

## MASTER

### Multi-echelon safety stock optimization under supply, process and demand uncertainties as a part of operational risk management a case study in the pharmaceutical industry

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**Multi-Echelon Safety Stock Optimization under  
Supply, Process and Demand Uncertainties as a part  
of Operational Risk Management:**

***A Case Study in the Pharmaceutical Industry***

by

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in partial fulfillment of the requirements of the degree of

**Master of Science  
in Operations Management and Logistics**

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## **I. Preface**

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This report is the outcome of my graduate internship and symbolizes not only the end of this project, but also the completion of the master Operations Management & Logistics at Eindhoven University of Technology. All in all, my professional and personal competences developed through my study and graduation project and right now I feel well-prepared to start my professional career. Therefore, I would like to thank the many people who have supported me.

I would like to thank Ton de Kok in particular. Ton fulfilled the role as first mentor and I did not only get to know Ton as an extremely knowledgeable and experienced expert in the field of Supply Chain Management (SCM), but also as a social, ambitious and friendly mentor with a good sense of humor. During the graduation project, I more and more appreciated his “know-how”, commitment and his inspiring enthusiasm about SCM-related topics. Despite his busy schedule, Ton took time to supervise and he even visited me at LSC. I am glad that Ton encourages students to conduct their graduation project in collaboration with industry, because it is both professionally and personally a valuable experience. Ton, thanks for the opportunity to graduate under your supervision within the field of SCM! Willem van Jaarsveld supported me as second mentor and gave me trust in my approach and my results. Thanks to Willem for those valuable moments, because it increased my motivation during tough phases.

Next, I would like to thank my supervisors from LSC for both the opportunity to conduct my graduate internship at LSC and their time to supervise. At forehand, I was told about stereotypes in the German working culture, such as hierarchy, extremely serious and an exclusive focus on content. However, my experience is that the Dutch and German culture is more similar than both of us would like to acknowledge. Both of you were interested in my research and your trust increased my motivation and made me feel responsible. Both of you tried to offer support in case it was needed and both of you showed me that the stereotypes did not apply at all.

I also would like to thank my colleagues (from other divisions), who showed interest in the multi-echelon safety stock optimization project and helped me, where necessary. Opinions in favor of LLamasoft challenged me and increased my motivation to pursue my comparative study.

Then, I would like to thank my friends from my hometown and my friends in my student city Eindhoven, who sometimes complained that I was away for such a long time. As a result, the moments we met became even better and I truly believe that this will stay the same after my graduation.

I also would like to thank my parents, who encouraged me to study and supported me during my graduation project and stay in Germany. It is great that you gave me the freedom to pursue my dreams. Last but not least, I would like to thank Sophie, with whom I experienced my German journey from the beginning onwards. Sophie, although you were living 700 kilometers away, you supported me. When we were together in “our city” Munich, it was easy to forget about the project, which dominated my stay here. Let us all see how my German journey continues ...

Arjan van Cruchten

## II. Abstract

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This research project contains a qualitative and quantitative assessment of the company's current risk management methodology and two multi-echelon safety stock methods, which are based on the Guaranteed Service Time (GS) Approach and the Synchronized Base Stock Policies (SBS) Approach. The case study is conducted for a primarily convergent supply chain at a pharmaceutical company in a non-stationary environment under supply, process and demand uncertainties in a challenging batch/mix environment. The **qualitative assessment** lists the pros and cons of the company's current supply chain risk management approach. The qualitative assessment also lists the pros and cons for the selected multi-echelon safety stock methods and tools. The **quantitative analyses** show again the more conservative safety stock allocation for convergent network structures according to the GS approach in comparison to the SBS approach. That seems to complement the finding about more conservative *average stocks* according to the GS approach in convergent networks in De Kok & Eruguz (2015). Although this research shows that the downstream safety stocks of GS are smaller than for SBS, it offers the insight that GS puts *relatively* most of its safety stocks downstream in the considered convergent network. Based on the case study, doubts have grown about the empirical validity of LLamasoft's safety stock optimization module. LLamasoft's optimized safety stock levels only achieve, according to ChainScope's validated base model with item-based random yield and inventory constraints, a 57.5% instead of 97.5% service level. This is explained by LLamasoft's end-item inventories, which are 50% lower, and that is most likely caused by other methodological assumptions about, for example, material availability. A further evaluation shows that these substantial service level deviations do not occur for single- and two-stage serial networks, but do occur for the company's convergent network. An evaluation of a reduced supply chain –the three most downstream stages- even shows that the downstream assembly step contributes to the majority of the service level decrease (60.4%). The research also shows that for ChainScope the inclusion of yield ratios smaller than 1 increases significantly the overall safety stock allocation and changes the distribution among product types. Another investigation shows that the inclusion of inventory constraints increases finished good safety stock levels and reduces component safety stock levels with respect to ChainScope. LLamasoft appears to be indifferent for both yield and inventory constraints.

In addition, the study confirms again the *empirical* validity of ChainScope. Furthermore, the study identifies common causes for deviations during model validation, such as human behavior that affects norm settings. Finally, the project contributes to the observed gap that safety stock optimization procedures are often not described in detail. This report explains both GS's and SBS's solution technique, defines the input of both models mathematically and proposes a procedure to deal with seasonality.

### III. Management Summary

Supply chain (SC) risks form an increasing concern for Life Science Company (LSC). Therefore, LSC requested an evaluation and improvement of the SC risk management approach and their safety stock allocation method, which should buffer against operational risks:

**Main research question:** What is for LSC’s business environment **qualitatively** and **quantitatively** the “best” risk management methodology, which is able to assign multi-echelon safety stock levels?

**SRQ1:** What is the qualitative performance of LSC’s current supply chain risk management method?

Although the current approach is a complete, quantitative, multi-disciplinary *strategic* risk management tool that is suited to identify both demand and supply risks, the LSC Method is undesired due to its single-echelon approach, stage-level granularity, excluded product types, parameter usage, *yearly* periods and the lack of supplier and country involvement in the risk management process. This disaffects the quality of the safety stock settings among product types.

**SRQ3:** What is the **qualitative** performance of LSC’s and ChainScope’s and LLamasoft’s **multi-echelon safety stock optimization method**?

In contrast to LSC’s method that is discussed above, ChainScope and LLamasoft have an academic basis, are multi-echelon, can deal with shelf life and product changes, and allow for safety stock setting for *all* items on an *item* level, which can be directly implemented in SAP.

**Specifically for ChainScope:** It is empirically valid, concise and offers the possibility to deal with item-based random yield. However, ChainScope is not able to deal with very small BOM quantities and multi-period models at once. Item-based yields are restricted to be smaller than or equal to 1.

**Specifically for LLamasoft:** It relies on an advanced demand pattern analysis, which should give a better density function. Furthermore, LLamasoft performs multi-period optimization runs at once. However, except from the operational flexibility assumption and the ignorance of yield, the major drawback of LLamasoft’s optimization is the lack of transparency about the formulae as well as the heuristics for the recommended lead time demand distributions and inventory control policies.

**SRQ2:** What is the **quantitative** performance of LSC’s and ChainScope’s and LLamasoft’s **multi-echelon safety stock optimization method** under different scenarios?

Before one can judge about the quantitative performance, one should first validate with LSC’s data the ChainScope model, which is based on Synchronized Base Stock Policies (SBS), and the LLamasoft model, which is based on the Guaranteed Service Time (GS) Approach. **ChainScope** is validated with its analytical evaluation mode and appeared to be valid. It achieved a service level of 97.5%, where in practice 100% is reported. **LLamasoft’s (GS)** optimization model input is validated with its built-in discrete event simulation. The simulated service level matched the reported service level. Although deviations occurred between the simulated and historical finished goods inventory levels, the model is considered as valid. Table 3 explains valid reasons for those deviations, such as human interventions.

From the “**Actual**” safety stocks, it is known that the reported service level is 100%. Unfortunately, the service level of the **LSC Methods** could not be assessed with ChainScope’s evaluation mode due to the brand-stage level granularity.

ChainScope is empirically valid for LSC’s data and it has been used to evaluate the service level of LLamasoft’s optimized inventory levels. LLamasoft optimized the safety stocks under a 97.5% service level constraint and only achieved a 57.5% service level according to ChainScope’s evaluation. Jongenelis (2014) reported a similar service level decrease based on LLamasoft’s safety stocks in his simulation study *within LLamasoft*. **Strong doubts** exist about the empirical validity of LLamasoft’s safety stock optimization, because **i)** ChainScope is empirically valid and only the average inventory has been changed and **ii)** a verification within LLamasoft in Jongenelis (2014) also showed large deviations.

The service level difference is explained by 50% less **end-item average inventory**, which is caused by methodological assumptions, such as 100% material availability at predecessors. Furthermore, De Kok and Eruguz (2015) and this study found evidence that it is related to the **convergent network structure**.

Although **yields** and **inventory constraints** increase ChainScope’s safety stock levels, they do not significantly affect the service level in ChainScope’s evaluation: users namely specify the average inventory and ChainScope’s algorithms search the best control parameters. In case yield and inventory constraints are given, the control parameters change, such that the average inventory remains similar.

Where inventory constraints are considered as essential to reflect shelf life and frequent product change considerations, one can discuss about the need of random yields ( $Y < 1$ ). Therefore, Figure 1 shows in the first two bars a ChainScope (CS) model with yield respectively without yield under inventory constraints (ST). The colored stacked bars represent the 7 defined product types. A model without yield ( $Y = 1$ ) reduces the average safety stock days of supply by roughly 30%, which is a 35% safety stock product value reduction that can be used for yield improvement programs. Although the difference with LLamasoft (LL) tends to decrease, the difference remains significant and is also partially caused by ChainScope’s sensitivity to inventory constraints (Chapter 4.1.3).

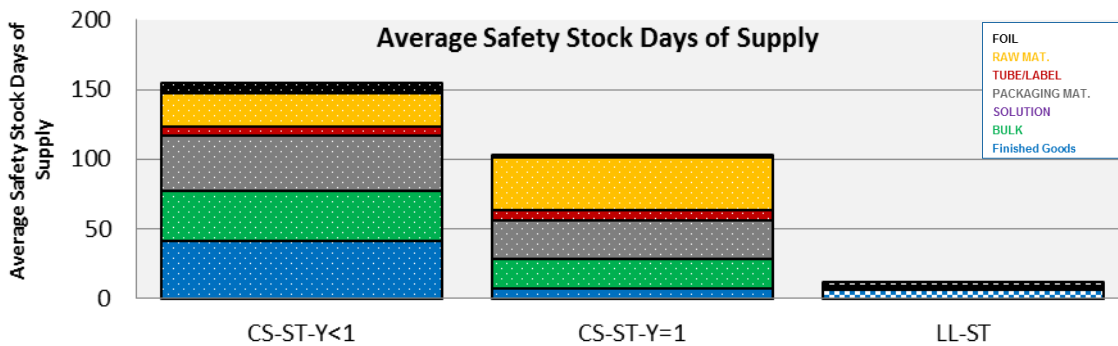


Figure 1, The Impact of Item-based Random Yield on Safety Stocks in ChainScope

The results of the quantitative comparison between product types, methods and over time are shown in average safety stock days of supply in Figure 2. The key findings are summarized in Table 1. Figure 2 shows the **safety stocks of ChainScope’s defined base model, which are substantially increased and shifted by item-based random yield and inventory constraints.**

The first four striped bars represent the average yearly LSC values (PC=Pipeline controller’s adjustment), the mottled bars represent ChainScope’s (CS) optimized monthly values, and the checkered bars represent LLamasoft’s (LL) optimized monthly values.

The big red arc on the right side represents an **“infeasibility gap”**: LLamasoft’s safety stocks are substantially lower than ChainScope’s base model, but they do not meet the desired service level of 97.5% according to ChainScope’s evaluation. Therefore, ChainScope is preferred over LLamasoft as multi-echelon safety stock optimization tool and LLamasoft’s cost advantage is ignored.

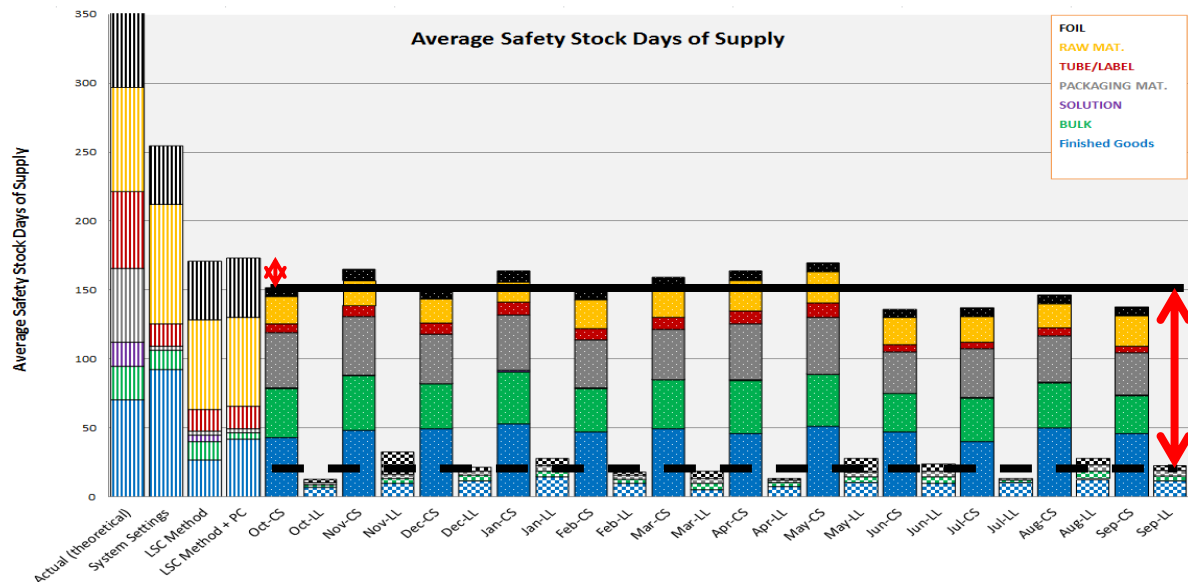


Figure 2, Average Safety Stocks between Product Types and Methods over Time

ChainScope’s results are also more trustworthy in comparison to Actual and System Settings, which partially contain safety stock against supply uncertainties. However, it is considered infeasible to remove those stocks from the comparison. Next, LLamasoft’s and ChainScope’s base model results are without any exception-based material and resource flexibility measures, such as described in Table 3, which can make them in practice even less expensive. Furthermore, Figure 1 has shown the safety stock inflating impact of yield in ChainScope, which makes ChainScope even less expensive under stable yield.

The LSC Method is not the preferred approach, because it is single-echelon, the service level could not be assessed due to its granularity and the allocations deviate from ChainScope’s and LLamasoft’s. As ChainScope’s base case model is empirically valid, multi-echelon, expected to be less expensive than Actual and System Settings and suggests safety stocks that deviate the least from the in practice seen safety stocks, which make a service level maintenance likely, it is the **preferred multi-echelon method**.

Table 1, Key Findings from the Quantitative Comparison

Key Findings	
1	Although ChainScope’s <i>total</i> and <i>product type</i> allocation structurally <b>exceeds</b> LLamasoft’s, the <b>directions of change</b> are often similar.
2	Where ChainScope allocates relatively more SS DOS <b>upstream</b> , LLamasoft does the opposite at FGs.
3	Although ChainScope and LLamasoft are modelled <b>without</b> any exception-based material and resource flexibility measures, Actual and LSC’s System Settings are still expected to be <b>higher</b> .
4	The comparison between Actual and System Settings is <b>disturbed</b> by seasonal stocks, minimum order quantities, large lot sizes, forecast bias and accuracy, and scrapping policies.
5	The LSC Method significantly <b>deviates</b> from LLamasoft’s and ChainScope’s product type allocation.
6	Pipeline controller’s higher allocations on FGs lead to <b>product value convergence</b> with ChainScope.
7	Safety stocks are <b>dynamic</b> over time, but are <b>not</b> mainly driven by seasonality.
8	Decreasing order of <b>costs</b> : System Settings >> Actual >> ChainScope >> LSC (both) (>> LLamasoft)
9	Zero safety stocks at TUB and FG at SC GER can be explained by a <b>flow concept</b> to the next stage.
10	Although ChainScope exploited SS DOS <b>at all stages</b> , LLamasoft only at PACK, FOIL, BULK and FG.



**SRQ4: What is the overall most desired **safety stock optimization method**?**

ChainScope is based on the qualitative and quantitative evaluation the recommended *multi-echelon* approach. Important aspects are the method's empirical validity at LSC and other companies, the safety stocks that better approach the current safety stock levels and give confidence about the claimed service level, and the expected costs benefits compared to Actual and System Settings. Moreover, cost differences tend to increase when yield appears to be stable.

**SRQ5: How should LSC **implement** the overall best supply chain risk management methodology?**

The implementation is answered by a strategic, tactical and operational recommendation as well as a graphical representation of the redesigned **strategic and operational risk management approach**:

**R1: Invest in *more* quantitative and advanced risk management methodologies**

The *SC and Risk Management Maturity Model* showed that mature stages differ from immature stages by using more extensively quantitative risk management techniques. Simchi-Levi (2015) found that mature companies outperform immature companies on all surveyed operational and financial KPI's. The assertion is that LSC can improve its maturity by more quantitative and advanced risk management methodologies. This positively affects KPI's, such as delivery performance, cycle time and inventory DOS.

**R2: Slightly extend the current approach and include multi-echelon safety stock optimization models**

Although the qualitative and quantitative evaluation show the acceptable quality of the current approach, the qualitative and quantitative evaluation also show the more preferred benefits of multi-echelon safety stock models. In fact, multi-echelon methods characterize the highest stage of inventory management professionalism. This stage leads to the highest cost savings and service level potential and would be the logical next step for LSC. Besides the inclusion of multi-echelon safety stock optimization, some slight extensions, such as a change in the granularity, are included in the redesign (Figure 3). Therefore, this redesign leads to an **integrated strategic and operational risk management methodology**.

