,855.00	99.1%	€ 131.04
Canesten Clotrimazole Creme 1%	Canesten External Cream 1% 15g CA	1	€ 1,364,443.02	419,845	€ 2,021,621.00	86.3%	€ 4.06
	Canesten Crema 1% 30g MX	2	€ 1,245,490.11	583,500	€ 3,532,096.00	99.9%	€ 10.34
	Canesten 1% CREA 15g GT	1	€ 1,137,240.56	325,182	€ 1,129,192.00	99.6%	€ 0.21
Canesten Creme 1% (2% B)	Clotrimazol Canesmed 10mg/g CREA 30g ES	1	€ 966,647.58	535,408	€ 2,189,505.00	100.0%	€ 0.06

C Appendix C - Sales & Operations Planning

Figure 20: Overview Sales & Operations Planning

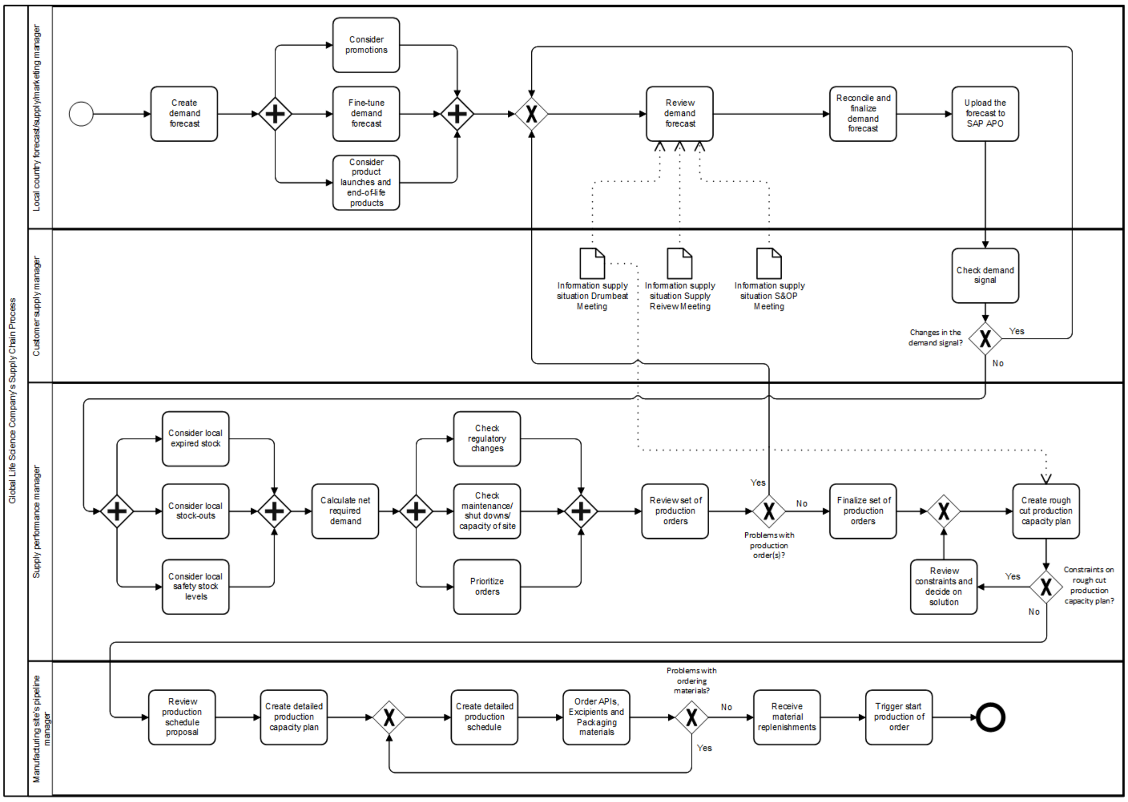
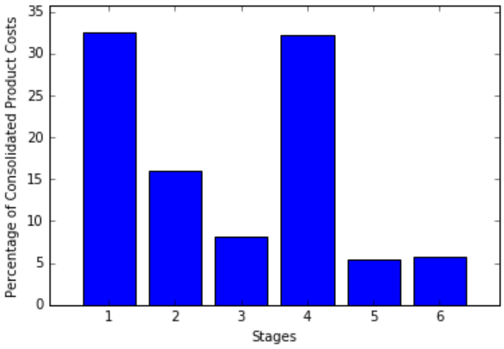


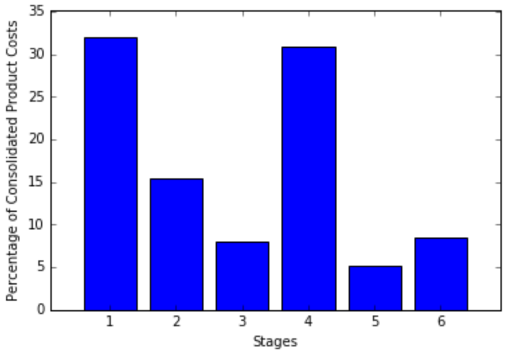
Figure 21: Supply Chain Planning Process