**R3: Apply ChainScope to benefit from a risk-free cost reduction and service level maintenance**

As found in the quantitative and qualitative analyses for the multi-echelon models, ChainScope should be deployed, because it is expected to maintain the service level and to reduce the inventory holding costs in comparison to Actual and System Settings. In case management decides to apply ChainScope, LSC should update the models with forecasts, automate the data pre-processing, and extend the scope to more pipelines and countries. LSC should also reassess the safety stock transformation formula that caused some unexpected directions in the scenario analysis. Furthermore, special attention needs to be paid to the exact yield modeling technique and the item-level inventory constraints that both heavily increase safety stocks. Furthermore, LSC should follow the described steps in the redesign.

As some factors, such as *inventory targets, budgets for licensing and human resources*, are not included in the qualitative and quantitative assessment, the operational implications for implementation are given in Chapter 7.2 for **i)** the multi-echelon tools and **ii)** an improvement of the current safety stock setting method.

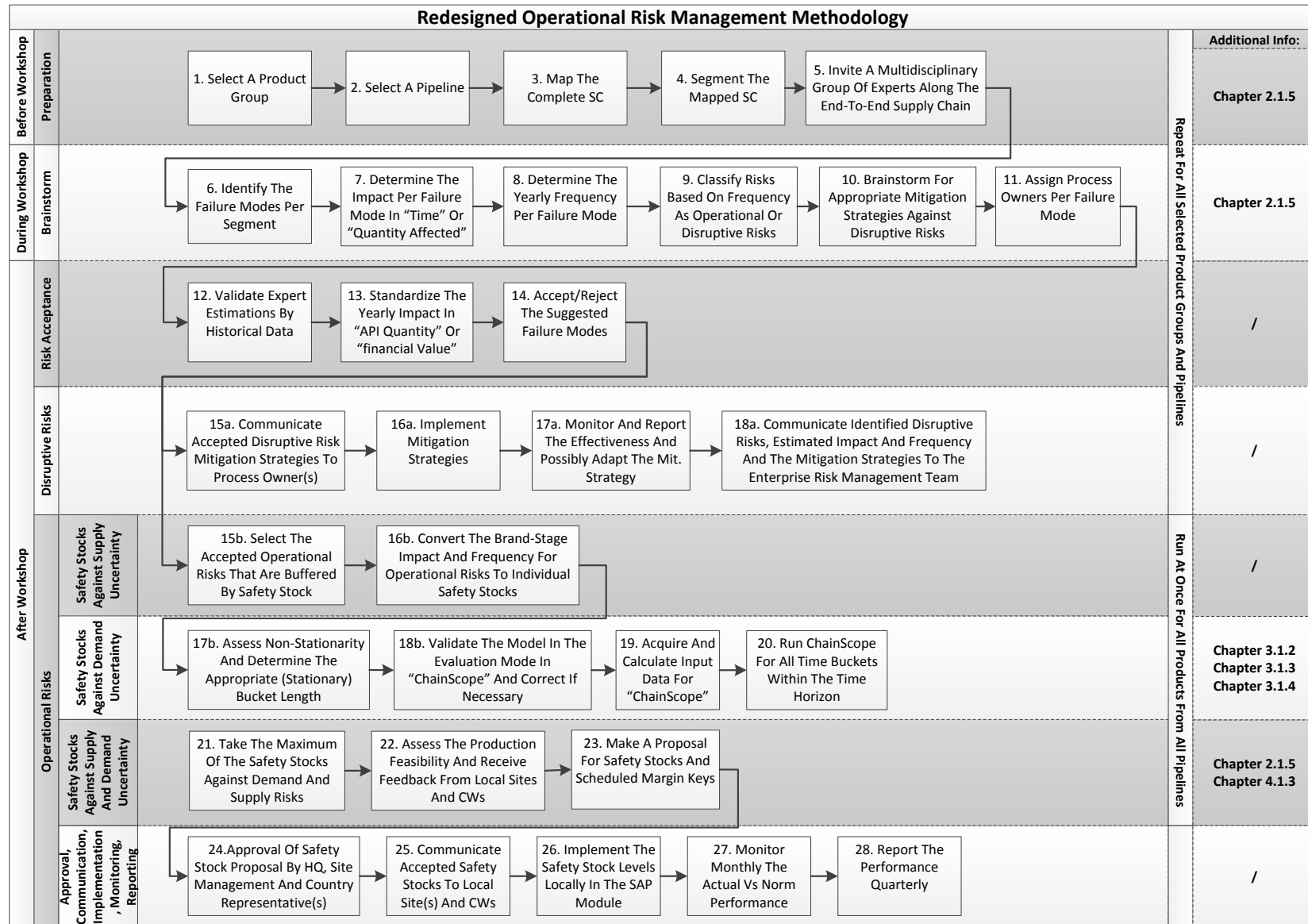


Figure 3, Redesigned Operational Risk Management Approach

**Academic question:** What has been the contribution of this project to academia?

**First**, the results proof again the more conservative safety stock allocation for convergent network structures with the GS approach, which seems to complement the finding about average stocks in De Kok & Eruguz (2015). In addition, this research shows that GS/LLamasoft puts the majority of its allocated safety stocks downstream for this convergent network structure. However, the described service level performance of LLamasoft in ChainScope’s evaluation raises questions about its empirical validity. An evaluation has also shown that such a service level deviation does not occur for single- and two-stage serial networks (99%), but does occur for LSC’s convergent network (57.5%). The evaluation has also shown that the largest contribution to the service level decrease is caused by the most downstream packaging step (60.4% for the reduced downstream network). All in all, LLamasoft appears to propose for this network an empirically invalid result. Further research is required for other network topologies.

Additionally, the tested sub hypotheses and scenario analysis also provide insights in the safety stock dynamics (Table 2).

**Second**, the project proofs again the empirical validity of ChainScope for networks similar to that of LSC. The report also identifies generic difficulties of model validation (Table 3).

**Third**, the project partially contributes to the lack of safety stock optimization *procedures* by a detailed explanation of the input parameters and a proposed approach to deal with non-stationary demand. In fact, it provides a generic redesigned operational risk management approach (Figure 3).

**Table 2, Summary of Sub Hypotheses and Scenario Analysis**

Sub Hypotheses	Outcome
A) Multi-echelon models allocate <b>less</b> safety stock than LSC’s single echelon method	Rejected
B) LLamasoft’s safety allocation in assembly networks is <b>more conservative</b> –which refers to less safety stocks- than ChainScope’s	Accepted
C) Relative differences between LLamasoft and ChainScope <b>decrease</b> in terms of safety stock value in comparison to safety stock days of supply	Accepted
D) ChainScope’s and LLamasoft’s safety stock allocations in contrast to LSC’s are relatively <b>dynamic over time</b>	Accepted
E) ChainScope’s, LLamasoft’s and LSC’s safety stock allocations show <u>always</u> a <b>similar direction</b> , but a <b>different magnitude</b> for different scenarios	Rejected

**Table 3, Reasons for Deviations During Model Validation**

Tool	Identified Reasons	Example(s)
<b>ChainScope and LLamasoft (common)</b>	Human interventions affect norm values	Humans steer with lead time reducing activities, such as rush lead times (priorities, air instead of sea freight) and combined shipments
	Data reliability	Historical data, estimations, deviation between SAP and Actual
<b>ChainScope</b>	Methodological	Stochastic demands with limited inventory can never reach a 100% service level
	Other definitions	The amount of lost sales is estimated by humans instead of counted
<b>LLamasoft Simulation</b>	Other limitations	Built-in decision rule functionalities in the tool ( <i>Fixed s,S-DOS levels, FIFO, Transport Modality</i> )

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**IV. List of Abbreviations**

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<b>API</b>	<i>Active Pharmaceutical Ingredient</i>
<b>APICS</b>	<i>American Production and Inventory Control Society</i>
<b>APS</b>	<i>Advanced Planning System</i>
<b>BOM</b>	<i>Bill of Material</i>
<b>CODP</b>	<i>Customer Order Decoupling Point</i>
<b>COV</b>	<i>Coefficient of Variation</i>
<b>CW</b>	<i>Country Warehouse</i>
<b>DOS</b>	<i>Days of Supply</i>
<b>FCA</b>	<i>Forecast Accuracy</i>
<b>FG</b>	<i>Finished Good</i>
<b>GS</b>	<i>Guaranteed Service Time Approach</i>
<b>GSCM</b>	<i>Global Supply Chain Management</i>
<b>iid</b>	<i>Independent and Identically Distributed</i>
<b>kg</b>	<i>Kilogram</i>
<b>KPI</b>	<i>Key Performance Indicator</i>
<b>LP</b>	<i>Linear Programming</i>
<b>LSC</b>	<i>Life Science Company</i>
<b>MES</b>	<i>Manufacturing Enterprise System</i>
<b>MRP I</b>	<i>Material Requirements Planning I</i>
<b>MTF</b>	<i>Make-to-Forecast</i>
<b>PC</b>	<i>Pipeline Controller</i>
<b>PRODUCT</b>	<i>Confidential</i>
<b>SBS</b>	<i>Synchronized Base Stock Policies</i>
<b>SC</b>	<i>Supply Center</i>
<b>SC</b>	<i>Supply Chain</i>
<b>SC GER</b>	<i>Supply Center Germany</i>
<b>SCM</b>	<i>Supply Chain Management</i>
<b>SCOP</b>	<i>Supply Chain Operations Planning</i>
<b>SCRMM</b>	<i>Supply Chain Risk Management Methodology</i>
<b>SKU</b>	<i>Stock Keeping Unit</i>
<b>SRQ</b>	<i>Sub Research Question</i>
<b>SS</b>	<i>Safety Stock in Units</i>
<b>SS</b>	<i>Stochastic Service Approach</i>
<b>SS DOS</b>	<i>Safety Stock Days of Supply</i>
<b>SSO</b>	<i>Safety Stock Optimization</i>
<b>SSPV</b>	<i>Safety Stock Product Value</i>
<b>US</b>	<i>United States of America</i>
<b>WIP</b>	<i>Work In Process</i>

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**V. List of Symbols**


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<b>APD</b>	<i>Actual Production Date</i>
<b>ASD</b>	<i>Actual Start Date</i>
<b>ASYD</b>	<i>Actual Subset Yearly Demand</i>
<b>AV</b>	<i>Added Value</i>
<b>BED</b>	<i>Basic End Date</i>
<b>BQ</b>	<i>Base Quantity</i>
<b>c</b>	<i>Cleaning Time</i>
<b>CLS</b>	<i>Calculated Lot Size</i>
<b>CPT</b>	<i>On-Hand Stock</i>
<b>D</b>	<i>Demand</i>
<b>DBP</b>	<i>Days Between Productions</i>
<b>DBR</b>	<i>Days Between Replenishments</i>
<b>DD</b>	<i>Daily Demand</i>
<b>DDSTD</b>	<i>Daily Demand Standard Deviation</i>
<b>DOSPLT</b>	<i>Days of Supply Planned Lead Time</i>
<b>DQ</b>	<i>Delivered Quantity</i>
<b>E</b>	<i>Set of End Items</i>
<b>EI</b>	<i>Set of External Items</i>
<b>Factor</b>	<i>Fraction</i>
<b>FCA</b>	<i>Forecast Accuracy</i>
<b>FCIA</b>	<i>Forecast Inaccuracy</i>
<b>FLS</b>	<i>Fixed Lot Size</i>
<b>FTYD</b>	<i>Forecasted Total Yearly Demand</i>
<b>GI</b>	<i>Goods Issue Time</i>
<b>GR</b>	<i>Goods Receiving Time</i>
<b>Gu(k)</b>	<i>Standard Loss Function</i>
<b>h</b>	<i>Inventory Holding Costs</i>
<b>i</b>	<i>Item</i>
<b>I</b>	<i>Set of Intermediate Items</i>
<b>II</b>	<i>Set of Internal Items</i>
<b>ILT</b>	<i>Immediate Lead Time</i>
<b>IP</b>	<i>Local Inventory Position</i>
<b>IT</b>	<i>Shipments during the lead time</i>
<b>J</b>	<i>Local On-Hand Stock Level</i>
<b>k</b>	<i>Safety Factor</i>
<b>LT</b>	<i>Lead Time</i>
<b>M</b>	<i>Set of Yearly Months</i>
<b>m</b>	<i>Margin</i>
<b>Max Inv</b>	<i>Maximum Inventory</i>
<b>Max SS DOS</b>	<i>Maximum Safety Stock in Days of Supply</i>
<b>MLS</b>	<i>Minimum Lot Size</i>
<b>mm</b>	<i>Month</i>
<b>n</b>	<i>Number of Production/Procurement Orders</i>
<b>O</b>	<i>Cumulative Outstanding Orders</i>

<b>OS</b>	<i>Order Size</i>
<b>OQ</b>	<i>Ordered Quantity</i>
<b>p</b>	<i>Purchasing Price or Internal Value</i>
<b>PDT</b>	<i>Planned Delivery Time</i>
<b>PLT</b>	<i>Planned Lead Time</i>
<b>PP</b>	<i>Proportion of Subset from Total Demand</i>
<b>pt</b>	<i>Production Time</i>
<b>prt</b>	<i>Total Production Time (incl. set-up)</i>
<b>PQ</b>	<i>Production Quantity</i>
<b>q</b>	<i>BOM Quantity</i>
<b>Q</b>	<i>Lot Size</i>
<b>R</b>	<i>Review Period</i>
<b>RLT</b>	<i>Replenishment Lead Time</i>
<b>s</b>	<i>Reorder point</i>
<b>S</b>	<i>Order-up-to-level</i>
<b>SI</b>	<i>Set of Shipped Items</i>
<b>SL</b>	<i>(Actual) Service Level</i>
<b>SLT</b>	<i>Service Level Target</i>
<b>SMKB</b>	<i>Scheduled Margin Key Before</i>
<b>SMKA</b>	<i>Scheduled Margin Key After</i>
<b>SOLT</b>	<i>Source Lead Time</i>
<b>sp</b>	<i>Stock Point</i>
<b>SP</b>	<i>Selling Price</i>
<b>SS</b>	<i>Safety Stock in Units</i>
<b>SSA</b>	<i>Actual Safety Stocks</i>
<b>SS DOS</b>	<i>Safety Stock Days of Supply</i>
<b>SS MOS</b>	<i>Safety Stock Months of Supply</i>
<b>ST</b>	<i>Service Time</i>
<b>sut</b>	<i>Set-up Time</i>
<b>t</b>	<i>Time</i>
<b>T</b>	<i>Number of Time Periods</i>
<b>TT</b>	<i>Transportation Time</i>
<b>US</b>	<i>Units Short</i>
<b>UT</b>	<i>Unit Time</i>
<b>WD</b>	<i>Weekly Demand</i>
<b>WDSTD</b>	<i>Weekly Demand Standard Deviation</i>
<b>x</b>	<i>Production Moment</i>
<b>X</b>	<i>Echelon On-Hand Stock level</i>
<b>y</b>	<i>Yield Ratio</i>
<b>Y</b>	<i>Echelon Inventory Position</i>
<b>YD</b>	<i>Yearly Demand</i>
<b><math>\mu</math></b>	<i>Mean Daily Demand</i>
<b><math>\sigma</math></b>	<i>Standard Deviation of Demand</i>

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## 1. Introduction

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Businesses are exposed to a variety of risks and Appendix A shows that “Business Interruption and Supply Chain” belong to the risk categories that are the most feared and which increased significantly from 2014 to 2015. Hendricks and Singhal (2005) reported that supply chain glitches disaffect the operating income, return on sales as well as short-term and mid-term inventory levels. In order to deal with (operational) risks that cause interruptions for a company’s supply chain, an advanced quantitative and qualitative supply chain risk management methodology is required. A quantitative and qualitative evaluation and therewith improvement of the supply chain risk management methodology of Life Science Company (LSC) is exactly the **objective** of this master thesis project. Within the general pipeline risk management approach, the focus is on optimal multi-stage safety stock allocations to buffer against operational risks.

Chapter 1 aims to provide preliminary background information about the company, its project motivation, and the considered scope of the project. Chapter 1 concludes with an outline of the report.

### 1.1 Company Background

Life Science Company (LSC) produces and worldwide sells drugs, such as antibiotics, nutritional supplements and vaccines, to different types of customers. The market is strictly regulated and LSC needs to deal with seasonal demand. LSC’s main supply center, SC GER, produces yearly half of the total sales volume and is fully responsible for the production of PRODUCT, for which their largest market is considered. PRODUCT is sold in many different configurations, which differ through the recipe, size and packaging.

This master thesis project takes place within the Global Supply Chain Management (GSCM) department of LSC. GSCM is responsible for the Pipeline Risk Management Methodology, which includes among others the safety stock optimization methods.

### 1.2 Project Motivation

LSC cannot fully rely on a lean supply chain due to a combination of complex low-volume-high-mix operations and a high desired service level in an environment with long lead times, single suppliers, long production campaigns, and volatile, seasonal customer demand. The assertion is that strategic safety stock settings can cost-efficiently mitigate the risks caused by frequent, but low-impact operational risks. Other mitigation strategies, such as dual sourcing and other forms of supply chain resiliency, appear to be more suitable for low-frequent-high-impact risks.

More specifically, LSC has the following motivations to evaluate and improve the current preventive pipeline risk management methodology, which allocates safety stocks on a brand-stage level. The **first** reason is the expectation that locked working capital can be released, because current system settings rely on a simplified methodology, which bases some parameter values on employees’ gut feeling. This might result in both too high and too low safety stock levels in comparison to the, currently unknown, optimal norm value (Figure 4). Potential evidence for incorrect parameter values is given by differences in the inventory-to-sales ratios for different products. LSC requests a benchmark to assess the quality of the current safety stock method. Appendix B shows by means of a so-called DuPont chart that a reduction in safety stock levels would reduce the working capital, which could increase the return on investment under the assumption that all other values do not change.

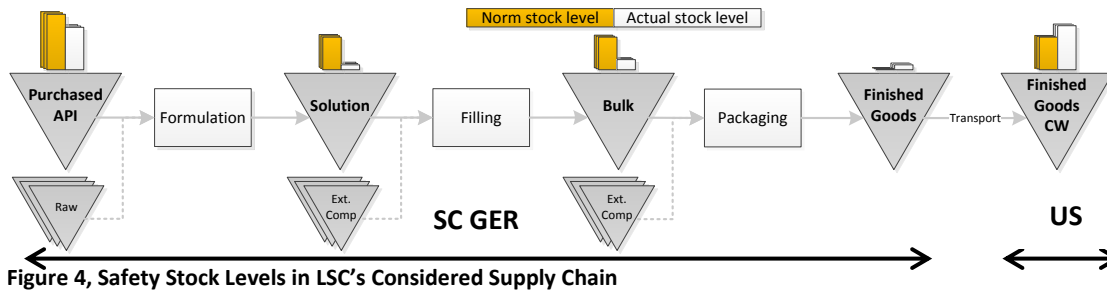


Figure 4, Safety Stock Levels in LSC's Considered Supply Chain

The **second** reason is that the current method neither determines safety stocks for all stages, which therefore requires an additional independent safety stock setting process, nor on item level, which makes it hard to translate it to operational SAP safety stock parameters.

Therefore, this project aims to **qualitatively** and **quantitatively evaluate** and **improve** the current supply chain risk management methodology to mitigate cost-efficiently **operational risks** by **multi-stage safety stock setting** (“Where?”, “How much?” and “When?”).

### 1.3 Scope

The project focused on the quantitative determination of the right safety stock levels for operational supply, process and demand risks. The project scope is limited to A-category products for three US market brands, which are fully produced at SC GER, and that all have the same major API. The considered time period is from October 2014 to September 2015.

This resulted in 28 FGs, which represent 5.8% of the total number of PRODUCT SKU's and represent 31.6% of the total sold PRODUCT products worldwide in 2014. Those 28 FG represent 87.5% of the total number of PRODUCT products in the US and represent 91.6% of the total sold PRODUCT products in the US. The model distinguishes 5 supply chain stages, which are represented by the large triangles in Figure 4.

It is supposed that this subset is large enough to get insights in the benefits of multi-stage safety stock optimization, is representative for A-category products as well as time-efficient to analyze and run.

### 1.4 Outline Report

The aim of Chapter 2 is to provide LSC's necessary supply chain background information, explain its current Pipeline Risk Management Methodology, outline relevant contributions from literature to SC risk management and safety stock setting, identify gaps in literature, present the followed research design, and provide the project's research questions. Subsequently, Chapter 3 explains and declares the multi-echelon models –ChainScope and LLamasoft- that are used as benchmarks for the current LSC method. Next, Chapter 4 provides the quantitative results for the considered base case and for the scenario analysis. This chapter also provides an overview of the advantages and disadvantages of the respective methods: ChainScope, LLamasoft and the LSC Method. Based on the quantitative and qualitative assessment, Chapter 5 shows the redesigned risk management and safety stock optimization methodology. Then, Chapter 6 formulates for LSC a strategic, tactical and operational recommendation with respect to the supply chain risk management approach and safety stock optimization method. Finally, Chapter 7 summarizes the implications of this project for both LSC and academia. It provides not only operational guidelines for implementation and further investigation at LSC, but also gives an overview of contributions to the in Chapter 2.2.5 identified gaps in the literature.

## 2. Analysis and Diagnosis

---

Chapter 2 represents the analysis and diagnosis phase and highlights LSC's environment and explains the current PRODUCT Pipeline Risk Management Process. It also classifies the risk management practices and inventory management practices in two existing frameworks. Additionally, the relevant literature, the identified gaps, the combined research design, and the research questions are discussed.

### 2.1 Environment and Pipeline Risk Management Process

Some background information is given about LSC's specific business environment, the seasonal demand characteristics, the PRODUCT planning and production processes, the pipeline concept and the current Pipeline Risk Management Processes, which include the safety stock setting method.

#### 2.1.1 Business Environment

LSC's business environment is complex and it is characterized by: a broad range in lot sizes, high mix, limited capacities, many product change requests per year (30%) and a limited shelf life. In addition, the global network, the long API procurement times (1 year) due to low order volumes, and seasonal demand lead to a challenging business environment. LSC's Customer Order Decoupling Point (CODP) is located relatively downstream, which is in accordance with the Make-to-Forecast (MTF) strategy, and the products become country specific latest at the packaging step due to language requirements and local regulations. Furthermore, authorities prescribe strict quality control and careful documentation at each production step.

On top, different supply, process and demand uncertainties occur, which need to be mitigated effectively and efficiently by safety stocks. Due to plenty of reasons, such as supplier's shortages, congestion and machine breakdowns, lead times of both external and internal components can increase. Furthermore, variable weather conditions and irrational customer behavior might cause demands that exceed forecasts and need to be fulfilled irrespective of the environmental difficulties.

#### 2.1.2 Demand Characteristics

LLamasoft's demand analysis classified the monthly FG and component demand as "smooth", which means that demand occurs non-intermittently and has a low coefficient of variation. LLamasoft characterized demand as non-intermittent, when the mean demand interval is less than 1.32 periods. Users can define themselves the period length. LLamasoft characterizes non-intermittent demand as smooth, when the squared coefficient of variation of the non-zero demands in the defined period is less than 0.49. According to Hopp and Spearman (2011), this indicates a low level of variability. The products are typically characterized by seasonality with peak demands in the spring. Although seasonality itself can be predicted, the demand variability still reduces the Forecast Accuracy (FCA). The complexity for LSC is the interplay of seasonal shifts, simultaneous peak demands, perishability and limited capacities within a batch environment.

Appendix C shows for three products the non-stationary demand as well as the differences between the products with respect to the timing of peak demands, the width of peak demands, the magnitude of peak demands and the number of peaks within a season. The coefficient of variation also shows large deviations over time and between products. It ranges from 0.11 to 0.90. This is caused by heavily changing *weekly* demands within a month, which makes the need to buffer against demand uncertainty with safety stock inevitable.

2.1.3 PRODUCT Production for SC GER

The high-level, generic planning process depicted in Figure 5 shows the process from forecasting until product delivery. First, marketing, forecast and supply representatives determine an accurate forecast, which is based on historical data and market insights. Then, based on available capacities, the forecast manager and the supply manager agree on a feasible supply plan. Subsequently, the production planner and the material manager create a packaging, bulk and API planning after which purchasing follows. When the API and all other materials arrived, the production can start. Although the showed process steps represent a flow shop with a strict sequence, different machines are used for different product configurations. The process is characterized as batch processing, because of fixed tank sizes. After production, a *final* quality control is conducted and the product is prepared for shipment and subsequently delivered to the country warehouse (CW).

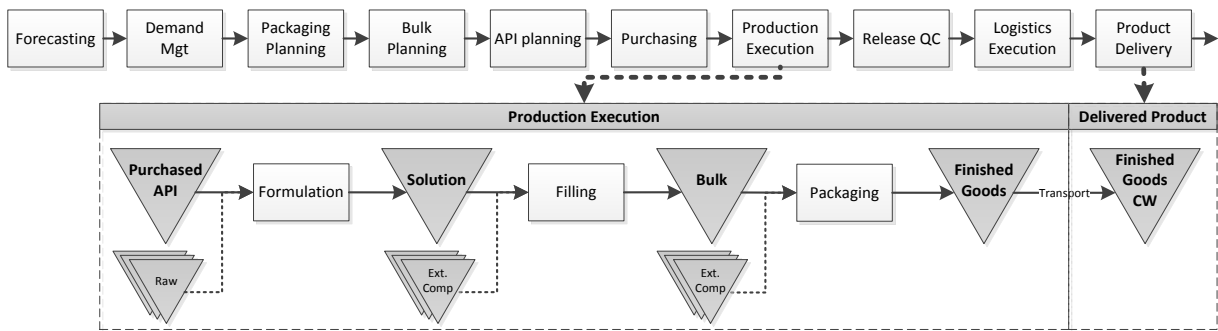


Figure 5, LSC's Planning and Production Process

As the focus is on safety stock setting within the internal supply chain and at the CW, the supply chain characteristics of the PRODUCT “Production Execution” step are described in more detail graphically in Figure 5 and in words below.

**Purchased API:** LSC does not produce the API’s themselves, but purchases those materials in relatively large quantities and up to 1 year in advance. Although the single-sourcing practice seems beneficial, LSC is exposed to a higher supply risk. However, it takes several months to identify and qualify additional suppliers due to the strictly-regulated environment.

**Formulation and solution:** The formulation step can be seen as mixing the API with the other substances under the right conditions, such as temperature. After formulation, the solution is stored in small tank pallets of 500 L, which can be easily moved through the plant.

**Filling and bulk:** The solution is then transported to multiple, on size dedicated filling lines, where the PRODUCTS are filled in many sizes.

**Packaging and finished goods:** The bulk-stored PRODUCTS are fed into the specific packaging line for final packaging. The number of PRODUCTS within one package is variable. The boxes are also provided with the right label, which contains the product information in the right language. Then, when the products are put into a “shipper”, they are moved to the warehouse. The cartons remain on pallets in the warehouse until shipment to a country is necessary.

Chapter 4.1 distinguishes **7 product types** of which 4 match with the large triangles in Figure 5: API, Solution (SOL), Bulk (BULK) and Finished Good (FG). For the external components, Raw, TUB and PACK are distinguished, which match with the first, second and third small triangle in Figure 5.

### 2.1.4 Pipeline Concept

LSC basically organizes its supply chain risk management method around a specific API. LSC introduced the site-independent “pipelines”, which correspond with all materials, articles and activities for the specific API, that have a major sales impact. The pipeline concept is brand independent, because one API can be used for multiple products and multiple API’s can be used for one brand. The risk management workshop, which identifies and quantifies supply uncertainties, is conducted per pipeline and per Supply Center. Every pipeline has a dedicated Pipeline Controller (PC) to manage the pipeline’s flow of products.

### 2.1.5 LSC Pipeline Risk Management Processes

LSC applies the following risk management methodology, which is built around the pipeline concept:

1. **Mapping:** All the stages of the pipeline, from API to the sales affiliates, are mapped by flow charts, such that the product flows per key brand are visualized and become understandable.
2. **Segmentation:** The complex pipeline is then split into smaller parts to make it more comprehensible and focused on a specific activity per stage during the workshop (e.g. 1. *Receive API at SC GER*, 2. *Release API at SC GER*). Although stages are segmented, the final safety stock allocation is on a brand-stage level.
3. **Brainstorming:** Possible supply or demand events, which can include sudden supply stops, machine failures, bad delivery performances as well as more disruptive risks are identified:
  - **Failure mode:** What could potentially disrupt or interrupt the supply chain?
  - **Severity:** a) If this happens, how much product would be affected? [kg of API]  
b) How long would the supply interruption or disruption be?
  - **Likelihood:** How often do we expect that such an event occurs? [X times/year]

Then, the identified risks are accepted or rejected and based on their frequency classified as “common” or “abnormal” events. Common causes require safety stock mitigation, where abnormal causes require contingency planning.

4. **Safety stock allocation (Method):** For common causes with an assigned safety stock mitigation strategy, the following procedure on brand-stage level is used to determine where and how much safety stock is needed. LSC distinguishes only demand and supply risks, because both supply and process risks cause a delay in supply.

#### A) Demand uncertainties:

Formula (1) calculates with the service level target (SLT), the Order Size (OS), the Forecast Inaccuracy (FCIA) and the Lead time (LT), the value for the standard loss function  $Gu(k)$ . LSC assumes that the coefficient of variation of the forecast error can be approximated by the FCIA. Their reasoning is that a high forecast accuracy is negatively correlated to the coefficient of variation. The standard loss function does consider the order size in months, because the demand mean is cancelled out through the replacement of the standard deviation by the “coefficient of variation” that is multiplied with the demand mean. It has been assumed that lead time variability can be ignored.

---


$$\overline{FCIA} = 1 - \overline{FCA} \tag{1}$$

$$Gu(k) = ((1 - \overline{SLT}) * \overline{OS}) / (\sqrt{\overline{LT}} * \overline{FCIA}) \tag{2}$$


---



Then, the safety stock in months of supply (SS MOS) per brand-stage combination is determined with single-echelon logic:

$$SS\ MOS = k * \overline{FCIA} * \sqrt{\overline{LT}} \quad (3)$$

The order size, the forecast inaccuracy, and the lead time are a weighted average of the historically produced quantities for the brands per stage. The order size is determined based on the time between historical production starts. The BULK lead time is equal to the production wheel cycle length. The lead time definition for other product types is described in Chapter 3.1.2.

**B) Potential supply uncertainties:**

The key supply risk parameters per stage are discussed during the yearly Pipeline Risk Management workshop, which is facilitated through Step 1, 2 and 3. Experts with different backgrounds answer the questions in “3. Brainstorming”. They estimate the yearly impact of the identified supply risks in months. Due to the assumption based on a “coincidence argument”, which means that it is unlikely that supply and demand uncertainties for a product happen simultaneously, they only take the *maximum* supply risk duration per stage per brand.

**C) Brand-stage level safety stock allocation (Appendix D):**

When the risks are accepted and are mitigated by safety stocks, one determines based on the coincidence argument the maximum of the supply and demand safety stocks per stage:

$$\max(\text{supply risk months coverage}; \text{demand risk months coverage}) \quad (4)$$

Subsequently, one starts at the most downstream stage and assigns the maximum amount of months coverage per brand. Then, one evaluates the next stage and guarantees again that the cumulative months of safety stock coverage will be equal to the cumulative risk. This procedure is repeated till one reaches the most upstream stage. Then, the method’s outcome is compared with the existing system’s safety stocks per brand-stage combination (5):

$$SS\ DOS = \max\left(\frac{\overline{SS*PP}}{\bar{\mu}}; \overline{SS\ DOS}\right) + \overline{SMKB} + \overline{SMKA} \quad (5)$$

*SS*: Safety stock in units

*SS DOS*: Safety stock days of supply

*PP*: Proportion of subset demand

$\mu$ : Mean daily demand

*SMKB*: Scheduled margin key before (=“float before production”)

*SMKA*: Scheduled margin key after (=“float after production”)

5. **Safety stock allocation (Human improvements):** Next, the method’s and system’s safety stock allocations are compared with a proposal of a pipeline controller, who can shift safety stocks between stages based on soft constraints and business insights. Based on this comparison, the management decides about the final safety stock levels.
6. **Contingency planning:** Risks that are classified as “abnormal” are mitigated by a so-called contingency plan, which is highly dependent on the identified risks. Those risks are out of the scope in this project.
7. **Information sharing with the Enterprise Risk Management team:** The identification of abnormal risk events and the quantification of the likelihood and impact of so-called abnormal risks are the input for the Enterprise Risk Management cycle, which is left out of scope.

2.1.6 Supply Chain Risk and Inventory Management Classifications

Based on the description of the Pipeline Risk Management Processes in the previous paragraph, LSC’s performance with respect to supply chain risk management and inventory management is classified:

**Supply Chain and Risk Management Maturity Model:** Simchi-Levi (2015) considered four stages for Supply Chain and Risk Management Maturity (Figure 6). The current Pipeline Risk Management approach is cross functional through the involvement of multiple disciplines during the workshop. Visibility is increased by a transparency tool, but sharing of information is limited to LSC’s its boundaries. As shown in the previous paragraph, a *basic quantitative* single-echelon risk management technique is present. Some basic segmentation strategies, such as pipeline selection based on sales and the separation in operational and disruptive risks, are also present. Therefore, LSC’s maturity is classified to *Stage 3 “Collaborative/Proactive”* with an element of stage 4.

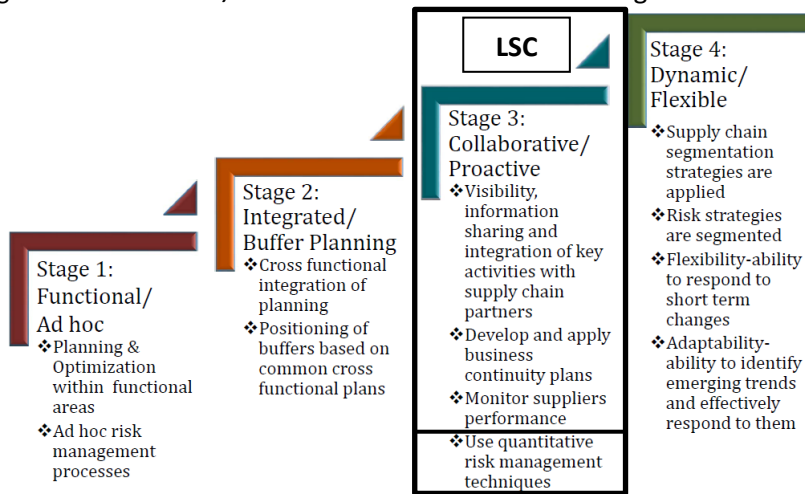


Figure 6, SC and Risk Management Maturity Model – Adapted from: (Simchi-Levi, 2015)

**Inventory Management Professionalism:** Groenewout (2015) described five phases for inventory management professionalism (Figure 7). As LSC deploys demand and forecast planning, has an S&OP process in place, applies single-echelon inventory methods and monitors its inventories, its performance is categorized in *phase 4*. The next phase differs through multi-echelon inventory optimization and a dedicated inventory management specialist. Both stages match with LSC’s desired service level.

	1	2	3	LSC	5
Symptoms	<ul style="list-style-type: none"> <li>Gut feeling inventory management</li> <li>Many back orders</li> <li>No idea about stock quantities and service level</li> </ul>	<ul style="list-style-type: none"> <li>Days on inventory policies</li> <li>Excel based computations</li> <li>Inventory is monitored</li> </ul>	<ul style="list-style-type: none"> <li>Basic statistic inventory calculations (P1) based on historic demand</li> <li>ERP or Excel based computations</li> <li>Inventory is monitored</li> </ul>	<ul style="list-style-type: none"> <li>Demand and forecast planning</li> <li>S&amp;OP processes</li> <li>Single echelon inventory optimization (P2)</li> <li>Inventory is monitored</li> </ul>	<ul style="list-style-type: none"> <li>Demand and forecast planning</li> <li>S&amp;OP processes</li> <li>Multi-echelon inventory optimization</li> <li>Inventory specialist</li> </ul>
Service level:	50-60%	60-80%	80-95%	Up to 99,9%	Up to 99,9%
Potential:	Base Case	Limited	20-30%	30-50%	> 50%

Figure 7, Inventory Management Professionalism – Adapted from: (Groenewout, 2015, p. 11)

## 2.2 Key Literature

Based on the conducted literature study, Chapter 2.2 highlights the challenges within a process environment, identifies typical supply chain risks, compares SC risk management processes, explains the concept of safety stock and gives an overview of two research paradigms about multi-echelon inventory management. Hence, it identified existing gaps in the literature, where this project might contribute.