D Appendix D - Supply Chain Characteristics

Added Value per Stage

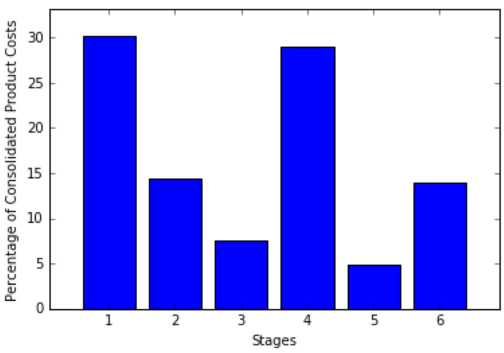


(a) Product 11873262 - SE Added Value per Stage

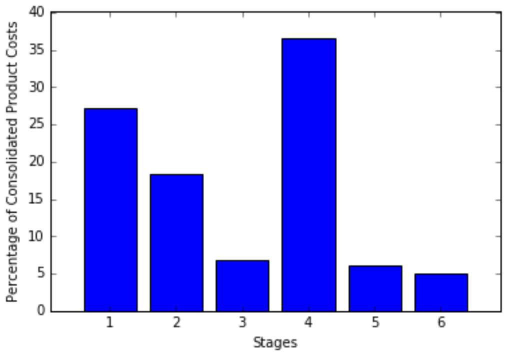


(b) Product 11873533 - SE Added Value per Stage

Figure 22: Single-Echelon Added Value per Stage - 1

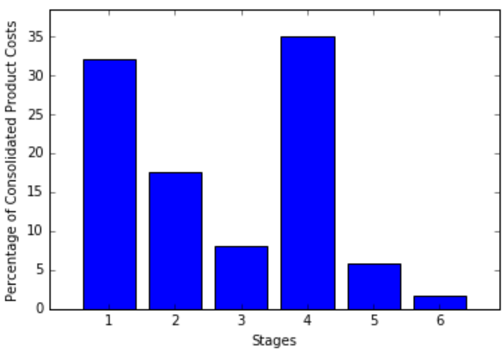


(a) Product 85690604 - SE Added Value per Stage

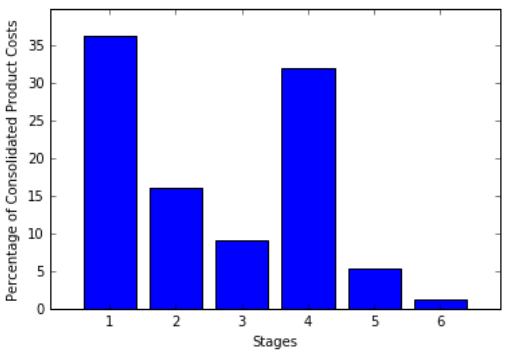


(b) Product 86189976 - SE Added Value per Stage

Figure 23: Single-Echelon Added Value per Stage - 2



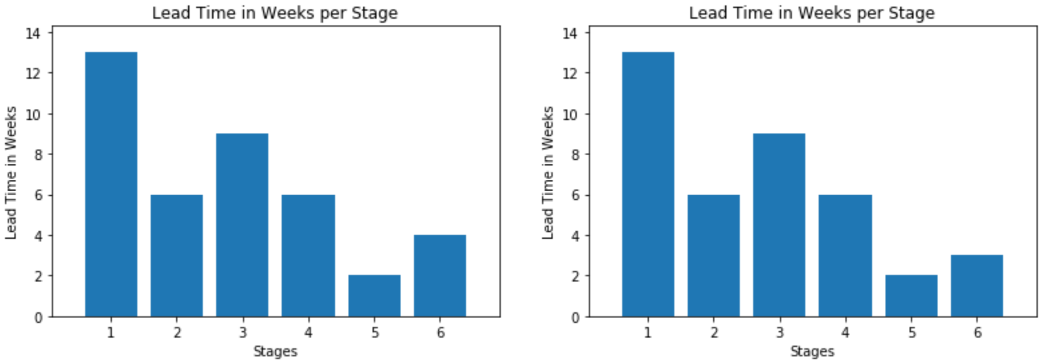
(a) Product 86570009 - SE Added Value per Stage



(b) Product 86947552 - SE Added Value per Stage

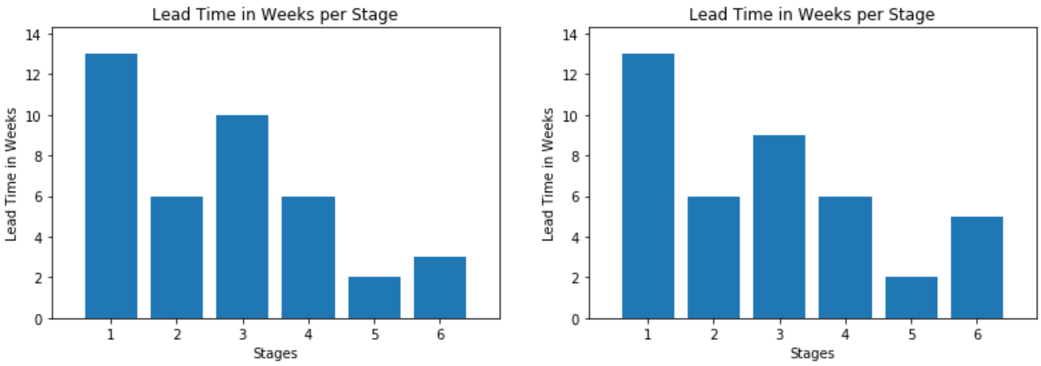
Figure 24: Single-Echelon Added Value per Stage - 3

Lead Time in Weeks per Stage



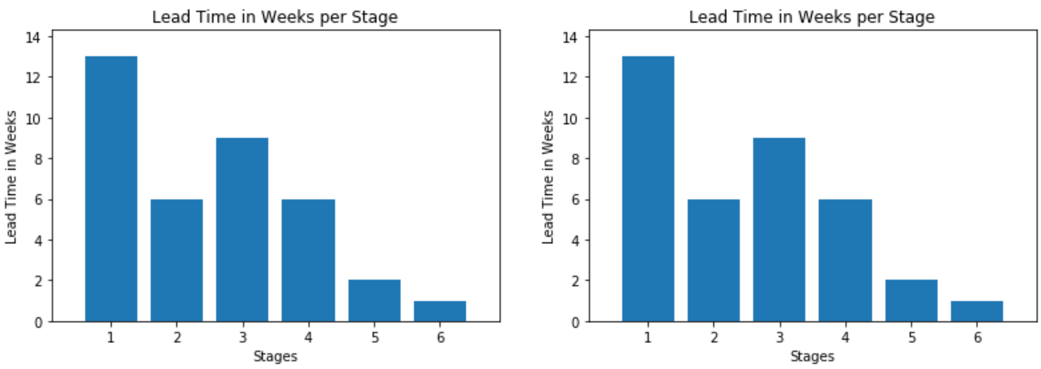
(a) Product 11873262 - SE Lead Time per Stage (b) Product 11873533 - SE Lead Time per Stage

Figure 25: Single-Echelon Lead Time in Weeks per Stage - 1



(a) Product 85690604 - SE Lead Time per Stage (b) Product 86189976 - SE Lead Time per Stage

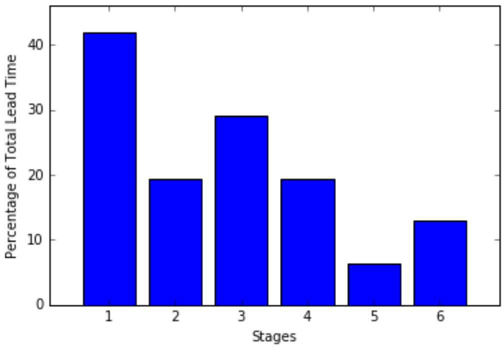
Figure 26: Single-Echelon Lead Time in Weeks per Stage - 2



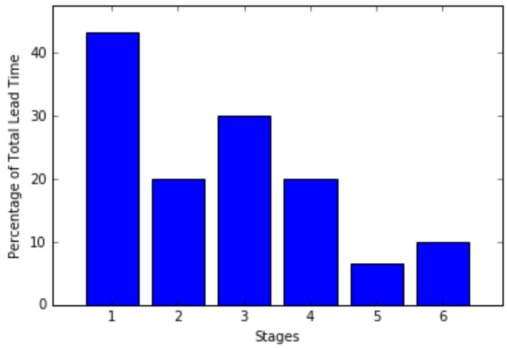
(a) Product 86570009 - SE Lead Time per Stage (b) Product 86947552 - SE Lead Time per Stage

Figure 27: Single-Echelon Lead Time in Weeks per Stage - 3

Lead Time Percentage of Total per Stage

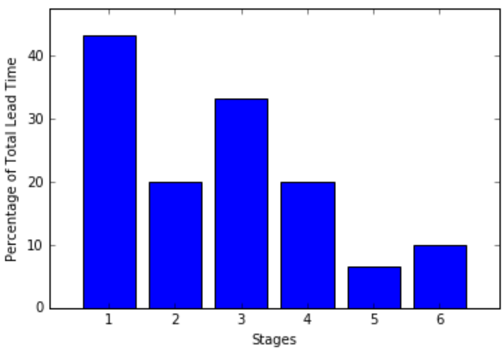


(a) Product 11873262 - SE Lead Time Percentage of Total per Stage

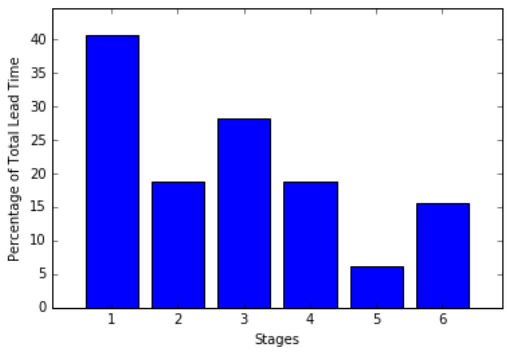


(b) Product 11873533 - SE Lead Time Percentage of Total per Stage

Figure 28: Single-Echelon Lead Time Percentage of Total per Stage - 1

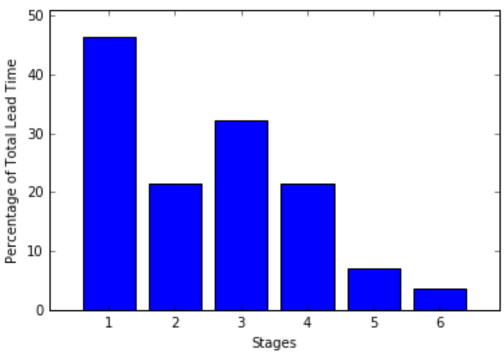


(a) Product 85690604 - SE Lead Time Percentage of Total per Stage

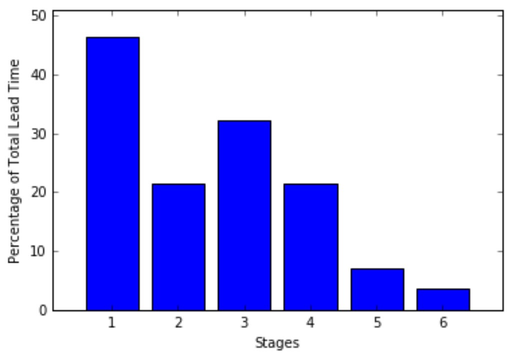


(b) Product 86189976 - SE Lead Time Percentage of Total per Stage

Figure 29: Single-Echelon Lead Time Percentage of Total per Stage - 2



(a) Product 86570009 - SE Lead Time Percentage of Total per Stage

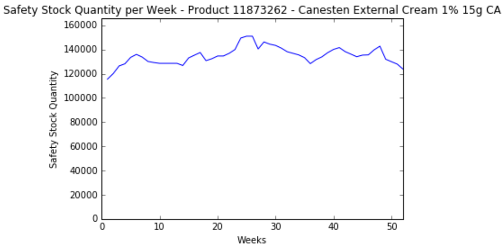


(b) Product 86947552 - SE Lead Time Percentage of Total per Stage

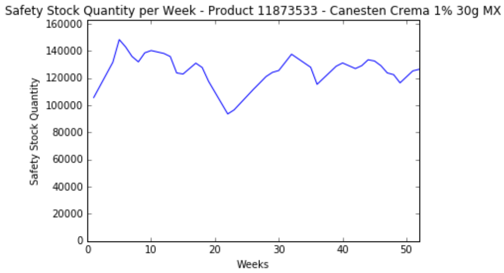
Figure 30: Single-Echelon Lead Time Percentage of Total per Stage - 3

E Appendix E - Single Echelon Performance

Single-Echelon Safety Stock Quantity per Week

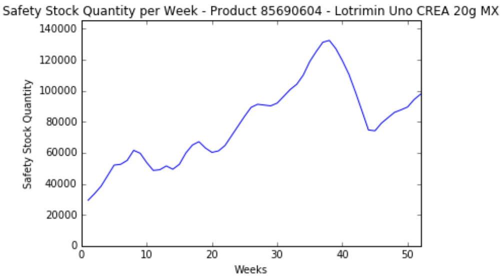


(a) Product 11873262 - SE Safety Stock Quantity per Week

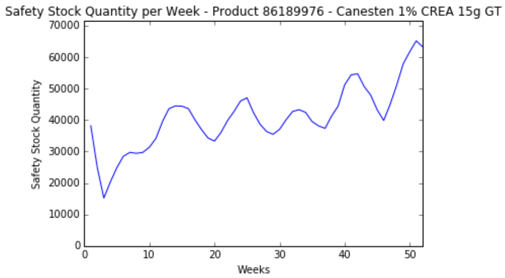


(b) Product 11873533 - SE Safety Stock Quantity per Week

Figure 31: Single-Echelon Safety Stock Quantity per Week - 1

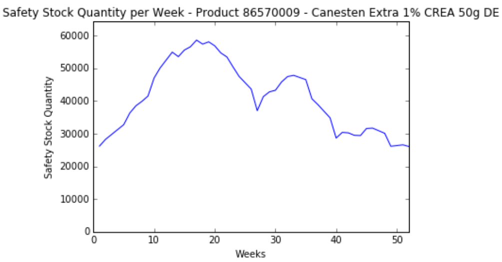


(a) Product 85690604 - SE Safety Stock Quantity per Week

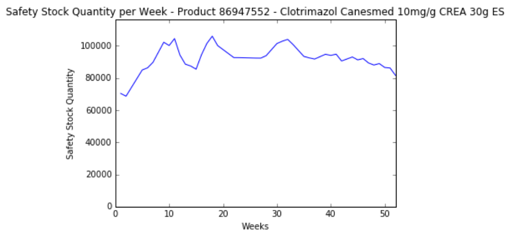


(b) Product 86189976 - SE Safety Stock Quantity per Week

Figure 32: Single-Echelon Safety Stock Quantity per Week - 2



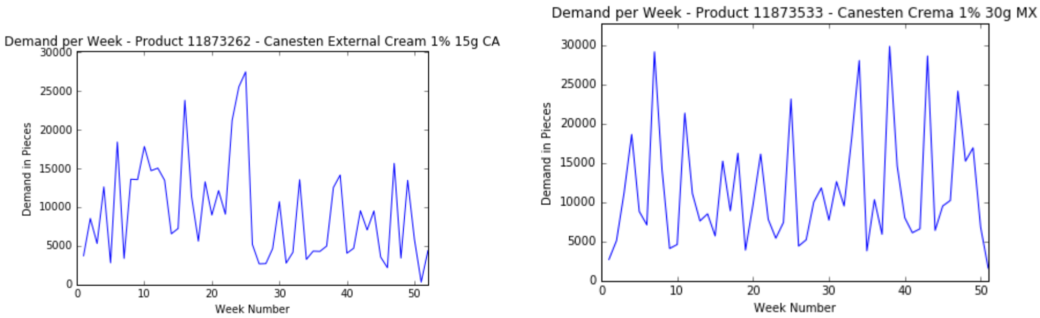
(a) Product 86570009 - SE Safety Stock Quantity per Week



(b) Product 86947552 - SE Safety Stock Quantity per Week

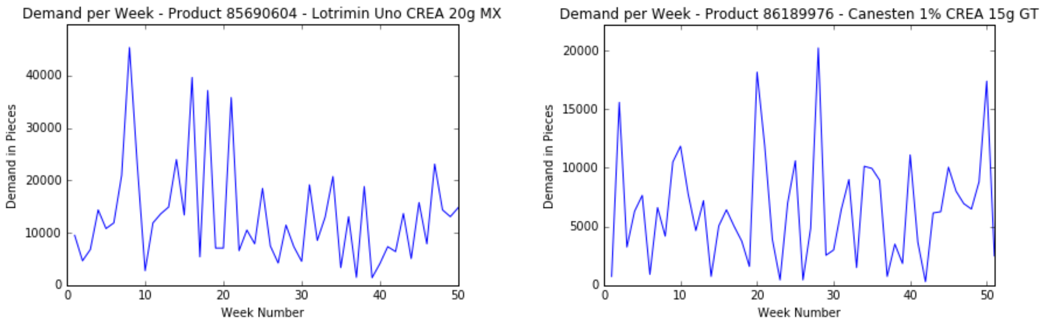
Figure 33: Single-Echelon Safety Stock Quantity per Week - 3

Single-Echelon Customer Demand



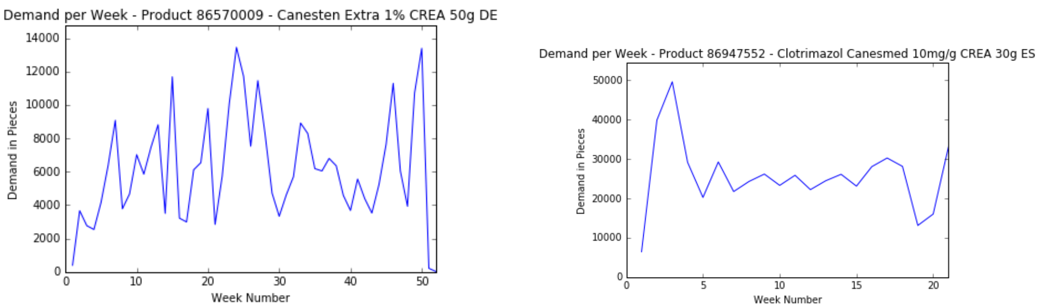
(a) Product 11873262 - SE Demand per Week (b) Product 11873533 - SE Demand per Week