### 2.2.1 Process Industry Environment

Figure 8 highlights the position of LSC within a one-dimensional typology for process industries.

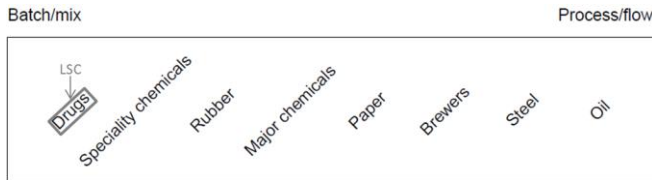


Figure 8, Typology for Process Industries – Adapted from: (Fransoo and Rutten, 1994)

APICS defined “batch/mix” as a type of process industry, which primarily schedules short production runs. Batch processes are further characterized by: long lead times, high WIP, complex routings, more complex products, high added values, and a small impact of changeover times (Fransoo & Rutten, 1994). More specifically, *pharmaceutical* supply chains are characterized by “time-to-market” requirements and “stringent regulations”, considerable inventories, long downtimes due to cleaning, large batches, a long total lead time, and multiple quality inspections (Shah, 2004).

### 2.2.2 SC Risks

According to Jüttner et al. (2003), supply chain risks can be defined as risks, which are related to the flow of information, materials or products within the supply chain. Other researchers distinguished supply chain risks into “disruptive risks” and “operational risks” (Kleindorfer & Saad, 2005), of which Chopra et al. (2007) argued that operational risks are characterized by their recurrent nature. Those high-frequent operational risks generally have a lower impact than low-frequent disruptive risks. That makes them appropriate for mitigation by safety stocks. According to Hallikas et al. (2004), the likelihood and severity can be qualitatively (“no impact ... catastrophic” respectively “very unlikely ... very probable”) and quantitatively (“0-1” respectively “months of lost supply”) plotted in a two-by-two risk matrix (Appendix E).

Appendix F shows an overview that structured the many identical or slightly different classifications of risk categories and risk triggers. Table 4 shows from this overview the three most relevant risk categories and their main risk sources. Then, Appendix G shows for those operational risks the place of occurrence in a supply chain.

Table 4, Main Risk Sources for Main Risk Categories

Relevant risk category	Main risk sources
<b>Supply Risk</b>	Production and delivery lead time variability of the supplier Rejection of supplies (yield)
<b>Process Risk</b>	Delivery lead time variability of the logistics service provider Process yield (per stage) Sudden machine breakdown
<b>Demand Risk</b>	Variability in customer demand / Forecast error

2.2.3 Supply Chain Risk Management Processes

Companies should undertake the activity of SC risk management, preferably together with supply chain partners, to reduce vulnerability or increase profitability by developing mitigation strategies (Thun & Hoenig, 2011). After an assessment of the main risk categories and risk sources, managers need to deploy effective and cost-efficient risk management procedures. However, the unknown relationship between the risk management strategy and the corresponding risks limits the applicability of cost-benefit analyses (Tang, 2006). Therefore, Bayesians allow additional expert opinions, by an analytical, iterative or interactive approach, to estimate probabilities and impact (Paté-Cornell, 1996).

Luckily, multiple SC risk assessment methodologies exist in literature. There is consensus about the order and type of activities, but methodologies differ in the level of detail and naming (Table 5).

Table 5, Overview of SC Risk Management Methodologies

SC Risk Management Methodologies					
Jüttner et al. (2003)	Tuncel & Alpan (2010)	Manuj & Mentzer (2008)	Tummala & Schoenherr (2011)	Hallikas et al. (2004)	Kleindorfer & Saad (2005)
			SCMR Process	'Network Approach'	SAM*
1. Assessment risk sources 2. Definition of adverse consequences 3. Identification of risk drivers 4. Risk mitigation	1. Risk identification 2. Risk assessment 3. Risk management 4. Risk monitoring	1. Risk identification 2. Risk assessment and evaluation 3. Risk management strategies 4. Implementation of SC risk management strategies 5. Mitigation of SC risks →back to step 1	1.1 Risk identification 1.2 Risk measurement 1.3 Risk assessment 2.1 Risk evaluation 2.2 Risk mitigation and contingency planning 3.1 Risk control and monitoring → back to step 1.1	1. (Mutual) identification 2. (Mutual) assessment 3. (Mutual) means for risk reduction 4. (Mutual) implementation 5. (Mutual) monitoring	1. Specify 2. Risk assessment 3. Mitigate
Alternative methodologies: Graph theory (Wagner & Neshat (2010)), Stress test (Chopra & Sodhi (2004))					

Several differences can be observed. The 'Network Approach' emphasizes the collaborative aspects, where both tiers first assess the supply chain themselves, but implement mutually beneficial mitigation strategies together. Tuncel & Alpan (2010) included the activity of risk monitoring, while Jüttner et al. (2003) do not recognize this step. Furthermore, Manuj & Mentzer (2008) and Tummala & Schoenherr (2011) model explicitly a feedback loop to indicate that it is an iterative process. Manuj & Mentzer (2008) showed very fine-grained steps and matrices to systematically assess SC risks and Tummala & Schoenherr (2011) included some drivers, evaluation criteria and performance measures, which might serve as inspiration. Due to the similar steps and their unique advantages, the two methodological schemes are combined into one approach that is graphically shown and explained in Appendix H.

2.2.4 Relevant Concepts for Safety Stock Optimization

As Guide and Srivastava (2000) summarized, uncertainty can be buffered by safety stock, safety lead time, safety capacity, and a concept called "operational flexibility". The last concept is situation specific and hard to quantify and is therefore not taken into account explicitly. Hopp and Spearman (2011) did also only distinguish inventory, capacity and time as a method to buffer against variability. However, operating flexibility that prevents material unavailability is automatically used for LLamasoft's safety stock optimization, which is based on the Guaranteed Service Time approach. Excessive capacity is also left out of the analysis, because multi-echelon assembly system analyses can only implicitly deal with capacity through the planned lead time concept. As LSC prefers to investigate safety stock allocation, there is not dealt with safety lead time explicitly. However, safety stock in units can be converted to time, when one divides it through the next period's demand.

Where cycle stock is dedicated to fulfill the forecasted demand, **safety stock** is, according to Silver et al. (1998), the net inventory just before replenishment. Therefore, safety stock is meant to protect against above-average demand during the lead time, which can be caused by lead time delays and above-average customer demand. Demand uncertainty, for example due to bad forecast through volatile customer behavior, appears to be the main source of variability. Although safety stock leads to additional inventory holding costs, a company might benefit from less lost sales, more goodwill and a reduced number of expensive emergency shipments (Sürie & Wagner, 2005). Safety stock appears to be a particularly good hedge, when it is for cheap, imperishable commodities (Chopra & Sodhi, 2004).

Classically, the safety stock for the probability of no stock-out immediately before arrival of a replenishment is determined separately per stage ((6)):

$$SS = k * \sigma * \sqrt{RLT + R} \quad (6)$$

The safety stock level,  $SS$ , depends on the safety factor  $k$ , the standard deviation of the demand  $\sigma$  over the replenishment lead time  $RLT$  and the review period  $R$ . The fill rate is the fraction of demand that is delivered on time from the on-hand stock. The expected amount of units short can be calculated with the standard loss function under the assumption that demand is normally distributed. Then, the safety factor  $k$  is derived from the standard loss function  $Gu(k)$  (Minner, 2015):

$$SL = \frac{OQ - E[US]}{OQ} \quad (7)$$

$$E[US] = \sigma * Gu(k) \quad (8)$$

$$Gu(k) = \frac{OQ}{\sigma} * (1 - SL) \quad (9)$$

$SL$ : Service level

$OQ$ : Ordered quantity

$\sigma$ : Standard deviation of the demand

$E[US]$ : Expected number of units short

Now, the more advanced multi-echelon safety stock concept will be shortly explained after highlighting some terminology. A **multi-echelon structure** can be described as serial, convergent, divergent or general. The convergent system has multiple predecessors and only one successor and the general network has multiple predecessors and successors (Appendix I). Due to common components and two serial relationships, LSC's assembly network became a general network.

**Centralized control concepts** consider all information that is available in the echelon network instead of exclusively local stock point knowledge. Control concepts effectively exploit the supply chain and support in answering "when, where and how much" items should be released. Echelon stock policies consider local stock levels, as well as stock in transit, stock on hand and backorders for its downstream stock points. A graphical overview of the echelon concept in a two-stage serial supply chain is shown in Appendix J. According to De Kok and Fransoo (2003), those echelon stocks can be recursively calculated:

$$X_i(t) = J_i(t), \forall i \in E \quad (10)$$

$$Y_i(t) = X_i(t) + O_i(t), \forall i \in E \quad (11)$$

$$X_i(t) = J_i(t) + \sum_{j \in V_i} Y_j(t), \forall i \in I \quad (12)$$

$$Y_i(t) = X_i(t) + O_i(t), \forall i \in I \quad (13)$$

$X_i(t)$ : Echelon on hand stock for item  $i$  at time  $t$

$Y_i(t)$ : Echelon inventory position for item  $i$  at time  $t$

$O_i(t)$ : Cumulative outstanding orders for item  $i$  at time  $t$

$J_i(t)$ : Local on hand stock for item  $i$  at time  $t$

$E$ : Set of end items

$I$ : Set of intermediate items

**Control strategies** indicate “where”, “when” and “how much” should be ordered. Those control strategies often strive to find the optimal balance between inventory holding costs and penalty costs for a pre-specified service level. Reorder point policies represent order policies, where an order is placed when the inventory position equals or falls below a pre-specified reorder point s.

**The Supply Chain Operations Planning (SCOP) function** possesses a centralized control assumption and Figure 9 shows its relationship to order acceptance, aggregate planning and parameter setting.

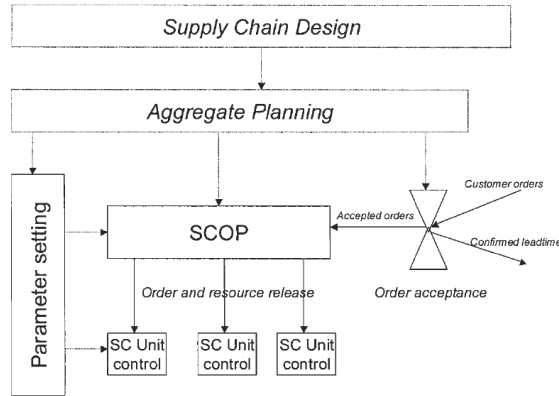


Figure 9, SCOP Function in the Planning Hierarchy – (De Kok & Fransoo, 2003, p. 618)

According to De Kok and Fransoo (2003), SCOP aims to coordinate by mechanisms, such as MRP I or reorder point systems, the short-term and mid-term release of materials and resources in a supply network, such that customer service levels are met against minimal costs. The parameter setting function should coordinate *safety stocks*, lead times and workload parameters (De Kok, 2014). However, the optimal value for the control parameters depends on the operational control strategies, such as (s,S) or (R,S), and the method (e.g. MRP I, LP), which are determined by the SCOP function. Therefore, the SCOP function needs to be supported by models and that can generally be done with:

- **Stochastic demand models** that incorporate random demand
- **Mathematical programming models** embedded in a rolling schedule approach

Uquillas (2010) gave, based on Boulaksil et al. (2009), a comprehensive overview of the major differences between those SCOP modelling approaches (Table 6):

Table 6, Two Major SCOP Modelling Approaches – (Uquillas, 2010, p. 7)

Factor	Stochastic demand models	Mathematical programming models
Demand	Stochastic variable	Forecast per period
Key decisions	Inventory positioning at the various stock points	Allocation of inventory at stock points
	Allocation of Inventory where product flow diverges	
	Safety stock determination	
Lead Times	Deterministic Input	Deterministic input or output variables
Capacity control	Workload control function	Aggregated constraints
	Demand management function	
Safety stock	Output	Input

As Table 6 shows, safety stock is an **output** for stochastic demand models and an **input** for mathematical programming models. De Kok and Fransoo (2003) also stated that mathematical programming does not determine “where” and “how much” safety stock is required.

According to Boulaksil et al. (2009), there is a lot of literature about safety stock levels, but no literature offers a **methodology** to successfully deal with capacity constraints, batch-size production and non-stationary forecasting processes. They also observed that some papers lack an explicit discussion about the safety stock setting process.

Moncayo-Martinez and Zhang (2013) argued that complexities in the multi-item, multi-stage safety stock setting process arise from *“(1) the nonlinear performance functions that relate the service level and expected inventory with safety stock control variables at each site; (2) the interdependence of the performances of different sites; and (3) finally the margin by which production capacity exceeds the uncertain demand”*.

Nevertheless many researchers search for a good solution methodology to set safety stock levels, which can be classified based on their assumptions about service times and the replenishment mechanism into a Stochastic Service (SS) approach and a Guaranteed Service Time (GS) approach (Graves and Willems (2003)). Humair and Willems (2006) stated that both approaches possess pros and cons. Although the GS approach results in a less exact system understanding, it possesses the possibility to take tactical decisions, even when the system is not a pure assembly system or another “standard topological representation”. The GS approach appeared to be less promising, when much commonality exists between two echelons. Klosterhalfen and Minner (2006) concluded from a detailed comparison that the low computational effort is an advantage of the GS approach. Now the two research paradigms are explained in more detail:

<b>Stochastic Service (SS)/ Synchronized Base Stock (SBS) approaches based on Clark and Scarf (1960)</b>
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Stochastic Service approaches check at “every” moment in time whether the material requirements can be satisfied and what the consequences are for the inventory position, production/ordering function and the fill rate (Humair & Willems, 2006). Stock outs of upstream stages cause delays that limit demand fulfillment, because no “doubtful” assumptions are being made about “operational flexibility”. Therefore Stochastic Service models possess a variable delivery or service time, which depends on the component’s availability. In contrast to the stochastic service approaches, the Synchronized Base Stock policy (SBS) explicitly deals with a lack of material availability. This means that SBS releases only orders that are material-feasible. In case a shortage occurs, the available materials are released in order to start production. The remaining materials are released as soon as they are available. The only form of flexibility in SBS is needed for resource issues. De Kok (2015) stated that SBS relies on the fact that average inventories are the main driver for the service level. Fortunately, the modeling of average inventory appears to imitate reality in validation studies. A tool based on SBS (ChainScope) converts this inventory level to synchronized base stock levels. The computational complexity of the SBS policies is comparable to MRP I logic once base stock levels have been determined. SBS differs from, for example, MRP, because it considers echelon instead of local inventory positions. This method forms the basis for the multi-echelon tool **ChainScope**, which is both tractable and empirically valid. More information about SBS can be found in Chapter 3.1.1, the key papers that are summarized in Appendix K, De Kok and Fransoo (2003) and Appendix A of De Kok et al. (2005). An easier read is De Kok et al. (2005), where they described a case study at Philips Electronics, in which the SBS concept dealt with stochastic demand, stochastic throughput times at fabrication, assembly and testing, and yield (through learning curves).

### Guaranteed Service Time (GS) approach based on Simpson (1958)

According to Klosterhalfen et al. (2014), the Guaranteed Service Time approach accepts, except from external resources such as on-hand stock (incl. safety stock), also “operational flexibility”. GS assumes less than 100% material availability at upstream nodes and supposes that 1) the goods acceptance function (SCOP) keeps demand below an upper bound or that 2) operational flexibility (or “the hand of god”) covers the remaining percentage to maintain nominal lead times. Therefore, GS does not model stochastic delays in the delivery of items. Moreover, this approach evaluates the demand fulfillment *over* instead of *within* an interval (Humair & Willems, 2006). In addition, the GS approach is based on a local base stock control policy, where the base stock level should cover the maximal cumulative unknown demand over the net replenishment lead time. The GS approach, newly applied by Graves and Willems (2000), assumes that supply always takes place within the guaranteed service times. Therefore, the aim is to allocate with dynamic programming exactly sufficient inventory at every stage, such that the guaranteed service times are met cost efficiently. GS literature included demand uncertainty and periodic review base stock policies, assumed deterministic lead times and bounded, stationary demands and did not consider capacity restrictions. Graves and Willems (2002) extended their original method – without clusters of commonality – for non-stationary demand. Based on a constant service time and similar stocking locations, they showed the equivalence, when one solves this problem under stationary demand. Humair and Willems (2006) adapted the model for common components between consecutive echelons. The GS method forms the basis for the used tool **LLamasoft**. More information about the GS approach is given in Chapter 3.2.1 and in the key papers, which are listed in Appendix K.

### 2.2.5 Gaps in Literature

The project motivation, the description of the current processes and the literature study revealed three main areas of contribution. **First**, this project offers the opportunity to qualitatively and quantitatively compare the GS with the SBS approach in a non-stationary environment (seasonality) under some supply-, process- and demand risks for a subset of a real life primarily convergent supply chain in a challenging batch/mix environment. **Second**, this case study also contributes to the assessment of the empirical validity of both research paradigms, which are often primarily focusing on mathematical modelling instead of “experiments with real-life supply chains”. **Third**, the lack of safety stock optimization procedures can be compensated by detailed descriptions of the input parameters within this batch/mix environment and a proposed approach to deal with seasonality.

## 2.3 Research Design

This project aims to solve both a real life problem, which can be classified within the field of Operations Management, and contribute to academia by deducting more generally applicable procedures from this explorative case study. Due to the variety of goals, three research methodologies are connected: the Regulative Cycle, Mitroff’s Four Phases Model and the Reflective Cycle (Figure 10).