Figure 34: Single-Echelon Demand per Week - 1



(a) Product 85690604 - SE Demand per Week (b) Product 86189976 - SE Demand per Week

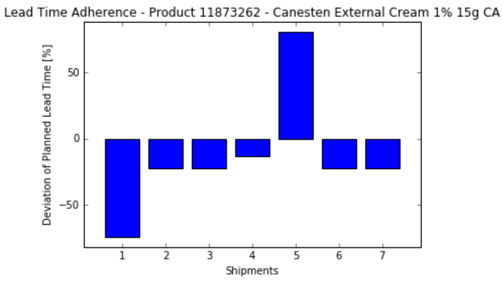
Figure 35: Single-Echelon Demand per Week - 2



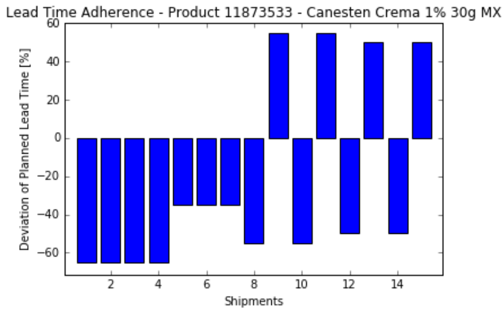
(a) Product 86570009 - SE Demand per Week (b) Product 86947552 - SE Demand per Week

Figure 36: Single-Echelon Demand per Week - 3

Single-Echelon Planned & Actual Lead Time

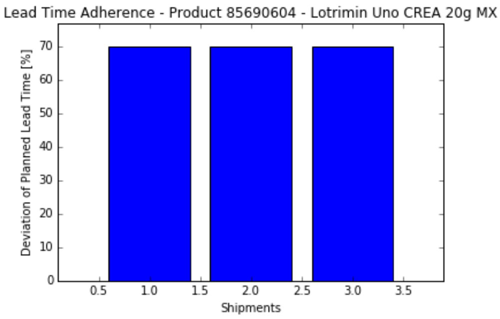


(a) Product 11873262 - SE Lead Time Adherence

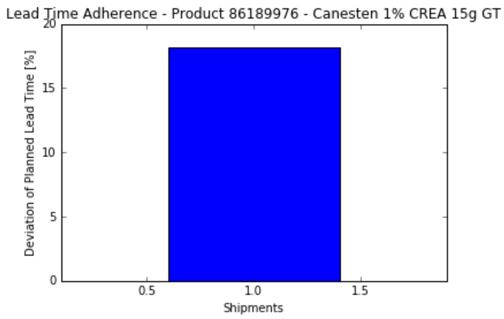


(b) Product 11873533 - SE Lead Time Adherence

Figure 37: Single-Echelon Lead Time Adherence - 1

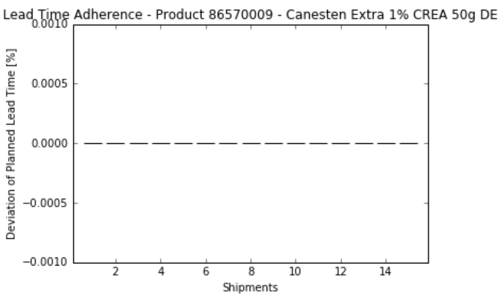


(a) Product 85690604 - SE Lead Time Adherence

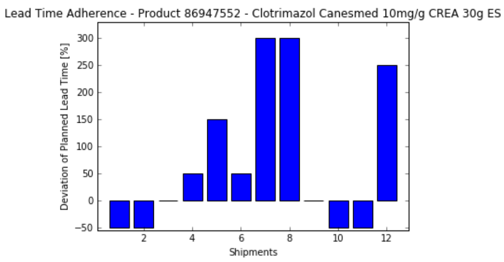


(b) Product 86189976 - SE Lead Time Adherence

Figure 38: Single-Echelon Lead Time Adherence - 2



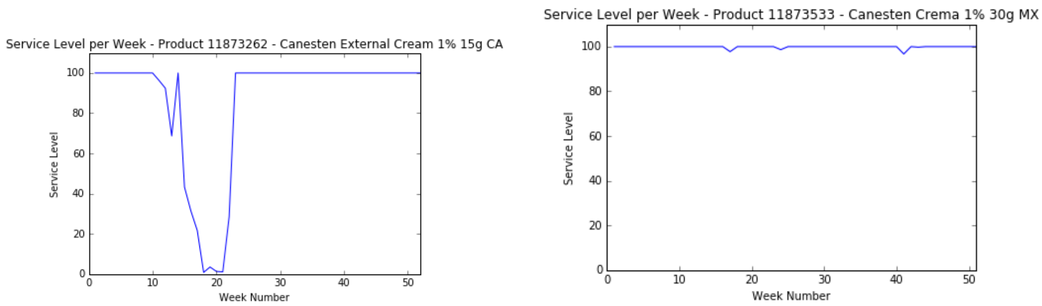
(a) Product 86570009 - SE Lead Time Adherence



(b) Product 86947552 - SE Lead Time Adherence

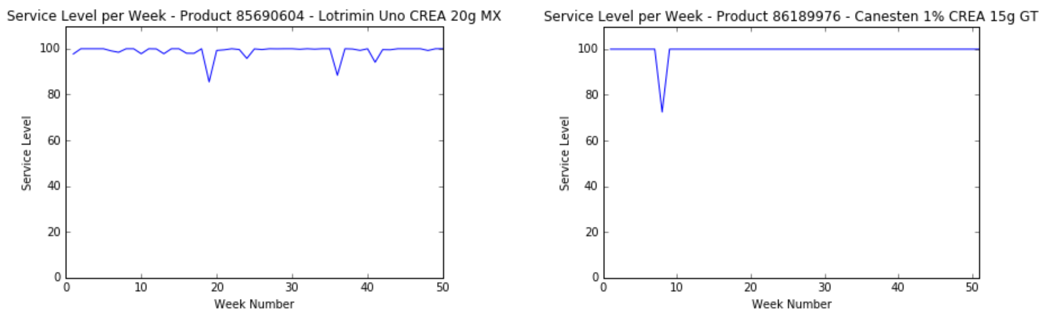
Figure 39: Single-Echelon Lead Time Adherence - 3

Single-Echelon Service Levels per Week



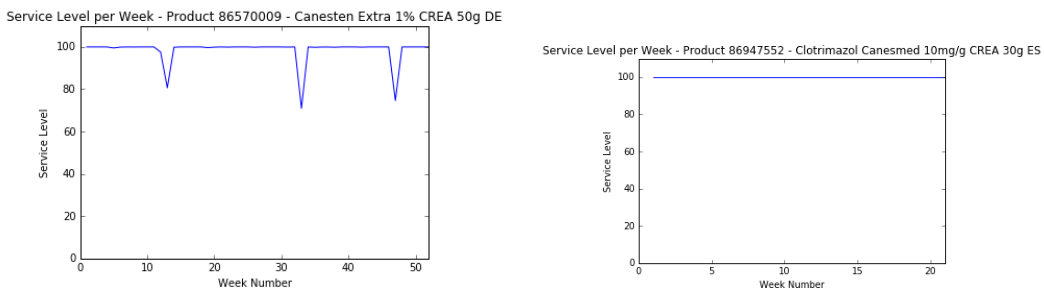
(a) Product 11873262 - SE Service Level per Week (b) Product 11873533 - SE Service Level per Week

Figure 40: Single-Echelon Service Level per Week - 1



(a) Product 85690604 - SE Service Level per Week (b) Product 86189976 - SE Service Level per Week