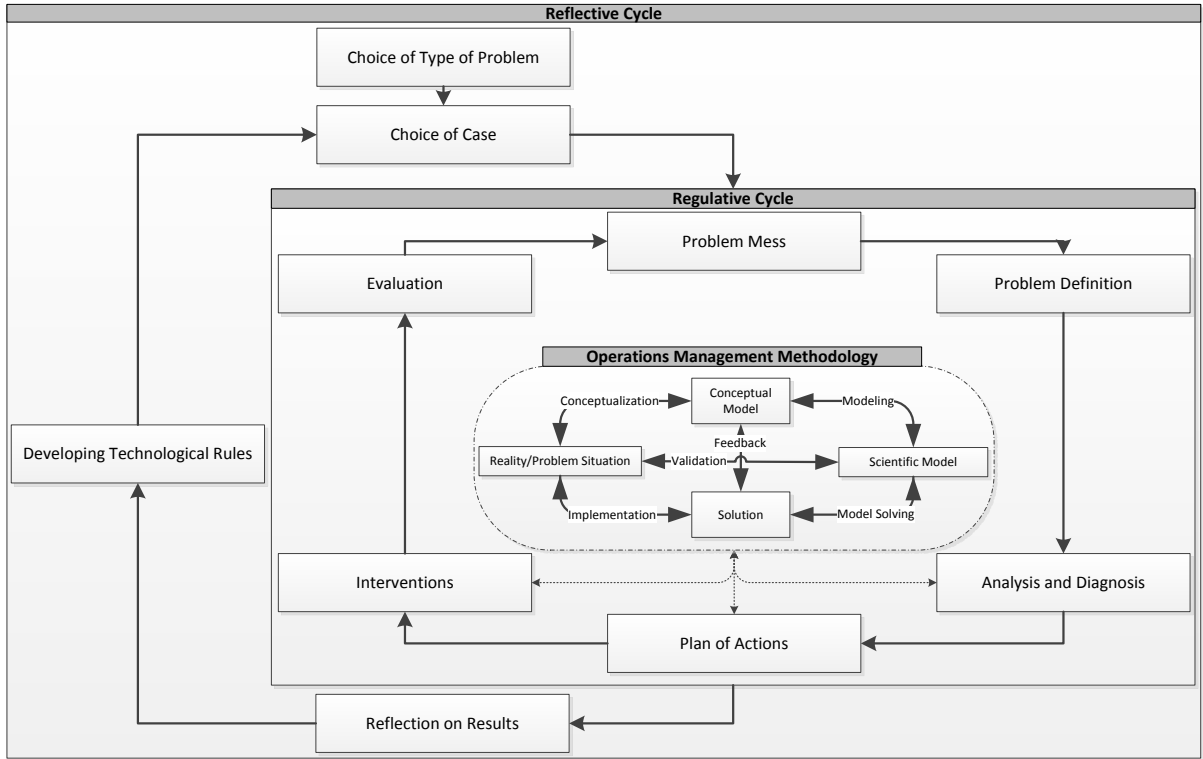


Figure 10, Research Design – Adapted from: (Van Aken et al., 2007 and Mitroff et al., 1974)

The **reflective cycle** consists of four main steps, of which the regulative cycle is one step. The **regulative cycle** is a learning cycle that is suited to solve feasible and high impact (root) business problems and it prescribes field-tested, and therefore effective, solution concepts for a problem (Van Aken et al., 2007). In order to find those solution concepts, an initial cause-and-effect diagram is constructed and qualitative analyses, conducted through desk research and unstructured interviews with SC practitioners, as well as quantitative analyses, conducted through **Mitroff's operations research methodology**, are carried out. Mitroff et al. (1974) described how the methodology helps to develop a causal model that represents reality, solves the real problem and can be mathematically solved. Therefore one follows iteratively some (not necessarily all) adjacent phases. This project mainly reiterated through the conceptual model, scientific model and solution phases. After synthesis of the quantitative and qualitative results, the regulative cycle ends with the recommended interventions. Then, some elements of the redesign can -after deduction according to the reflective cycle- form a general operating procedure (*technological rule*) for SC risk management and safety stock optimization.

This combined research design scored high on both of Shrivastava's (1987) objectives for research: **rigor** and **relevance**. **Rigor** is obtained through the previous literature overview that contributes to *conceptual adequacy*. The research methodologies as well as the academic supply chain risk management approaches (incl. safety stock optimization methods) guarantee *methodological rigor*. And last, *empirical evidence* is obtained through an explorative case study. **Relevance** is high, because the project supports management to reduce the working capital (*goal relevance*) and it offers an improved methodology (redesign) to deal with the strategic risk management problem (*meaningfulness*). In addition, Chapter 7.1 describes the implications for implementation, which increase *operational validity*.

## 2.4 Research Questions

The project question below is derived from LSC's project motivation, the analysis of the current Pipeline Risk Management Process, the identified gaps in literature and the more detailed cause-and-effect diagram (Appendix L). Based on this cause-and-effect diagram and in alignment with LSC, the choice has been made to restrict the scope to "Risk Methodology" and "Unsophisticated SS determination". The "Risk Methodology" and "Unsophisticated SS determination" are namely actively controlled and relatively unaffected by other (human) factors, a high improvement potential of multi-echelon approaches is expected, and it is academically interesting, because of the identified gaps (2.2.5).

The overall project question is then split into sub questions, which leads to a qualitative and quantitative evaluation of the current risk management approach and safety stock method. It also leads to the evaluation of alternative multi-stage safety stock optimization methods. This results in a recommendation of the overall "best" supply chain risk management methodology and implications for implementation. Hypotheses are only formulated for sub research question 2, because those are quantitatively and objectively testable. It is split into multiple hypotheses to make each hypothesis unidimensional. The quantitative comparison in Chapter 4.1 accepts and rejects the formulated hypotheses. Finally, an academic question is formulated to guarantee an explicit academic contribution.

### Overall project research question:

What is for LSC's business environment **qualitatively** and **quantitatively** the "best" risk management methodology, which is able to assign multi-echelon safety stock levels?

### Sub research questions:

1. What is the **qualitative** performance of LSC's current **supply chain risk management method**? [Chapter 4.2.4]
2. What is the **quantitative** performance of LSC's and ChainScope's and LLamasoft's **multi-echelon safety stock optimization method** under different scenarios? [Chapter 4.1]
3. What is the **qualitative** performance of LSC's and ChainScope's and LLamasoft's **multi-echelon safety stock optimization method**? [Chapter 4.2]
4. What is the **overall** most desired **safety stock optimization method**? [Chapter 6]
5. How should LSC **implement** the overall best supply chain risk management methodology? [Chapter 7.1]

### Sub research hypotheses for research question 2:

- A) Multi-echelon models allocate **less** safety stock than LSC's single echelon method.
- B) LLamasoft's safety allocation in assembly networks is **more conservative** than ChainScope's.
- C) Relative differences between LLamasoft and ChainScope **decrease** in terms of safety stock value in comparison to safety stock days of supply.
- D) ChainScope's and LLamasoft's safety stock allocations in contrast to LSC's are **dynamic over time**
- E) ChainScope's, LLamasoft's and LSC's safety stock allocation show always a **similar direction**, but a **different magnitude** for different scenarios.

### Academic question:

1. What is the contribution of this project to academia?

### 3. Validation of Multi-Echelon Models for a Real-Life Supply Chain

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As in Chapter 2.1.5 described, the LSC method relies on adapted single-echelon logic. The LSC Method needs to be compared with multi-echelon models to assess whether LSC's brand-stage safety stock allocation is a good approximation. Chapter 2.2.4 showed that two research paradigms, SBS and GS, exist simultaneously and that the superiority debate is not yet settled. As multi-echelon safety stock optimization tools are too hard to develop yourself in a master thesis project, we relied on existing and licensed tooling. Therefore, a comparison is conducted between the LSC Method, ChainScope (SBS) and LLamasoft (GS). However, one first needs to validate the model input for the last two tools (Chapter 3).

Although the models have different assumptions about replenishments and service times, many necessary input parameters are similar for both models. An overview of the input parameters for both tools is shown in Appendix M. With respect to LLamasoft: the purple respectively blue boxes represent the input parameters that are used for *simulation only* respectively *optimization only*. Except from many similar input parameters, ChainScope and LLamasoft also assume the same order of events: **i)** For every item in each stage an order is placed (if necessary), **ii)** The order arrives after the planned lead time, **iii)** The period's demands occur, and finally **iv)** The costs are assessed.

Chapter 3.1.1 respectively 3.2.1 discusses the solution technique of ChainScope respectively LLamasoft. Those paragraphs extend the background information, which was already given in Chapter 2.2.4. Then, Chapter 3.1.2 respectively 3.2.2 discusses the optimization model input for ChainScope respectively LLamasoft. Subsequently, Chapter 3.1.3 respectively 3.2.3 elaborates on the model validation for both methods. Specifically for ChainScope, Chapter 3.1.4 presents a procedure to deal with seasonality. Specifically for LLamasoft, Chapter 3.2.4 ends with some concluding notes about LLamasoft's simulation and optimization modules.

#### 3.1 ChainScope

As mentioned above, the next paragraphs elaborate on the solution technique, the optimization model input, the model validation and the seasonality modeling procedure.

##### 3.1.1 Solution Technique

ChainScope's objective is to meet the end-item-specific target fill rate against minimal inventory capital investments. The SBS method relies on fundamental insights from multi-echelon inventory theory, which are highlighted and also shown in Appendix K. Desired (mathematical) details can be found in the original papers.

The SBS policy extends Rosling's concept for pure assembly systems, where an item always has only one successor and that could be translated to a serial system, to a *general* supply network. The method is composed of base stock policies and allocation rules to guarantee material-feasible order releases. A crucial distinction between the SBS policy and *pure* base stock policies is that SBS possesses an allocation mechanism and a pure base stock only an order mechanism. SBS's allocation rule allocates the shortages in fixed fractions to successive stages. Furthermore, SBS offers the possibility to define a dedicated service level for each end item, which is not possible with pure base stock policies. SBS may have multiple base stock levels for one item. The most upstream of these is comparable to the pure base stock level. This leads in the end to the flexibility to meet the service level requirement for each end-item (and more general for each item with independent demand).

Synchronization refers to the combination of coverages of future demand as WIP, in transit stock and actual stock, which depends on the control policy. Synchronization can be done by Linear Programming (LP) or by SBS. De Kok and Fransoo (2003) found out that SBS outperformed the LP allocation for all 12 test cases significantly: 8-18% less inventory capital. Although SBS splits the coverage of future demand for common items already before it is needed, the model appeared to be tractable and control appeared to be more effective due to the inclusion of demand uncertainty (De Kok, XXXX).

SBS relies on a finding in De Kok and Visschers (1999). De Kok and Visschers (1999) proposed, partially based on Diks' and De Kok's (1999) close-to-cost-optimal periodic echelon order-up-to-policy (R,S) for *divergent* systems under stochastic stationary demand and linear holding and penalty costs, a decomposition method for *general* assembly systems. This method decomposes *assembly* networks into pure divergent multi-echelon systems by pre-allocating common components to end products. Thanks to this artificial hierarchy, which is based on the BOM structure and the planned lead times, this divergent decision node (=items sets) network is constructed (Appendix N). Then the divergent network can be translated into cost-optimal Newsvendor equations, which synchronize order release decisions of items over time. Therefore, the Newsvendor equation, as described in Diks and De Kok (1999), is solved recursively. Then, those order releases are converted back to the original network structure.

However, although simulation studies showed the good quality of the analytical expressions for *divergent* systems, its quality cannot be generalized to *general* structures. In fact, De Kok (2015) stated that there it is not expected that tractable, optimal policies exist for multi-item, multi-echelon systems. However, multiple case studies, such as Uquilas (2010), contributed to empirical validity of the SBS logic.

#### 3.1.2 Optimization Model Input

Chapter 3.1.2 outlines and explains the parameter input for ChainScope's evaluation, which is used for model validation, and for ChainScope's optimization. All time units are specified in calendar days, holding costs are assumed to be linear and there are 365 periods per year. ChainScope relies on the following input:

**Expected Lead Time per Item:** Figure 11 shows the components of the nominal planned lead time for externally procured items, internally made items and the supplement to the lead time, when the item needs to be delivered to a CW. The expected lead time is a normative time, which models implicitly capacity. For this normative lead time the assumption is made that components are most of the time available. De Kok (2015) emphasized that the normative lead time is the outcome of "*the confrontation between resources with stochastic processing times and stochastic item demand*". It is assumed that item lead times remain stable and are expressed in integer numbers. As shown in Figure 11, the actual order release can happen at different moments. Planners can determine themselves, as long as all the components are available, how many days before the actual production start they release the materials. Therefore, the actual release dates should not be used to determine the planned lead times.

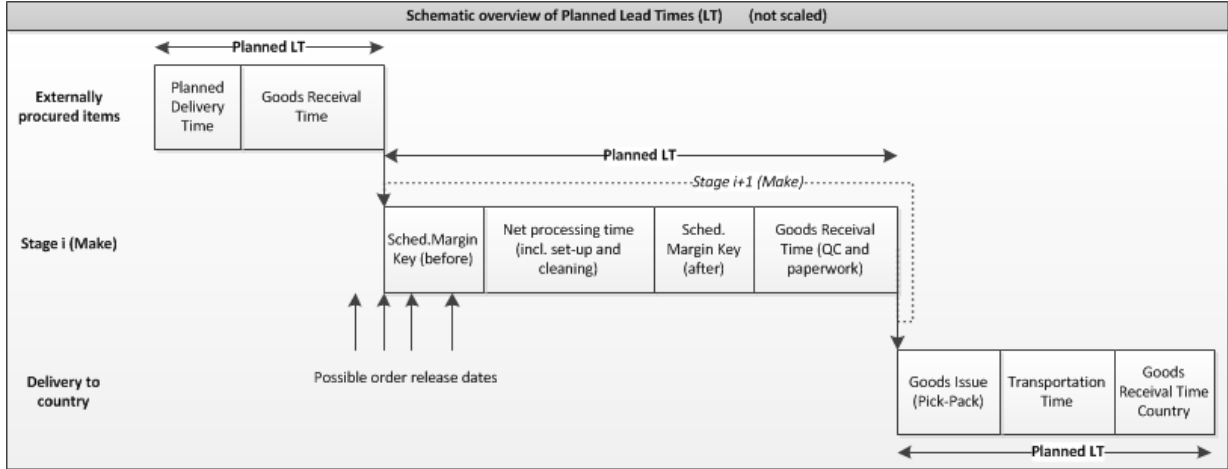


Figure 11, Planned Lead Time Overview

The planned lead time of **external items** consists of the system's planned delivery time, which contains the estimated required time to **i) place and process the order, ii) produce the order at the supplier's site and iii) transport the item to LSC**. Then, LSC checks the quality and/or the attached documentation. After approval, the item can be processed at the next stage. Due to special ordering conditions for API's, pipeline controllers estimated the API lead time.

$$PLT_{i \in EI} = \text{ROUND}(PDT_{i \in EI} + GR_{i \in EI}) \quad (14)$$

$PLT_i$ : Planned lead time for item  $i$

$PDT_i$ : Planned delivery time for item  $i$

$GR_i$ : Goods receiving time

$EI$ : Set of external items

The planned lead time of **internally made items** contains a scheduled margin key *before* (SMKB) and *after* (SMKA), the total processing time of the order (incl. set-up and cleaning) and the goods receiving time in which the quality and/or the documentation is checked. The scheduled margin key enables planning flexibility and functions as a safety lead time. The internal transportation occurs within the SMKB. The order can be postponed, when capacity needs to be used for a priority order and the item can be finished before the end of the SMKA. However, the value is historically determined from the so-called basic start and end date. After the goods receiving time, the order can either be further processed internally, which is represented by the loop, or be transported to the receiving CW.

$$PLT_{i \in II} = \text{ROUND}(\overline{BED}_{i \in II} - \overline{ASD}_{i \in II} + GR_{i \in II}) \quad (15)$$

$BED_i$ : Basic end date of item  $i$

$ASD_i$ : Actual start date of item  $i$

$II$ : Set of internal items

The **movement to the CW** does not only consist of transportation time, but it also contains a good issue time in SC GER's warehouse to "pick-and-pack" the materials. Then, the items are shipped and the receiving country checks again the quality of the received materials. The transportation time has been assumed to be the regular and least expensive sea shipment time.

$$PLT_{i \in SI} = \text{ROUND}(GI_{i \in SI} + TT_{i \in SI} + GR_{i \in SI}) \quad (16)$$

$TT_i$ : Transportation time of item  $i$

$GI_i$ : Goods issue time of item  $i$

$SI$ : Set of items to ship

**Added Value per Item:** The added value per item represents the added value during the transformation process. The added value for external items (EI) represents the purchasing price. The added value for internal items (II) represents the total interval value of the assembled item minus the total value of the items that are used for the assembly. Finished goods from SC GER (SI) are transferred against a shipment cost to a local country warehouse in which the product value does not increase.

$$AV_{i \in EI} = p_{i \in EI} \quad (17)$$

$$AV_{i \in II} = (p_j * BQ_j - \sum_{i \in j} p_i * q_i) / BQ_j \quad (18)$$

$$AV_{i \in SI} = 0 \quad (19)$$

$AV_i$ : Added value for item  $i$

$p_i$ : Purchasing price or internal value of item  $i$

$p_j$ : Internal value of assembly step for item  $j$ , which consists of item(s)  $i$

$q_i$ : BOM quantity per base quantity of item  $i$  to assemble item  $j$

$BQ_j$ : Base quantity of production for processing item  $j$

---

**Release Costs:** The release costs represent the fixed costs per order. For internal items where significant capacity losses occur due to changeovers, a fixed order cost is charged. The ordering costs of a sea container are used as input for the shipped FG items.

**Yield:** The yield value represents the ratio of the number of products that are functioning well. Although the actual produced quantity can be above the norm value, the maximum item-based random yield ratio is then set to 1 due to ChainScope's limitation.

$$y_{i \in II} = \min \left( \frac{DQ_{i \in II}}{OQ_{i \in II}}; 1 \right) \quad (20)$$

$$y_{i \in EI} = 1 - \text{scrap factor from master data}$$

$$y_{i \in SI} = 1$$

$y_i$ : Yield ratio of item  $i$

$DQ_i$ : Delivered quantity of item  $i$

$OQ_i$ : Ordered quantity of item  $i$

---

**Target Stock:** The average stock quantity is derived from the end-of-the-week on-hand stock figures. Due to non-stationarity, which is caused by seasonality, the average should be limited to a couple of weeks in advance of the considered month. A yearly average would disturb the analysis, because stocks are pre-built and then depleted in the peak season. In addition, the system's values contain inventory values for all products. Therefore, the *component* inventory figures need to be multiplied with a proportional factor that represents the subset's share, which is based on last year's actual usage and next year's forecasted usage.

$$\overline{CPT}_i = PP_i * (\overline{CPT}_i) \quad (21)$$

$$PP_i = \min (ASYD_i / FTYD_i; 1) \quad (22)$$

$\overline{CPT}_i$ : (Proportional) on – hand stock for item  $i$

$PP_i$ : Proportion of subset vs total demand for item  $i$

$ASYD_i$ : Actual subset yearly demand for item  $i$

$FTYD_i$ : Forecasted total yearly demand for item  $i$

---

**Review Period:** The review period indicates the time period between two subsequent order releases. The inventory positions are periodically checked and replenishment orders are then created. For some internal or external items a minimal number of days between replenishments and/or a minimal number

of days between productions exist. As historical minimum values do not guarantee the *real* minimum times between replenishments or productions, expert estimations are used. For example, due to a high delivery and production flexibility and to prevent inflated safety stocks, experts advised to set the review period to 1 for supplies and internal productions. The review period is set to 30 days to model the replenishment frequency from SC GER to the CW *under regular conditions*.

**Lot Size:** The lot size is derived from the master data and for API's slightly adapted during validation with experts:

---


$$CLS_i = \max (MLS_i; FLS_i) \quad (23)$$

$CLS_i$ : Lot size of item  $i$

$MLS_i$ : Minimum lot size of item  $i$

$FLS_i$ : Fixed lot size of item  $i$

---

**BOM Structure:** As ChainScope can handle non-integer BOM quantities, the BOM quantity is calculated per item instead of per base quantity. However, ChainScope is not able to handle very small BOM quantities. Therefore, one BOM quantity is multiplied by a factor 10 to solve the tool's infeasibility (0.0005 instead of 0.00005). Furthermore, the BOM is extended by a shipment relationship between SC GER and CW with a BOM quantity of 1.

**Expected Demand:** The stationary monthly demand is converted to *daily* demand means and *daily* standard deviations. It has been assumed that this demand is independent and identically distributed.

---


$$DD_{i,mm \in M} = WD_{i,mm}/7 \quad (24)$$

$$DDSTD_{i,mm \in M} = WDSTD_{i,mm}/\sqrt{7} \quad (25)$$

$DD_{i,mm \in M}$ : Average daily demand per item  $i$  per month  $mm$

$WD_{i,mm \in M}$ : Average weekly demand per item  $i$  per month  $mm$

$DDSTD_{i,mm \in M}$ : Average daily demand standard deviation per item  $i$  per month  $mm$

$WDSTD_{i,mm \in M}$ : Average weekly demand standard deviation per item  $i$  per month  $mm$

$M \in \{\text{January, February, ..., November, December}\}$

---

Sometimes really small or even negative demands occurred, which indicated stock-outs and/or product returns. Those left-tail demand outliers inflated the standard deviation and are therefore removed. However, right-tail outliers, which might indicate special weather conditions, are not removed. Those outliers are kept, because those demands drive safety stocks in the model, which are needed in practice to achieve a good service level. Furthermore, one should be aware that stochasticity of end items is propagated to components. According to De Kok and Fransoo (2003), exactly this reoccurring item level stochasticity makes the analysis of multi-item, multi-echelon systems mathematically hard.

**Customer Order Lead Time:** The Customer Order Lead Time is the number of periods between a customer order placement and the delivery to the customer. As the CW needs to deliver instantly after demand occurrence, the Customer Order Lead time is modelled as 0 days.

**Margin:** The margin represents the ratio of the profit and the selling price on every *end item*:

---


$$m_i = \frac{SP_i - AV_{i \in II}}{SP_i} \quad (26)$$

$m_i$ : margin of end item  $i$

$AV_i$ : Added value of end item  $i$

$II$ : Set of internal items

$SP_i$ : Selling price of end item  $i$

---

**Max Stock:** In agreement with stakeholders, the maximum inventory for labels and packaging materials has been defined in order to limit the safety stock allocations to those items. Labels and packaging materials are characterized by frequent product changes or a limited shelf life. This constraint should reduce the amount of scrapped items. The maximum inventory has been defined as a fixed fraction of the yearly demand:

---


$$Max\ Inv_i = Factor * YD_i \tag{27}$$

*Max Inv<sub>i</sub>*: Maximum inventory for item *i*  
*Factor*: Fraction of yearly demand of an item that should be stored at most  
*YD<sub>i</sub>*: Yearly demand for item *i*

---

**Other Input Data:** In addition, one specifies all item codes, item descriptions, customer information, service level targets on item-customer level, and the inventory holding cost percentage.

### 3.1.3 Model Validation by “Evaluation”

ChainScope’s evaluation mode is based on analytical expressions and not on a discrete event simulation. It is used to validate the base model. This base model is based on October’s demand, which is for 90% of the products a month with below-average demand. Although one would, based on the month’s historical service level performance, expect a service level of 100%, ChainScope indicated only a 97.5% fill rate. The 10% of the items with above-average demand indeed showed a lower fill rate, which reduced the overall fill rate. It is supposed that flexibility measures, which are described below and cannot be modelled in the considered optimization models, contribute to achieve the 99% service level target. **Therefore, the optimization with ChainScope, and later with LLamasoft as well, is conducted with a target fill rate of 97.5%.** Despite this 2.5% difference, the model is considered as valid, because four reasons are identified that caused the deviation between the actual and evaluated fill rate:

- 1. Methodological:** ChainScope considers stochastic demand for which a mean and standard deviation are specified. As inventory is limited and there is always a small probability of extremely high demand, it is not possible to achieve a 100% service level, such as reported in practice.
- 2. Other service level definition:** In contrast to ChainScope, LSC does currently not *measure*, but *estimate* the service level based on the number of days out of stock and the average daily demand:

---


$$SL_i = 1 - \frac{E[US_i]}{OQ_i} \tag{28}$$

*SL<sub>i</sub>*: Service level for item *i*  
*E[US<sub>i</sub>]*: Expected number of units short for item *i*  
*OQ<sub>i</sub>*: Total demand for item *i*

---

**3. Human intervention affects norm values:** Often, human interventions aim to correct an undesired situation, such as a stock-out. Flexibility measures are different forms of lead time reducing activities that happen in practice, but cannot be included in the (optimization) model. Lead times for orders can be reduced by **i)** rescheduling to allow for priority orders instead of FIFO processing, **ii)** reduction of the SMKB, SMKA, goods issue and goods receiving times, **iii)** combined shipments for multiple products, such that items arrive earlier in the CW, **iv)** air instead of sea freight, and **v)** the postponement of promotional orders. Similarly, LSC can also request lead time reductions from suppliers.

**4. Data reliability:** Deviations are also caused by estimations, variability in historical data, and deviations between SAP data and actual data.



#### 3.1.4 Seasonality Modelling Procedure

ChainScope relies on recursively solving generalized Newsvendor equations. However, those cost-optimal outcomes cannot be guaranteed anymore under non-stationary demand. Based on Silver et al. (1998), the Chase strategy, in which the production output follows the demand patterns some time in advance, is applied as a part of the safety stock optimization procedure to deal with the seasonal demand pattern. A Chase logic appeared to be applicable, when it is relatively cheap to increase and decrease production outputs, which is typically applicable for small batch productions in SC GER. As *monthly* demand is considered as stationary for all products and existing SAP functionalities support *monthly* dynamic safety stock days of supply, *monthly* buckets are appropriate. This leads to the following procedure to deal with seasonality:

1. **Identify the bucket length:** monthly
2. **Calculate the demand's average and standard deviation for the bucket length**
3. **Keep all other input parameters similar**
4. **Optimize the target inventories and safety stock levels bucket-by-bucket**

Of course, this procedure decouples the monthly models over time. However, it is assumed that the insights on and benefits of dynamic safety stocks outweigh the drawbacks of decoupling over time.

#### 3.2 LLamasoft:

LLamasoft's recommended approach is to optimize the network, conduct the SSO, rerun the network optimization module and the SSO module and verify by means of simulation whether the service level can be achieved. *Theoretically*, LLamasoft proposes in the SSO an appropriate inventory policy and the corresponding inventory policy parameters for the simulation.

However, this approach is not followed for two reasons. **First**, the product flows and the network structure are fixed. The network structure is fixed, because this pilot study only considered one factory and one CW. Furthermore, the number of sourcing suppliers per item is limited and the suppliers per item cannot be easily changed through strict regulations and small volumes. **Second**, LLamasoft's optimization cannot propose any forecast-based inventory control parameters for LSC, because LLamasoft's optimization does not rely on any forecast information. LSC needs dynamic and forecast-based inventory parameters due to the dynamic and seasonal environment. Therefore, this offered functionality does not offer any value for LSC.

Therefore, the current network is considered as fixed and a model is created, which is validated directly by simulation with some *estimated* inventory control parameters. In this way, the model input can be validated and then the SSO module can be used to find the optimal safety stock levels according to GS.

There are three guidelines formulated as a starting point for the modeling process. **First**, the simulation and optimization should remain as similar as possible in order to claim the validity of the optimization model. **Second**, *historical* demand and inventory levels are taken to validate the *estimated* inventory policy parameters, which are only required for the simulation module. **Third**, for FGs both the simulated service level and the most downstream inventory profiles are compared with the actual historical data.

This chapter starts -for comparison reasons with ChainScope- with information about the solution technique (3.2.1) and the optimization model input (3.2.2). Then it describes the model validation by simulation (3.2.3) and subsequently reflects on optimization and simulation with LLamasoft (3.2.4).

### 3.2.1 Solution Technique

LLamasoft uses the **branch-and-bound algorithm** to solve problems with binary or integer variables, which are enforced by integer constraints. It calculates the gap between the best continuous, linear solution and the best integer solution. When this amount matches with the gap settings, the solution is considered as optimal. This method guarantees both feasible and optimal solutions.

The **objective** of the safety stock optimization is the minimization of the total safety stock holding cost. The decision variable is the service time  $ST$  between echelons. The objective function for a two-stage serial supply chain is shown in Formula (29).

$$\text{Min } C = h_{i,sp-1} * k_{i,sp-1} * \sigma_{i,sp-1} * \sqrt{(LT_{i,sp-1} - ST_{i,sp-1} + R_{i,sp-1})} + h_{i,sp} * k_{i,sp} * \sigma_{i,sp} * \sqrt{(LT_{i,sp} + ST_{i,sp-1} + R_{i,sp})} \quad (29)$$

$$S. t. : 0 \leq ST_{i,sp-1} \leq LT_{i,sp-1} \quad (30)$$

$h_{i,sp}$ : Holding cost of item  $i$  at stock point  $sp$

$k_{i,sp}$ : Safety factor item  $i$  at stock point  $sp$

$\sigma_{i,sp}$ : Standard deviation of demand of item  $i$  at stock point  $sp$

$LT_{i,sp}$ : Lead time of item  $i$  at stock point  $sp$

$ST_{i,sp}$ : Service time of item  $i$  at stock point  $sp$

$R_{i,sp}$ : Review period of item  $i$  at stock point  $sp$

This concave objective function between the retailer's and the warehouse's safety stock (Appendix O) results in an optimal solution that is located in the extreme points ( $ST_{sp-1} = 0$  or  $ST_{sp-1} = L_{sp-1}$ ), which means that a stock point does decouple itself and possibly other upstream stages or does not decouple at all. The exact allocation depends on the inventory holding costs of both stages, which triggers or stops the downstream pushing of items. This objective function can be adapted for assembly structures by considering the maximum service times of the item's predecessors. In case point of sales information is shared with all stages, the review period of the upstream stages becomes 0.

The **service time**, which does not include any transportation time, can be interpreted as the waiting time until a shipment is ready to be transported to the next stage. The service time determines the coverage. The coverage value, or net replenishment lead time, represents the net period of risk instead of the full lead time that the safety stock at a stage will cover and ranges from zero to the maximal lead time. Formula (31) shows the formula for an assembly network with two components:

$$\text{Coverage}_{i,sp} = \text{Net Period of Risk}_{i,sp} = \text{Max}(ST1_{i,sp-1}; ST2_{i,sp-1}) + ILT_{i,sp} - ST_{i,sp} \quad (31)$$

The **immediate lead time (ILT)** differs per instance and is shown in Formula (32) and (33).

$$\text{Goods movement: } ILT_{i,sp} = SOLT_{i,sp} + TT_{i,sp} + R_{i,sp} \quad (32)$$

$$\text{Make policies: } ILT_{i,sp} = SOLT_{i,sp} + prt_{i,sp} + R_{i,sp} \quad (33)$$

$SOLT_{i,sp}$ : Source lead time for item  $i$  at stock point  $sp$  (assumed zero)

$TT_{i,sp}$ : Transportation time for item  $i$  to stock point  $sp$

$R_{i,sp}$ : Review period for item  $i$  at stock point  $sp$

$prt_{i,sp}$ : Total production time (incl. set up) for item  $i$  at stock point  $sp$

Classically, the GS approach only considers demand variability and assumes deterministic lead times. However, Humair et al. (2011, 2013) recently showed an algorithm to incorporate stochastic lead times. Although Appendix P shows LLamasoft's assumed lead time demand distributions per demand class, it remains **unclear** from which LLamasoft derived this classification and which algorithms they exactly use to determine the safety stocks.

Then, based on all possible coverage values a non-linear safety stock curve is constructed for every facility-product-period combination by piecewise-linearization. From all curves, the optimizer selects the best safety stock coverage value for each curve, such that the *total* safety stock holding costs are minimized. It has been assumed that the service time at the customer site is 0, which enforces safety stocks at this stage. Eventually, the safety stocks per item can be determined for a serial two-stage supply chain with Formula (29), when the multiplication with the inventory carrying cost is left away.

**Example**

When a supplier has a service time of 2 days, the transportation time is 7 days and the manufacturer guarantees its customers a delivery within 4 days ( $ST_{i,s} = 4 \text{ days}$ ), the net period of risk then equals  $2 + 7 - 4 = 5 \text{ days}$ . This means that the safety stock should be able to fulfill 5 days of demand. In case the manufacturer is able to deliver instantly, its service time  $ST$  equals 0. If the manufacturer promised to deliver always within 9 days, the manufacturer does not carry safety stock. Appendix Q presents a schematic overview of a safety stock curve as well as the coverage calculation and the relevant ranges, which range from zero to the maximum lead time.

**3.2.2 Optimization Model Input**

This paragraph declares all the input parameters that are required for the SSO.

**Products table:** The products table lists all the items, that occur in the BOM and lists the product cost per item and the selling price of FGs to its customers.

**Sites table:** The sites table lists the sites, such as suppliers, SC GER, CW and the aggregated customers.

**Sourcing Policies table:** The sourcing policies table indicates whether items are produced internally or sourced externally. The specific source and order lead time are included in the overall transportation lead time, which is in ChainScope called the Planned Lead Time. In addition, minimum order quantities are specified. As mentioned, only single-source relationships are allowed for optimization. This requirement is a realistic simplification, because the second supplier concept is a risk mitigation strategy and those suppliers often fulfill only small percentages of the total demand. Moreover, lead times for the different suppliers are similar due to geographic proximity. Days between productions is also added:

$$\overline{DBP}_i = \frac{1}{x} \sum_x (APD_{i,x+1} - APD_{i,x}) \tag{34}$$

$APD_{i,x}$ : Actual Production Date for item  $i$  at production moment  $x$

**Inventory Policies table:**

**Review Period:** Similar to ChainScope.

**Service Level:** A service level of 97.5% is inserted in order to keep ChainScope's and LLamasoft's input similar. This is valid, because LLamasoft neither allows a full modeling of flexibility measures.

**Safety Stock Constraints:** The maximum safety stock DOS has been defined to limit safety stock allocations at TUB and PACK, which have a limited shelf life or frequent product changes.

$$\text{Max SS DOS}_i = \frac{\text{Max Inv}_i - \overline{Q}_i}{\mu_i} - \overline{SMKA}_i - \overline{SMKB}_i \tag{35}$$

$\text{Max SS DOS}_i$ : Maximum safety stock DOS of item  $i$

$Q_i$ : Lot size of item  $i$

$\mu_i$ : Mean daily demand of item  $i$

$SMKB$ : Scheduled margin key before (= "float before production")

$SMKA$ : Scheduled margin key after (= "float after production")

**Transport Policies table:** The transport policies table contains the planned lead times, as described in Figure 11, per source-destination-product combination. Days between replenishments is added to this table and derived in a similar way as Formula (34). The only difference is that not the production date, but the replenishment date is taken.

**Processes table:** The processes table lists the processes and contains lot sizes, yields, and the weighted unit time per process step:

$$\overline{UT_{i \in II, w}} = (\overline{sut_{i \in II, w}} + \overline{pt_{i \in II, w}} + \overline{c_{i \in II, w}} + \overline{GR_{i \in II, w}}) / \overline{Q_{i \in II, w}} \quad (36)$$

$UT_{i, w}$ : Unit time per work center  $w$

$sut_{i, w}$ : Setup time for item  $i$  at work center  $w$

$pt_{i, w}$ : Production time for item  $i$  at work center  $w$

$c_{i, w}$ : Cleaning time for item  $i$  at work center  $w$

$Q_{i, w}$ : Production lot size of item  $i$  at work center  $w$

$GR_{i, w}$ : Goods receiving time for item  $i$  at work center  $w$

---

**BOM table:** Similar to ChainScope.

**Work Center table:** The work center table lists the machine-process step combination(s). In order to fulfill the single routing criteria for optimization, only one machine per process step is modeled. This table also contains the scheduling rule (FIFO) and the operating hours per week. Unfortunately, more advanced scheduling rules, which consider due dates and other priorities, required scripting.

**Period table:** The period table allows the user to create periods of a length of choice. In this case study, twelve monthly periods for the time period October 2014 – September 2015 are modelled.

**Customer Demand Profile table:** All twelve periods received their corresponding demand mean and demand standard deviation, for which the left-tail outliers were removed as described in 3.1.3.

### 3.2.3 Model Validation by Simulation

As described by Pels et al. (2012): although simulation projects are time consuming, simulation can, when used wisely, increase understanding, improve predictions, speed up data-collecting and decision-making processes, convince stakeholders and be an alternative for infeasible analytical models. Except from face validity, simulation is also used to validate the model in this project. However, one needs to be aware that simulations also rely on modeling assumptions.