Figure 41: Single-Echelon Service Level per Week - 2

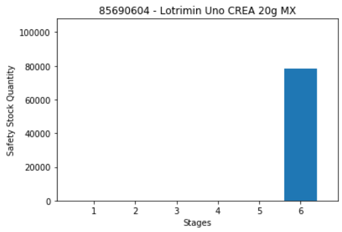


(a) Product 86570009 - SE Service Level per Week (b) Product 86947552 - SE Service Level per Week

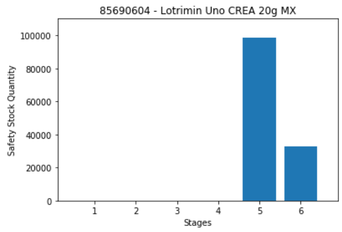
Figure 42: Single-Echelon Service Level per Week - 3

F Appendix F - Model Comparisons

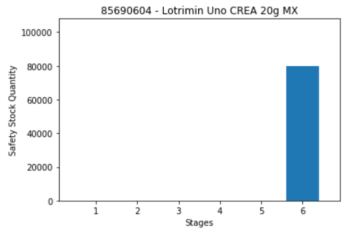
Model Comparison Safety Stock Quantities & Costs



(a) Product 85690604 - SE Safety Stock Quantity

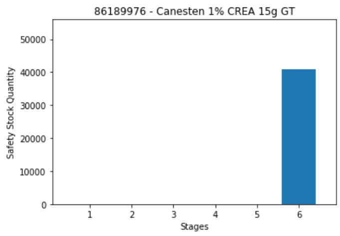


(b) Product 85690604 - GSM Safety Stock Quantity

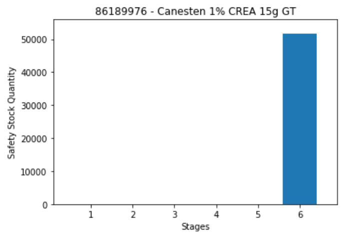


(c) Product 85690604 - SBSP Safety Stock Quantity

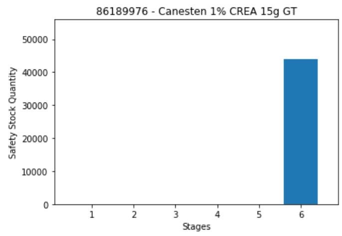
Figure 43: Comparison Safety Stock Quantity Proposals - 85690604



(a) Product 86189976 - SE Safety Stock Quantity

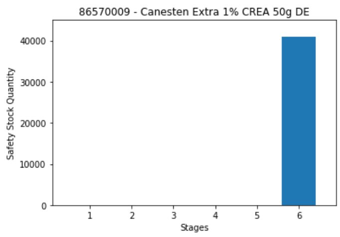


(b) Product 86189976 - GSM Safety Stock Quantity

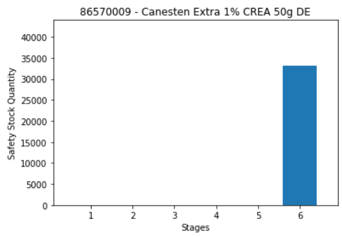


(c) Product 86189976 - SBSP Safety Stock Quantity

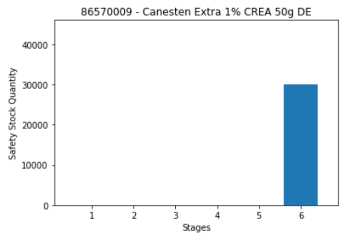
Figure 44: Comparison Safety Stock Quantity Proposals - 86189976



(a) Product 86570009 - SE Safety Stock Quantity

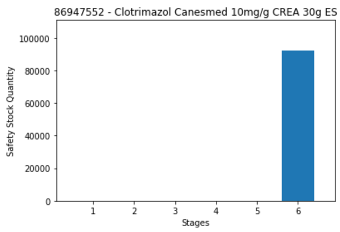


(b) Product 86570009 - GSM Safety Stock Quantity

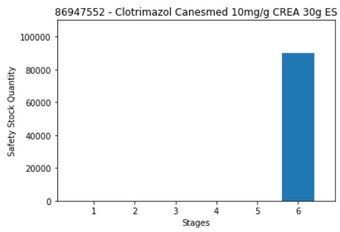


(c) Product 86570009 - SBSP Safety Stock Quantity

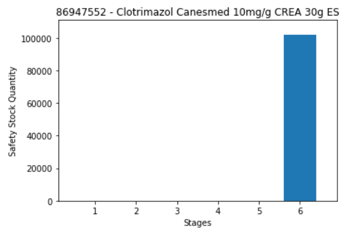
Figure 45: Comparison Safety Stock Quantity Proposals - 86570009



(a) Product 86947552 - SE Safety Stock Quantity



(b) Product 86947552 - GSM Safety Stock Quantity



(c) Product 86947552 - SBSP Safety Stock Quantity

Figure 46: Comparison Safety Stock Quantity Proposals - 86947552

G Appendix G - Sensitivity Analysis

Service Level

Table 15: Results Sensitivity Analysis GSM Service Level - 1

Product	11873262		11873533		85690604	
Service Level	Quantity	Costs	Quantity	Costs	Quantity	Costs
95.0%	69,415	€ 37,396.00	98,257	€ 61,930.00	131,553	€ 82,113.00
95.5%	70,997	€ 38,249.00	100,497	€ 63,342.00	134,552	€ 83,985.00
96.0%	72,736	€ 39,186.00	102,958	€ 64,894.00	137,848	€ 86,043.00
96.5%	74,670	€ 40,228.00	105,696	€ 66,620.00	141,513	€ 88,331.00
97.0%	76,857	€ 41,405.00	108,792	€ 68,570.00	145,657	€ 90,916.00
97.5%	79,382	€ 42,766.00	112,366	€ 70,824.00	150,442	€ 93,905.00
98.0%	82,391	€ 44,387.00	116,625	€ 73,507.00	156,145	€ 97,464.00
98.5%	86,146	€ 46,410.00	121,940	€ 76,857.00	163,261	€ 101,905.00
99.0%	91,226	€ 49,147.00	129,132	€ 81,390.00	172,890	€ 107,915.00

Table 16: Results Sensitivity Analysis GSM Service Level - 2

Product	86189976		86570009		86947552	
Service Level	Quantity	Costs	Quantity	Costs	Quantity	Costs
95.0%	52,557	€ 27,519.00	33,198	€ 37,948.00	91,572	€ 45,379.00
95.5%	53,756	€ 28,147.00	33,955	€ 38,813.00	93,660	€ 46,414.00
96.0%	55,072	€ 28,836.00	34,786	€ 39,763.00	95,954	€ 47,550.00
96.5%	56,536	€ 29,603.00	35,711	€ 40,821.00	98,506	€ 48,815.00
97.0%	58,192	€ 30,470.00	36,757	€ 42,016.00	101,390	€ 50,244.00
97.5%	60,104	€ 31,471.00	37,965	€ 43,397.00	104,722	€ 51,895.00
98.0%	62,382	€ 32,664.00	39,403	€ 45,041.00	108,690	€ 53,862.00
98.5%	65,225	€ 34,152.00	41,199	€ 47,094.00	113,644	€ 56,317.00
99.0%	69,072	€ 36,167.00	43,629	€ 49,872.00	120,347	€ 59,638.00

Table 17: Results Sensitivity Analysis SBSP Service Level - 1

Product	11873262		11873533		85690604	
Service Level	Quantity	Costs	Quantity	Costs	Quantity	Costs
95%	59,375	€ 31,987.00	64,161	€ 43,172.00	79,870	€ 55,697.00
97%	64,799	€ 34,909.00	69,177	€ 46,547.00	86,007	€ 59,977.00
99%	74,114	€ 39,928.00	78,311	€ 52,693.00	99,025	€ 69,055.00

Table 18: Results Sensitivity Analysis SBSP Service Level - 2

Product	86189976		86570009		86947552	
Service Level	Quantity	Costs	Quantity	Costs	Quantity	Costs
95%	44,006	€ 23,042.00	30,008	€ 34,301.00	101,888	€ 50,491.00
97%	48,107	€ 25,189.00	32,170	€ 36,772.00	107,938	€ 53,489.00
99%	55,189	€ 28,897.00	36,366	€ 41,569.00	118,300	€ 58,624.00

Table 19: Results Sensitivity Analysis GSM Standard Deviation - 1

Product	**11873262**		**11873533**		**85690604**	
Standard Deviation of Demand	**Quantity**	**Costs**	**Quantity**	**Costs**	**Quantity**	**Costs**
50%	34,713	€ 18,701.00	49,128	€ 30,965.00	65,776	€ 41,056.00
75%	52,064	€ 28,048.00	73,693	€ 46,447.00	98,664	€ 61,585.00
100%	69,415	€ 37,396.00	98,257	€ 61,930.00	131,553	€ 82,113.00
125%	86,766	€ 46,744.00	122,821	€ 77,414.00	164,441	€ 102,642.00
150%	104,117	€ 56,092.00	-	-	-	-

Table 20: Results Sensitivity Analysis GSM Standard Deviation - 2

Product	**86189976**		**86570009**		**86947552**	
Standard Deviation of Demand	**Quantity**	**Costs**	**Quantity**	**Costs**	**Quantity**	**Costs**
50%	26,278	€ 13,759.00	16,604	€ 18,979.00	45,786	€ 22,689.00
75%	39,418	€ 20,639.00	24,901	€ 28,464.00	68,679	€ 34,034.00
100%	52,557	€ 27,519.00	33,198	€ 37,948.00	91,572	€ 45,379.00
125%	65,697	€ 34,399.00	41,494	€ 47,432.00	114,466	€ 56,724.00
150%	-	-	49,791	€ 56,916.00	-	-

Table 21: Results Sensitivity Analysis SBSP Standard Deviation - 1

Product	**11873262**		**11873533**		**85690604**	
Standard Deviation of Demand	**Quantity**	**Costs**	**Quantity**	**Costs**	**Quantity**	**Costs**
50%	38,563	€ 20,775.00	43,801	€ 29,472.00	52,632	€ 36,703.00
100%	59,375	€ 31,987.00	64,161	€ 43,172.00	79,870	€ 55,697.00
150%	83,737	€ 45,112.00	88,671	€ 59,664.00	111,633	€ 77,847.00

Table 22: Results Sensitivity Analysis SBSP Standard Deviation - 2

Product	**86189976**		**86570009**		**86947552**	
Standard Deviation of Demand	**Quantity**	**Costs**	**Quantity**	**Costs**	**Quantity**	**Costs**
50%	27,925	€ 14,621.00	21,993	€ 25,139.00	80,365	€ 39,825.00
100%	44,006	€ 23,042.00	30,008	€ 34,301.00	101,888	€ 50,491.00
150%	62,625	€ 32,791.00	38,908	€ 44,475.00	125,020	€ 61,954.00

Added Value

Table 23: Results Sensitivity Analysis GSM Added Value - 1

Product	11873262		11873533		85690604	
Added Value	**Quantity**	**Costs**	**Quantity**	**Costs**	**Quantity**	**Costs**
50%	69,415	€ 36,333.00	77,679	€ 50,063.00	131,553	€ 80,509.00
100%	69,415	€ 37,396.00	98,257	€ 63,325.00	131,553	€ 82,113.00
150%	89,716	€ 46,730.00	98,257	€ 64,720.00	131,553	€ 83,718.00
200%	89,716	€ 47,112.00	98,257	€ 61,930.00	131,553	€ 85,322.00
250%	89,716	€ 47,494.00	98,257	€ 62,628.00	131,553	€ 86,926.00
300%	89,716	€ 47,876.00	98,257	€ 64,023.00	131,553	€ 88,530.00

Table 24: Results Sensitivity Analysis GSM Added Value - 2

Product	86189976		86570009		86947552	
Added Value	**Quantity**	**Costs**	**Quantity**	**Costs**	**Quantity**	**Costs**
50%	52,557	€ 28,216.00	33,198	€ 37,636.00	91,572	€ 45,099.00
100%	52,557	€ 26,823.00	33,198	€ 37,948.00	91,572	€ 45,379.00
150%	52,557	€ 27,519.00	33,198	€ 38,260.00	91,572	€ 45,658.00
200%	69,950	€ 35,960.00	33,198	€ 38,572.00	91,572	€ 45,937.00
250%	69,950	€ 36,554.00	33,198	€ 38,884.00	91,572	€ 46,217.00
300%	69,950	€ 36,257.00	33,198	€ 39,196.00	91,572	€ 46,496.00

Table 25: Results Sensitivity Analysis SBSP Added Value - 1

Product	11873262		11873533		85690604	
Added Value	**Quantity**	**Costs**	**Quantity**	**Costs**	**Quantity**	**Costs**
50%	61,371	€ 33,062.00	66,562	€ 44,788.00	83,282	€ 58,076.00
100%	59,375	€ 31,987.00	64,161	€ 43,172.00	79,870	€ 55,697.00
200%	57,277	€ 30,857.00	61,702	€ 41,518.00	76,322	€ 53,223.00
300%	56,052	€ 30,197.00	60,117	€ 40,451.00	73,936	€ 51,559.00

Table 26: Results Sensitivity Analysis SBSP Added Value - 2

Product	86189976		86570009		86947552	
Added Value	**Quantity**	**Costs**	**Quantity**	**Costs**	**Quantity**	**Costs**
50%	44,993	€ 23,558.00	30,481	€ 34,842.00	102,494	€ 50,791.00
100%	44,006	€ 23,042.00	30,008	€ 34,301.00	101,888	€ 50,491.00
200%	42,293	€ 22,145.00	28,987	€ 33,134.00	100,663	€ 49,883.00
300%	41,439	€ 21,697.00	28,494	€ 32,570.00	99,616	€ 49,365.00

Lead Time

Table 27: Results Sensitivity Analysis GSM Lead Time - 1

Product	**11873262**		**11873533**		**85690604**	
Lead Time	**Quantity**	**Costs**	**Quantity**	**Costs**	**Quantity**	**Costs**
50%	67,138	€ 36,170.00	87,875	€ 54,944.00	117,653	€ 72,420.00
75%	68,286	€ 36,788.00	93,749	€ 58,897.00	125,518	€ 77,905.00
100%	69,415	€ 37,396.00	98,257	€ 61,930.00	131,553	€ 82,113.00
125%	70,525	€ 37,995.00	102,057	€ 64,487.00	136,641	€ 85,661.00
150%	71,619	€ 38,584.00	105,405	€ 66,740.00	141,123	€ 88,787.00
175%	72,696	€ 39,164.00	108,432	€ 68,777.00	145,176	€ 91,613.00
200%	73,757	€ 39,736.00	-	-	-	-

Table 28: Results Sensitivity Analysis GSM Lead Time - 2

Product	**86189976**		**86570009**		**86947552**	
Lead Time	**Quantity**	**Costs**	**Quantity**	**Costs**	**Quantity**	**Costs**
50%	49,269	€ 25,798.00	-	-	89,980	€ 44,590.00
75%	50,940	€ 26,672.00	-	-	-	-
100%	52,557	€ 27,519.00	33,198	€ 37,948.00	91,572	€ 45,379.00
125%	-	-	-	-	-	-
150%	54,126	€ 28,341.00	-	-	93,138	€ 46,155.00
175%	-	-	-	-	-	-
200%	55,651	€ 29,139.00	-	-	94,677	€ 46,917.00