#### Simulation Approach

The simulation is conducted with historical transactional data, master data and some parameter estimations (e.g.  $s$  and  $S$ ). As no probability distributions are modelled, only one model run is conducted. The simulation started 11 months earlier to model the in-transit shipments and initialize the model. According to Law and Kelton (2000), a model can be **verified** with domain experts to check whether all elements of the conceptual model are included correctly. The outcomes of the simulation model are afterwards also **validated** with domain experts to ensure face validity. The simulation outcomes are validated with respect to the beta service level and the match, with respect to timing and magnitude, between historical and simulated inventory profiles for the FGs at SC GER and the CW. Common component inventory profiles are not compared, because those components are not exclusively used for the 28 FGs, which might cause unpredictable disturbances. As no flexibility measures are modelled in LLamasoft's base model, deviations between historical and simulation outcomes are inevitable.

**Simulation Model Input**

This paragraph explains the additional input parameters for the simulation model “table-by-table”:

**Demand table:** The demand table specifies the historical weekly demand quantities and times of occurrence. As described in ChainScope, the left-tail outliers are removed.

**Inventory Policies table:**

**s, S Levels:** In accordance with the SAP planning logic, a forward-looking inventory policy is required. The inventory policy parameters need to be, in units, dynamic over time due to the seasonality. In contrast to previous theses with Llamasoft, such as Meunier (2013) and Jongenelis (2014), a pure Base Stock policy is not an option, because the products do not represent a slow-moving product where the lot size is 1. The chosen “DOS – Forecast based s,S policy” looks like a regular s,S policy, except that the reorder level *s* and the order-up-to-quantity *S* are not expressed in units, but in DOS. Therefore the s,S levels *in units* are adapted proportionally to changes in the rolling horizon forecast, which follows the seasonal pattern. First the **reorder point s** is for the s,S logic in *units*:

$$\widehat{s}_{i,t} = SS_{i,t} + D(t - PLT_i, t) = SS_{i,t} + \sum_{z=1}^{PLT} \mu_{i,t-z} \quad (37)$$

This reorder point can be expressed in *DOS* as well:

$$s_i = SS \text{ DOS}_i + PLT_i \quad (38)$$

$$s_i = \max \left( SS \text{ DOS}_i; \frac{SS_i * PP_i}{\mu_i} \right) + PLT_i \quad (39)$$

$$\mu_i = \overline{D(t - PLT_i, t)} / PLT_i \quad (40)$$

As *s* and *S* in *DOS* should be one fixed value for the simulated period, the time index *t* is left away and the yearly average daily mean ( $\mu_i$ ) is taken. Due to the subset and the usage of common components, it is necessary to take the proportion, similarly to Formula (22). However, this is only required for *SS* in units, because all other variables are expressed in *DOS* and are therefore automatically scaled.

Now the **order-up-to-quantity S** can be determined, which is also formulated time-independently:

$$S_i \geq s_i \quad (41)$$

$$S_i = s_i + \frac{\overline{Q}_i}{\mu_i} \quad (42)$$

$$S_i = s_i + \overline{DBR}_i \quad (43)$$

In order to make a better estimation of the average days between replenishments *DBR*, the historical average over multiple years is taken.

The *S* level for the country warehouse (CW) *deviates*, because late deliveries disaffect the “end customer” and in this way the service level. The CW inventory policy is modelled as an *s=S* policy, because it is supposed that employees use all flexibility measures to deliver on time to the CW.

**Initial Inventory:** The simulation requires an initial inventory (IP) for both suppliers’ and LSC’s stock points. An “infinite” inventory is modelled for suppliers by a large number and for SC GER and CW the following formulas are used:

$$IP_{i \in EI}(t) = PP_{i \in EI} * CPT_{i \in EI}(t) + E[IT_{i \in EI}(t)] \quad (44)$$

$$IP_{i \in II}(t) = PP_{i \in II} * CPT_{i \in II}(t) \quad (45)$$

$$IP_{i \in SI}(t) = PP_{i \in SI} * CPT_{i \in SI}(t) + E[IT_{i \in SI}(t)], \text{ where } PP_{i \in SI} = 1 \quad (46)$$

The initial inventory is equal to the proportional on-hand stock and the modelled shipments (IT), which arrive every week of the item’s lead time. Therefore, the initial inventory for **external items** and **shipped items** is the system’s proportional initial inventory plus the expected demand during the lead

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time. The proportion is 1 for the shipped FG items, because the products are solely dedicated to the US market. As the MES is updated every couple of hours, the WIP is minimal and can be neglected. Therefore, the initial inventory of **internal items** is limited to the proportional on-hand stock.

**DOS Planning LT:** The DOS Planning Lead Time is considered when a replenishment order to S should take place. As deliveries are not instant, one needs to order materials a time period in advance. The most upstream items need to be ordered a cumulative lead time in advance (Figure 12).

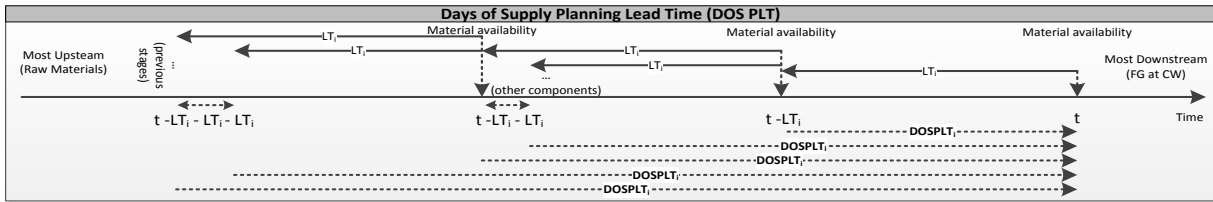


Figure 12, DOS Planning Lead Time

**Forecasts table:** The forecasts table contains the daily forecast per item, which is kept equal within a month. It has been assumed that s,S-levels that change within a month are infeasible to maintain due to infrequent production campaigns. The daily forecast is based on the historical 1-leg FG forecasts and the BOM structure. The s,S-DOS levels are multiplied by the rolling forecast to obtain a dynamic level s, S-level in units. As item lead times are up to 210 days and the DOS Planning Lead Time exceeds this item's lead time, the model is run with 11 months of 0 demand. This initialized the model through shipments on the one hand and did not disturb the ordering behavior beforehand on the other hand.

**Shipments table:** The shipments table models the expected weekly in-transit inventory over the item's lead time as discussed at "Initial Inventory". The shipments occur every week of the item's lead time to limit the impact on the s,S system behavior. Although this modelling choice ignored minimum order quantities and days between replenishments, the benefit is considered more important.

#### Simulation Results

In order to get a better understanding of the behavior, exclude capacity issues and to reduce the run times, the comparison is first conducted for 1 FG.

**1 FG product simulation:** In a one product simulation, where capacity and stocks are considered sufficient, a service level of 100% is obtained as well as a roughly comparable inventory profile. Where Figure 13 shows the historical end-of-the-week inventory figures for SC GER (red) and the CW (blue), Figure 14 shows the simulated on-hand stock for those two stock points. In addition, Figure 14 contains the reorder points (s) and order-up-to-quantities (S) over time. Unfortunately, due to an error in Llamasoft, the results could not be exported and integrated into one graph.

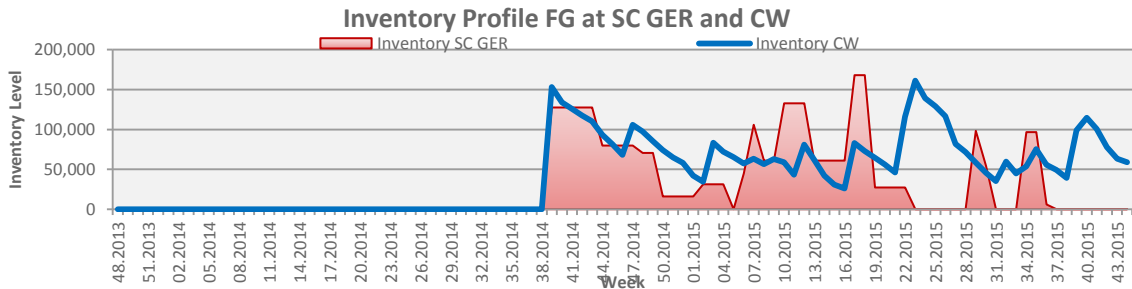


Figure 13, Historical Inventory Profile

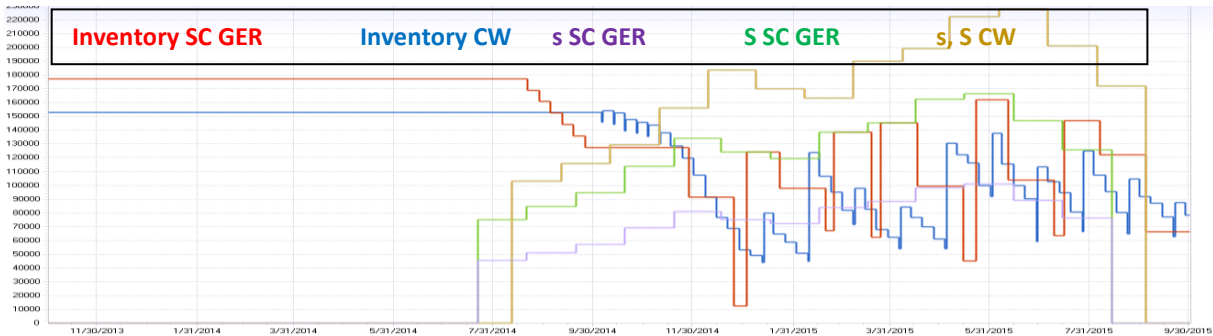


Figure 14, Simulated Inventory Profile

Figure 14 shows that the starting inventory in the first month is increased with the expected demand during the lead time, which is subsequently reduced in an equal weekly quantity and delivered one lead time afterwards. Due to the modelled 11 zero-demand forecasts, the *s* and *S* level in *units* are zero till October 2014. In addition, Figure 14 shows that the *s*, *S*-levels change on a monthly (30 day) basis for both locations and are shifted a DOS Planned Lead Time in advance. The DOS Planned Lead Time is larger for SC GER, because it is located more upstream. Furthermore, the inventory level at SC GER is reduced every 30 days, which is modelled by the review period to represent the monthly shipments.

The **outcomes of the simulation study** are twofold. *On the one hand*, similar patterns in comparison to history occurred in the simulation. For example, the comparison shows till the end of May a similar number of peaks, which all match to some extent in magnitude. It also shows a matching interrelationship between the inventory at the CW and at SC GER. One should be careful to not only assess the magnitude, but consider the “area” of the respective peak. *On the other hand*, slight differences in timing as well as magnitude occurred. For example, out-of-stock situations did occur in reality, but did not occur in the simulated model, which can be explained by sufficient inventories and capacities for a 1-product simulation. In reality a stock-out occurred at the end of January, where the simulation showed only a valley in the middle of January. Due to insufficient capacity and/or inventories to replenish, the valley became a stock-out in reality. Although the absolute replenishment quantity of 100 000 units matches with reality, the new inventory at the end of January is still higher due to the “instant” replenishment in the simulation. Furthermore, the historical overview showed two peaks at the end of the period. Those peaks indicate the lack of inventories due to capacity issues for many products together in reality. The short replenishment (rush) lead times also showed the reliance on air shipments in case of shortages. The simulation model contains the nominal sea shipment lead time, which is 2.7 times longer than the air shipment lead time. It appeared that air shipment formed up to 30% of all shipments. This also causes a deviation in both timing and magnitude between the simulated and historical profile. Logically, early deviations affect the future behavior and deviations.

**28 FG Product Simulation:** Although the directions and magnitudes for one product appeared to be *roughly* similar, this is not the case for a simulation study in which *all* 28 finished goods are modelled (Appendix R). The pattern for the product appeared to be roughly similar in the first months. However, component demand then exceeded the component inventory, which first reduced the inventory levels at SC GER and subsequently at the CW. The replenishment orders were then almost directly consumed due to the built-up backorders.

The **typical deviations** are assigned to three categories, which are explained in the next paragraph.

**Explanations for Deviations**

As practitioners validated the simulation model input and stochasticity is not considered, other reasons for LLamasoft’s deviations with the historical pattern have been identified. Except from those reasons, one should realize that inventory levels are dependent on time. This implies that early deviations affect the future simulation results. The following three main reasons, which are somewhat generic for mathematical models and simulation models, are identified:

- 1. Human interventions affect norm values:** Many reasons can be traced back to human interventions, which cannot be modelled in LLamasoft nor any other model, unless one carefully studies the *impact* of human interventions. For example, it has been assumed that a s,S DOS policy, which is offered in LLamasoft, can approximate the SAP planning. However, planners do steer on both inventory positions and net inventories. Furthermore, planners receive forecast insights from country representatives and will incorporate that into the planning, which is not necessarily reflected in the base model forecasts. When the net inventory is insufficient, they rely on flexibility instruments (3.1.3). Those measures cannot be modelled in LLamasoft’s base functionalities, because scripting documentation lacks, debugging support is limited and the outcomes appeared to be unstable.
- 2. Parameter estimation and data quality:** Other deviations are caused by parameter estimations, deviations between master data and actual data as well as variability in historical data due to incidents. For example, “s, S parameters” needed to be estimated based on the historical data. As the data varies over time, the average is influenced by the taken period, which might contain one-time incidents. Typical incidents are machine down times and supply and transportation delays.
- 3. Other limitations:** For example, the simulated inventory can only be compared with the end-of-the-week historical on-hand inventories. Although historical data analysis – monthly maximal inventory divided by the monthly forecast – points in the direction of a dynamic s,S-DOS level, LLamasoft only provides the opportunity of a fixed s,S-DOS level. Other fields, such as days between productions, also only allow a single mean value. Finally, as in ChainScope, the regular sea freight lead time is modelled despite the 30% air shipment fraction. More advanced decision rules, such as shown by the pseudo-code below, could hardly be programmed in the scripting module due to its limitations:

$$\text{IF } \frac{\text{On-hand stock}_{i,t}}{\text{Forecast}_{i,t+1}} < \text{RATIO} \quad \text{THEN Transport Modality}_{i,t}: \text{"AIR"} \quad (47)$$

$$\text{ELSE Transport Modality}_{i,t}: \text{"SHIP"} \quad (48)$$

LLamasoft’s most advanced, but also very naïve policy, would be to model the lead time with a “Split-by-Ratio” policy, which implies that of every order X% will be shipped by sea and 1-X% by air. This does not match reality, because air shipments are avoided for cost reasons, when inventories can cover the forecasted demand until the next sea replenishment arrives. As a consequence, the inventory became in “regular” periods higher due to the constant air shipments. There is chosen to maintain 100% sea shipments in order to keep the LLamasoft and ChainScope models similar.

Although similar explanations apply for the deviations in a **28 FG** simulation, capacity management and machine allocation rules become more important in case of more products. Simulation results appeared to be disturbed by long *normative* lead times, when, for example, multiple orders had depleted the inventory for common items at the same moment in time. Although the component could be replenished after a lead time, which was sometimes also restricted by limited inventory levels of more upstream stages, the amount of backorders depleted (almost) directly the replenished quantity.



#### 3.2.4 Concluding Notes: Model Validation by Simulation and Optimization

As the simulation showed a similar pattern and validated explanations for deviations were identified, the model is considered as **“valid” for optimization**. Moreover, the optimization mode does neither rely on the inventory policy parameters nor on capacity allocation rules, which both caused deviations.

Jongenelis (2014) used LLamasoft’s simulation module to assess the service level after LLamasoft’s safety stock optimization. The simulation showed that those safety stocks only resulted in a 60% service level. His reported outcomes and the above described deviations raise the question about the quality of the simulation. However, this service level can also be caused by the quality of the optimization.

**About the simulation:** although LLamasoft does offer a possibility for simulation, the practical usability is low, because standard built-in functions appeared to be insufficient to mimic the historical behavior for many products in a real-life context. Therefore, simulation does have a very limited predictive value. However, this does not mean that modelling with LLamasoft is a “bad idea”, because it requires employees to rethink about processes and simulation can offer insights for scenarios.

Confidence in the simulation model could be increased, when LLamasoft would offer a possibility to automatically conduct many simulation runs while varying the input parameters in a certain pre-specified range. In this way parameters could be calibrated and deviations could be minimized.

**About the optimization:** it is unlikely that the less advanced decision rules in the simulation module fully caused the difference between the 60% and 95% service level. An evaluation of LLamasoft’s optimized inventory levels in ChainScope’s base model showed that the service level was 40% less than the claimed 97.5%. This decrease can be explained through 50% less *end-item average inventory* in LLamasoft, which is caused by other methodological assumptions about material availability. Moreover, the service level decrease is caused by its allocation among product types. For example, according to ChainScope, dead stock investments that do not contribute to the service level, which are shown in red, occurred at Raw, PACK, BULK, TUB and FOIL (Appendix S). Additionally, an evaluation within ChainScope for a single-stage and two-stage serial network with LLamasoft’s average inventory levels showed a 99% service level. At the same time, it showed only a 60.4% service level for the reduced convergent network, which considered the three downstream stages. This highlights that the network structure affects LLamasoft’s empirical validity and that the service level decrease is mainly caused downstream.

*A possible explanation* for the bad performance in a convergent network is that the GS approach does not properly consider additional waiting times due to differences in lead times for the assembly of multiple components. It probably excludes the interaction effect, where ordering decisions of components with shorter lead times occur at a different time and rely on other information.

As those service level differences are found with LLamasoft’s own simulation tool as well as an external tool (ChainScope), it is likely that it mainly depends on LLamasoft’s modelling assumptions and resulting safety stock optimization method and less on the simulation model. This statement can be made, because ChainScope was already validated (Chapter 3.1.3) and the only changed input parameter within ChainScope is the average inventory level. Unfortunately, it cannot be investigated in more detail which part of the LLamasoft algorithm caused the difference, because this is LLamasoft’s protected knowledge.

The **first implication** is for practitioners, who should be careful with LLamasoft’s safety stock levels, because they risk a substantial service level reduction (in exchange for a large stock reduction). The **second implication** is for scholars, who should compare LLamasoft with the original GS algorithm.