Table 29: Results Sensitivity Analysis SBSP Lead Time - 1

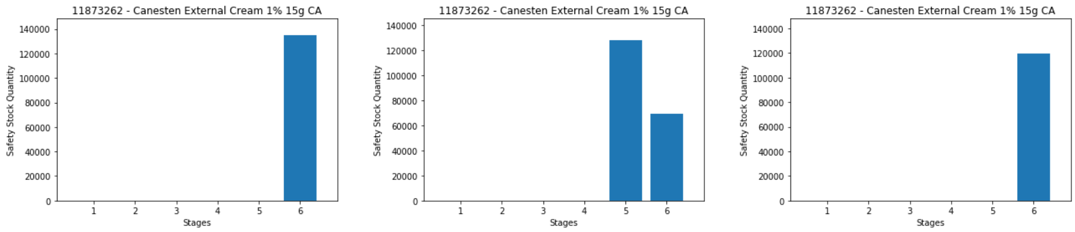
Product	**11873262**		**11873533**		**85690604**	
Lead Time	**Quantity**	**Costs**	**Quantity**	**Costs**	**Quantity**	**Costs**
50%	53,896	€ 29,035.00	60,034	€ 40,395.00	74,103	€ 51,675.00
100%	59,375	€ 31,987.00	64,161	€ 43,172.00	79,870	€ 55,697.00
200%	67,519	€ 36,375.00	71,483	€ 48,099.00	89,242	€ 62,233.00

Table 30: Results Sensitivity Analysis SBSP Lead Time - 2

Product	**86189976**		**86570009**		**86947552**	
Lead Time	**Quantity**	**Costs**	**Quantity**	**Costs**	**Quantity**	**Costs**
50%	39,780	€ 20,829.00	30,001	€ 34,293.00	101,798	€ 50,446.00
100%	44,006	€ 23,042.00	30,008	€ 34,301.00	101,888	€ 50,491.00
200%	50,107	€ 26,236.00	30,004	€ 34,297.00	102,801	€ 50,943.00

H Appendix H - Factorial Analysis

Scenario 1

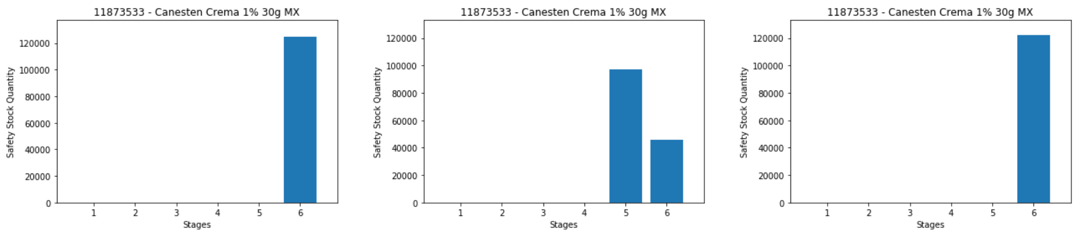


(a) 11873262 - SE Factorial Analysis Safety Stock Quantity

(b) 11873262 - GSM Factorial Analysis Safety Stock Quantity

(c) 11873262 - SBSP Factorial Analysis Safety Stock Quantity

Figure 47: Comparison Scenario 1 Factorial Analysis Safety Stock Quantity Proposals - 11873262

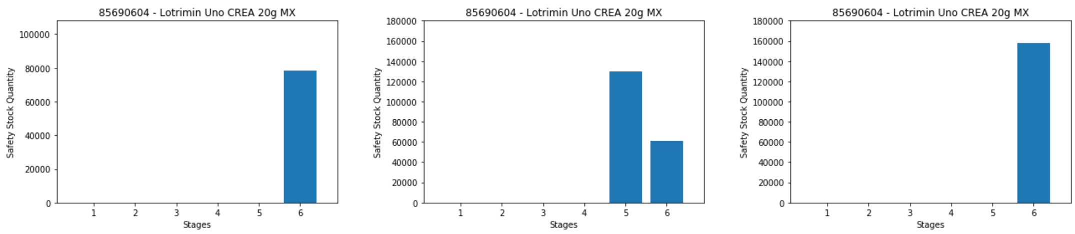


(a) 11873533 - SE Factorial Analysis Safety Stock Quantity

(b) 11873533 - GSM Factorial Analysis Safety Stock Quantity

(c) 11873533 - SBSP Factorial Analysis Safety Stock Quantity

Figure 48: Comparison Scenario 1 Factorial Analysis Safety Stock Quantity Proposals - 11873533

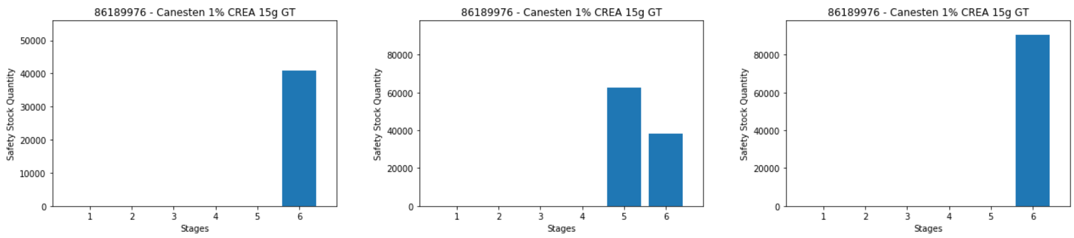


(a) 85690604 - SE Factorial Analysis Safety Stock Quantity

(b) 85690604 - GSM Factorial Analysis Safety Stock Quantity

(c) 85690604 - SBSP Factorial Analysis Safety Stock Quantity

Figure 49: Comparison Scenario 1 Factorial Analysis Safety Stock Quantity Proposals - 85690604

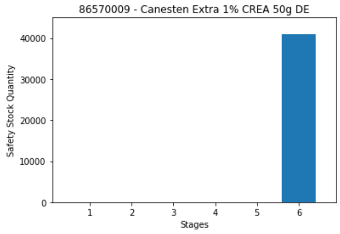


(a) 86189976 - SE Factorial Analysis Safety Stock Quantity

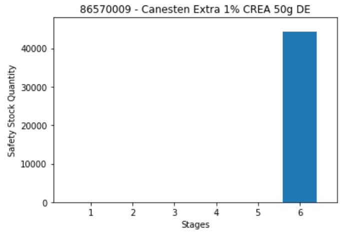
(b) 86189976 - GSM Factorial Analysis Safety Stock Quantity

(c) 86189976 - SBSP Factorial Analysis Safety Stock Quantity

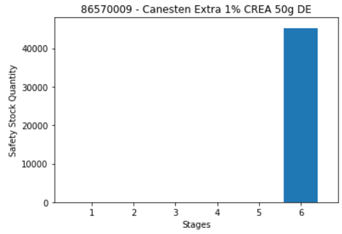
Figure 50: Comparison Scenario 1 Factorial Analysis Safety Stock Quantity Proposals - 86189976



(a) 86570009 - SE Factorial Analysis Safety Stock Quantity

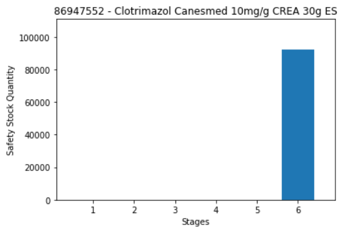


(b) 86570009 - GSM Factorial Analysis Safety Stock Quantity

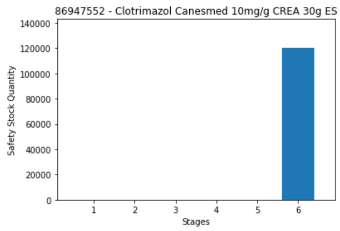


(c) 86570009 - SBSP Factorial Analysis Safety Stock Quantity

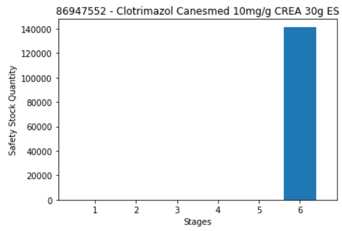
Figure 51: Comparison Scenario 1 Factorial Analysis Safety Stock Quantity Proposals - 86570009



(a) 86947552 - SE Factorial Analysis Safety Stock Quantity



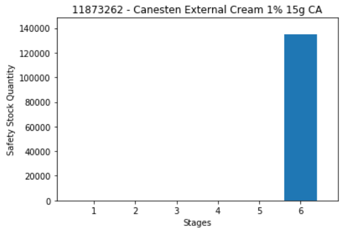
(b) 86947552 - GSM Factorial Analysis Safety Stock Quantity



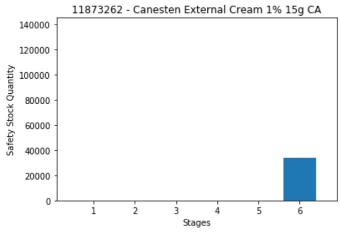
(c) 86947552 - SBSP Factorial Analysis Safety Stock Quantity

Figure 52: Comparison Scenario 1 Factorial Analysis Safety Stock Quantity Proposals - 86947552

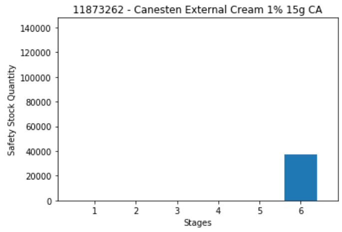
Scenario 2



(a) 11873262 - SE Factorial Analysis Safety Stock Quantity

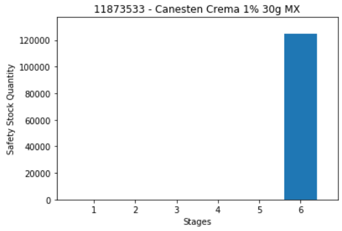


(b) 11873262 - GSM Factorial Analysis Safety Stock Quantity

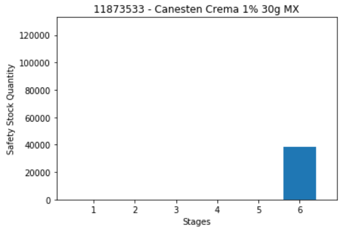


(c) 11873262 - SBSP Factorial Analysis Safety Stock Quantity

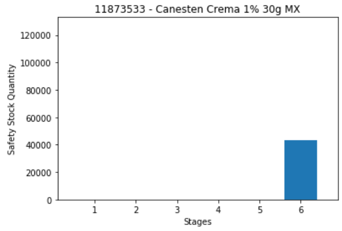
Figure 53: Comparison Scenario 2 Factorial Analysis Safety Stock Quantity Proposals - 11873262



(a) 11873533 - SE Factorial Analysis Safety Stock Quantity

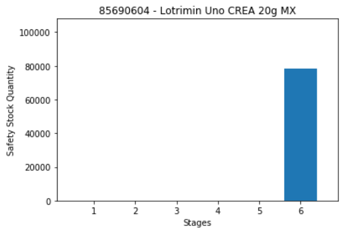


(b) 11873533 - GSM Factorial Analysis Safety Stock Quantity

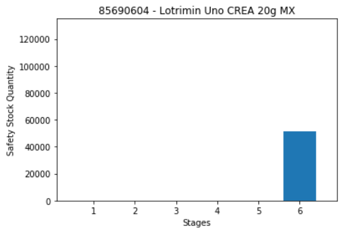


(c) 11873533 - SBSP Factorial Analysis Safety Stock Quantity

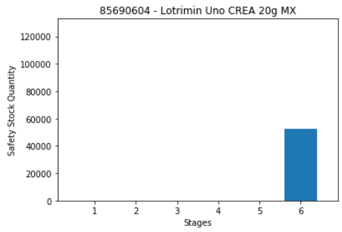
Figure 54: Comparison Scenario 2 Factorial Analysis Safety Stock Quantity Proposals - 11873533



(a) 85690604 - SE Factorial Analysis Safety Stock Quantity

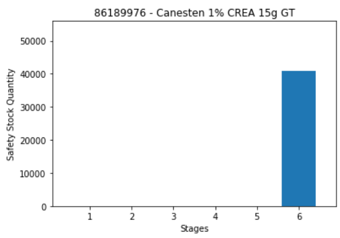


(b) 85690604 - GSM Factorial Analysis Safety Stock Quantity

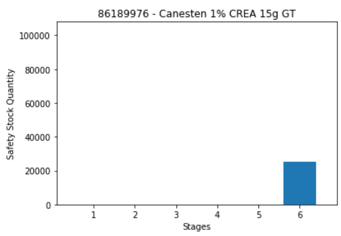


(c) 85690604 - SBSP Factorial Analysis Safety Stock Quantity

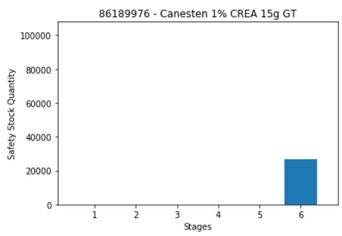
Figure 55: Comparison Scenario 2 Factorial Analysis Safety Stock Quantity Proposals - 85690604



(a) 86189976 - SE Factorial Analysis Safety Stock Quantity

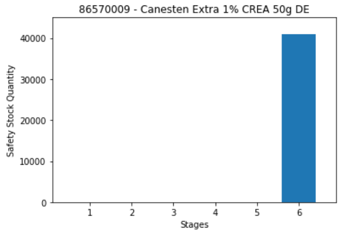


(b) 86189976 - GSM Factorial Analysis Safety Stock Quantity

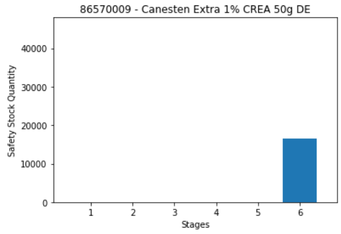


(c) 86189976 - SBSP Factorial Analysis Safety Stock Quantity

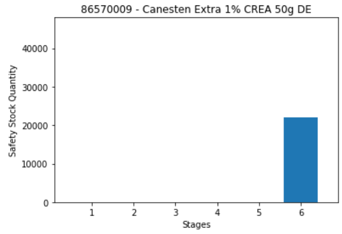
Figure 56: Comparison Scenario 2 Factorial Analysis Safety Stock Quantity Proposals - 86189976



(a) 86570009 - SE Factorial Analysis Safety Stock Quantity

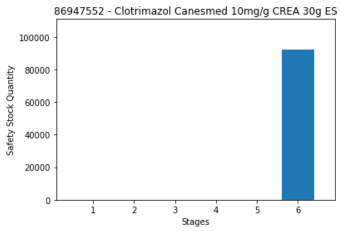


(b) 86570009 - GSM Factorial Analysis Safety Stock Quantity

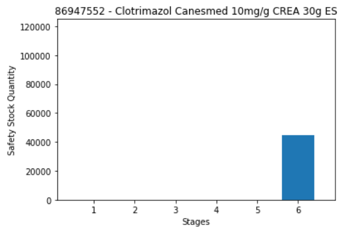


(c) 86570009 - SBSP Factorial Analysis Safety Stock Quantity

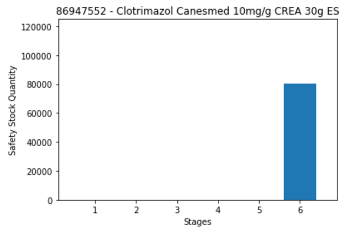
Figure 57: Comparison Scenario 2 Factorial Analysis Safety Stock Quantity Proposals - 86570009



(a) 86947552 - SE Factorial Analysis Safety Stock Quantity



(b) 86947552 - GSM Factorial Analysis Safety Stock Quantity



(c) 86947552 - SBSP Factorial Analysis Safety Stock Quantity

Figure 58: Comparison Scenario 2 Factorial Analysis Safety Stock Quantity Proposals - 86947552