## 4. Results

Chapter 4.1.1 describes the quantitative results for the base case scenario and Chapter 4.1.2 discusses the scenario analysis. This results in an overview of the method's quantitative performance and therewith **answers SRQ 2**. Based on the outcomes, two further analyses are conducted for a better understanding in Chapter 4.1.3. Then, in Chapter 4.2 the three methods are qualitatively evaluated, such that **SRQ 3 is answered**. The qualitative evaluation of the LSC Method considers the complete SC risk management approach, which includes the safety stock method, and therewith **answers SRQ 1**. The quantitative and qualitative outcomes are then synthesized and form the basis for the redesigned operational risk management strategy in Chapter 5.

### 4.1 Quantitative Comparison

This paragraph shows the outcomes of a quantitative comparison between two multi-echelon models and the LSC Method. Before moving forward to the comparison, one needs to realize that the purpose of models is to make an abstraction of the reality to support humans in decision making. However, the modeler first perceives reality and creates therewith a so-called mental model. Then, the modeler translates this into a formal model. Therefore, Zoryk-Schalle et al. (2004) stated that in complex environments always differences between reality, mental models and formal models exist (Figure 15).

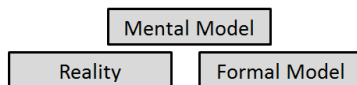


Figure 15, Deviations between Models and Reality –Adapted from: (Zoryk-Schalla et al., 2004)

Due to those inherent deviations, this paragraph aims to identify *structural* differences, which are more generally applicable than this case study. Therefore, this quantitative analysis does not focus on item level comparisons, but focuses on differences among product types, over time (seasonality) and between the methods:

- LSC's System Settings *(explained below)*
- LSC Method *(Chapter 2.1.5)*
- LSC Method with manual improvement *(explained below)*
- ChainScope – Chase *(Chapter 3.1)*
- LLamasoft *(Chapter 3.2)*

The outcomes of the quantitative analyses are provided to LSC in three relevant measures: (*average*) safety stock units, (*average*) safety stock DOS and total safety stock product value. Several assumptions are made for the comparisons. **First**, the comparison with the current LSC method only includes the so-called “4A. Demand Uncertainties” to get a fair comparison. ChainScope and LLamasoft are namely not able to include supply interruptions, which cause one-time lead time delays, in the optimization model. However, one needs to be aware that both Actual and LSC's System Settings contain safety stocks against those supply interruptions. In agreement with the stakeholder, it is considered infeasible to estimate this amount accurately. **Second**, although it later unexpectedly appeared that LLamasoft ignores yields, ChainScope's base model has been run with yields to make the results more realistic and valuable for LSC. **Third**, consignment stocks are excluded from the comparison. **Fourth**, the product value is based on the September 2015 prices. **Fifth**, *average* scheduled margin keys are used per product type.

For benchmarking reasons, the **Actual** safety stock levels are theoretically derived. Those are derived from the average historical on-hand stock values, half of the average lot sizes, and the scheduled margin key demand (Appendix T) and then converted to SS DOS. Actual is calculated as a yearly average due to disturbances by pre-built stocks and infrequent production campaigns. It also makes the comparison overviews more comprehensible.

$$SSA_i = \max\left(\left(\overline{CPT}_i - \frac{\overline{Q}_i}{2}\right) * PP_i - (\overline{SMKB}_i + \overline{SMKA}_i) * \overline{\mu}_i; 0\right) \quad (49)$$

$$\overline{Q}_i = \frac{\frac{Q_{i,1}}{2} + \dots + \frac{Q_{i,n}}{2}}{n} \quad (50)$$

$SSA_i$ : Safety stock levels Actual for item  $i$

$CPT_i$ : On – hand stock for item  $i$

$Q_i$ : Lot size for item  $i$

$n$ : Number of observed production/procurement starts

Although **LSC's System Settings** are derived from the system's safety stock units, safety stock DOS and the SMKB and SMKA, a slight adaptation is needed. As ChainScope and LLamasoft consider goods receiving and goods issue times in the lead time and as the system's inventory data are without, the respective goods receiving and goods issue times are added to the item's safety stock (FG and API).

**LSC Method with manual improvement by the pipeline controller (PC)**: The pipeline controller shifts the by the LSC Method allocated safety stocks on SOL and BULK to the downstream stage. No safety stock at SOL is desired, because of slack capacity and shelf life reasons. Furthermore, LSC prefers to move BULK safety stocks to the most downstream stage, because BULK items are country specific.

#### 4.1.1 Base Case Outcomes and Explanations

For ease of representation, it has been decided to only present the safety stock DOS graph (SS DOS) (Figure 16). The SS DOS graph is preferred, because otherwise large differences in demand figures as well as different item values disturb the representation. However, some findings are based on product type level or confidential product values, which are all derived through a similar transformation. Furthermore, the representation of the LSC Method includes the safety stocks that are independently set for the in the pipeline risk management tool excluded stages. It is also important to realize that Scheduled Margin Keys are included for the striped LSC bars. This quantitative analysis resulted in 9 observations, which are described below and summarized in Table 1 in the Management Summary.

**Note: I) one needs to be aware that the safety stocks of ChainScope's defined base model, which are shown, are substantially increased and shifted by item-based random yield and inventory constraints (Chapter 4.1.3) and II) although LLamasoft's safety stocks were not empirically valid due to the lower service level (Chapter 3.2.4), the differences in the outcomes are still described.**

#### The 9 Observations

**First**, ChainScope's SS DOS allocation is structurally higher than LLamasoft's. Relatively large differences occur on Raw, TUB, PACK, BULK and FG. ChainScope and LLamasoft often show similar directions of change over the months, which is explained by similar standard deviations. At the same time, the standard deviations, which differ due to another demand propagation method in LLamasoft and ChainScope, also explain the different directions of change over the months.

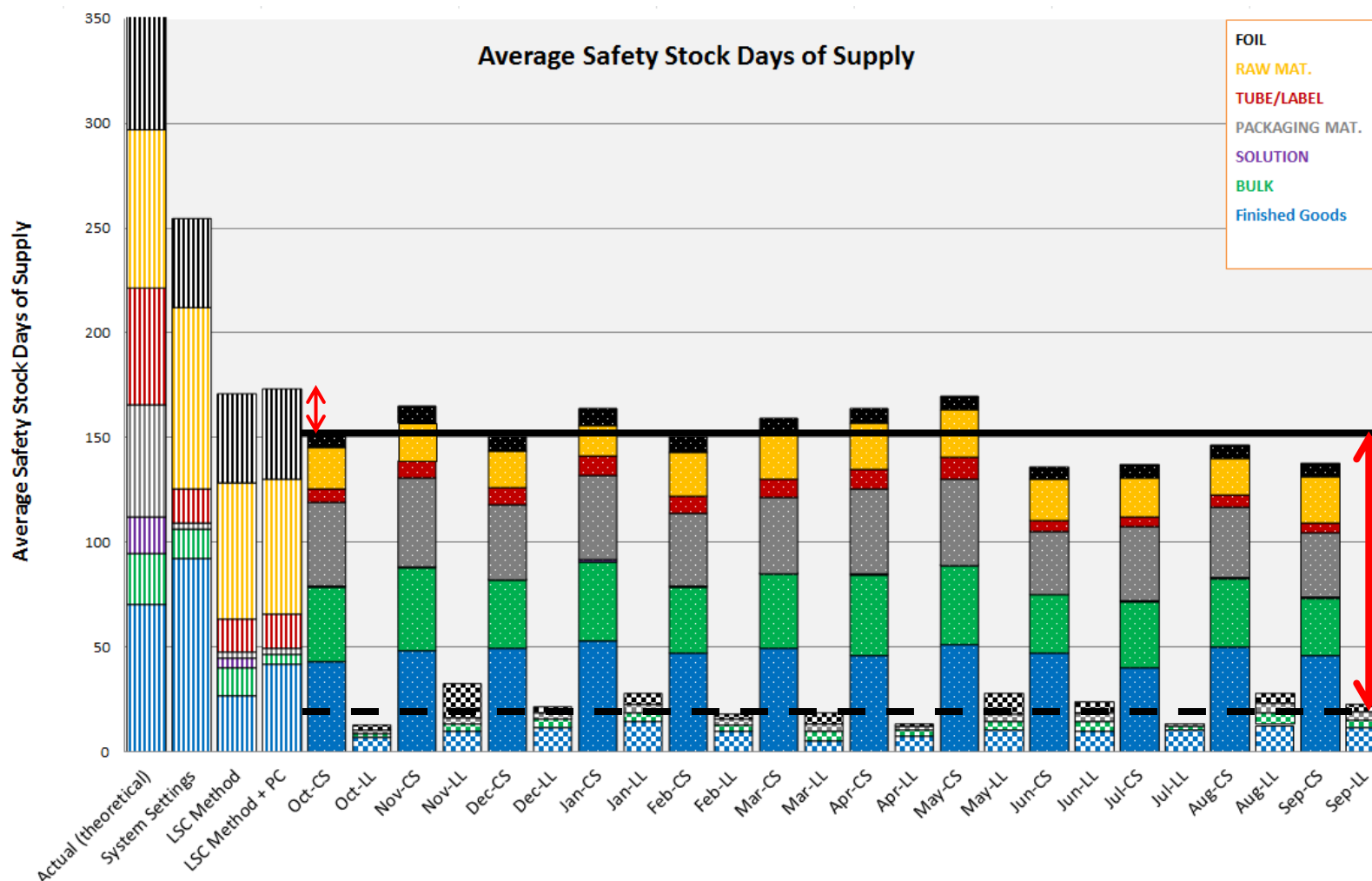


Figure 16, Average Safety Stock among Product Types and Methods over Time

**Explanation:** The colored stacked bars represent the 7 product types, the four striped bars represent the average yearly LSC values (PC = Pipeline Controller), the mottled bars represent ChainScope’s (CS) optimized monthly values, and the checkered bars represent LLamasoft’s (LL) optimized monthly values. The horizontal lines represents the yearly average of ChainScope respectively LLamasoft.

ChainScope's higher *upstream* allocation can be partially explained, because ChainScope tends to put more safety stock at cheap items before assembly stages, at predecessors with a long lead time or at items before they enter a high value adding step. In addition, LLamasoft always assumes full material availability due to bounded demand or operating flexibility, where ChainScope buffers against a lack of material availability in assembly. Finally, ChainScope's demand propagation method corrects the demand mean and the demand *standard deviation* for random yield and is impacted through inventory constraints (Chapter 4.1.3). Moreover, the extreme differences ("zero vs a lot") in LLamasoft can be explained, because LLamasoft searches for extreme solutions in which no or full decoupling occurs.

Those reasons explain both why ChainScope allocates more safety stock upstream and why the difference is substantial on Raw, TUB, PACK and BULK. This logically explains also why ChainScope puts *relatively* less of its safety stocks on FG level. Nevertheless, one would then expect that LLamasoft would put on average more safety stock at FG to cover the same risks.

However, it is known from literature about convergent networks that GS not only tends to put average stocks at a different stage, but also tends to allocate less average stocks for convergent networks (De Kok & Eruguz, 2015). This comparison shows a similar finding for safety stocks, which complements earlier research. Possible explanations are: **i)** The GS approach does not properly consider the interaction effect, where ordering decisions of components with shorter lead times occur at a different time and rely on other information and **ii)** For such a strongly convergent supply chain, ChainScope cannot -as LLamasoft probably does by risk pooling heuristics- exploit commonality, because *specific* components generally have longer lead times than common components. However, it remains questionable how much risk pooling is actually possible in this convergent supply chain. As a matter of fact, those significant differences between LLamasoft and ChainScope in location and optimal safety stock levels were also reported in Jongenelis (2014).

**Second**, as ChainScope and LLamasoft are modelled without any exception-based material and resource flexibility measures, one would expect smaller differences with Actual and LSC's System Settings, because all variability needs to be buffered by safety stocks. The higher safety stocks of Actual and LSC's System Settings can be explained by a combined effect of overestimation, safety stock against supply interruptions, and capacity considerations thanks to experience, which led to pre-built stocks.

**Third**, the differences between Actual and LSC's System Settings are considerable. Remarkably, although safety stocks at SOL are not recommended, because there are no capacity issues and shelf life starts ticking, Actual shows relatively high safety stock at SOL. Caution is required, because the theoretically derived Actual safety stocks can be affected by seasonal stocks, minimum order quantities, lack of lot size data and large lot sizes due to capacity and efficiency reasons. Differences are also caused by the 6-month forecast bias prior to and during the investigated period. Another explanation are lower-than-forecasted demands and items that are kept on stock instead of scrapped. *Therefore, no judgments are made based on this observation.*

**Fourth**, ChainScope's respectively LLamasoft's safety stock DOS is on average 2 respectively 0.25 times higher than LSC's Method for the *included stages FG, BULK, SOL and Raw*. When the system's safety stocks of the excluded stages are included, LSC generally allocates in total more SS DOS than ChainScope and LLamasoft. One might have expected that LLamasoft and the LSC Method would perform more equally, because their single-echelon like formula and the fact that the LSC Method's normality assumption fits with LLamasoft's lead time demand classification. The differences can be explained, because of other formulae, other input, and other assumptions.

About the allocation among product types: it appeared that the safety stock setting of the LSC Method on FG level is somewhere between LLamasoft's and ChainScope's. Also for the other product types large differences with LLamasoft and ChainScope are observed.

**Fifth**, in the LSC Method with manual improvement by the Pipeline Controller (PC), there were no safety stocks placed any longer at SOL and BULK level. The only safety stock that is still visible for BULK is the scheduled margin key. The pipeline controller decided to shift the safety stocks to FG level, which caused an increase in the total safety stock product value. It appeared that the safety stock DOS setting of the LSC Method after manual improvement now matches on FG level with ChainScope's allocation. The shift of safety stocks did not change the total amount of allocated SS DOS. However, it changed the distribution among product types and therefore it became relatively more expensive in comparison to LLamasoft and the difference in cost with ChainScope reduced significantly. That can be explained, because ChainScope allocates less safety stock on expensive items, such as FG.

**Sixth**, based on LSC's current philosophy, one would expect a nearly constant SS DOS over the year, which is translated into dynamic safety stock levels due to different monthly average demands. However, the average safety stock DOS appeared to be varying through the year and the relative difference between the maximum and minimum SS DOS was 23% on average for *all* FG's according to ChainScope. This relative difference even increased, when sets of finished goods, which might have different peak months, were assessed separately. Although for some products the peaks coincided with the peak season, there were also separate peaks outside of the peak season. Weather conditions, such as an "early spring", can cause inflated demands for some weeks and therewith inflated standard deviations. Therefore, the assertion is that seasonality (shifts) affect(s) the standard deviation, but it is not the sole and main driver. Other factors, such as a combination of irrational customer behaviors, also cause safety stock peaks during the *whole* year. Moreover, it is *known* that demand is seasonal, which is therefore included in the forecasts and makes higher safety stocks less necessary.

In contrast, at BULK level the safety stock DOS – suggested by ChainScope- are structurally higher for the months October till May. This might support the observation that there is a seasonal effect for FGs from November to June, which would be in accordance with the lead time shift. Even more upstream it is hard to derive conclusions, because ChainScope and LLamasoft do not structurally allocate SS DOS to SOL and Raw. All in all, the results are ambiguous and do not allow for a general statement about the relationship between seasonality and the safety stock levels.

**Seventh**, a comparison of safety stock product value showed that ChainScope, as seen in **Fifth**, and the other methods (Actual, LLamasoft and LSC System Settings) move to each other thanks to their high and costly FG allocation. However, Actual and LSC System Settings still remain the most expensive and are more expensive than ChainScope's peak allocations, which are strongly increased by yield modeling and inventory constraints. The LSC Method stays significantly more expensive than LLamasoft and has lower average yearly costs than ChainScope's base model. After manual improvement, the LSC Method would be even more expensive in comparison to LLamasoft, but better approaches the average yearly safety stock product value of ChainScope's base model.

**Eight**, it appeared that for roughly 30% of the products no safety stock should be kept. Based on De Kok (2015), this implies a flow of the respective item to the next stage. Typically, this occurred for TUB, which then explains the relatively high BULK safety stock levels. Similarly, both LLamasoft and ChainScope shifted all safety stocks from SC GER to the CW, because no value is added in this transportation step and safety stock is then preferably located closer to the customer.

**Ninth**, when considering all methods, it appeared that ChainScope allocated safety stocks to *all* product types and that LLamasoft only put safety stock at PACK, FOIL, BULK and FG. This can be explained by the product value ratios between those stages and LLamasoft’s optimal extreme solutions. Another intuitive explanation is that downstream safety stocks contribute “more” to high service levels than upstream stocks. An alternative explanation is that due to the portfolio effect for common items, upstream demands are more stable than individual demands. That explains why LLamasoft allocated relatively a lot of safety stocks to diverse or even customer-specific product types, which logically occurred more downstream. ChainScope exploited safety stock allocation to low-cost and more upstream items. LSC does currently not exploit safety stocks at PACK for product change reasons.

### Hypotheses SRQ 2

Based on those observations, the **hypotheses** of Chapter 2.4 can be confirmed and rejected. **Fourth** showed that not all multi-echelon models allocate less safety stocks than LSC’s single-echelon method. **First** showed that LLamasoft’s total safety stock allocation for an assembly network is more conservative than ChainScope’s. **Seventh** showed the benefits of stocking many units at relatively cheap items, because in this way risks can be mitigated and simultaneously lead to a product value convergence. **Sixth** showed that safety stock levels for ChainScope and LLamasoft are dynamic over time, which is most likely a combined effect of seasonality (shifts) and other time-independent demand fluctuations.

#### 4.1.2 Scenario Analysis

The models are run for multiple scenarios to assess the robustness of the model outcomes and to understand the safety stock allocation dynamics. In agreement with key stakeholders three scenarios are identified (Table 7). Table 7 shows per scenario the affected product types, the parameters changes, and the hypothesized and actual effects on the safety stock product value (SS PV).

Table 7, Scenario Outcomes

Scenario	Product Type	Change	Hyp. Effect (SS PV)	Act. Effect (SS PV)		
				CS	LL	LSC
<b>Combined shipments</b>	FG	Rev. Period CW: -50%	SS ↓	↑	↓	↑
<b>Lead time length</b>	Ext. items: API	LT: -10%	SS ↓	↓↓	↓	-
	Ext. items: all except API	LT: -10%	SS ↓	↓	↓	-
	Int. items: SOL	LT: -10%	SS ↓	↓	↓	↓
	Int. items: BULK	LT: -10%	SS ↓	↑	↓	↓
	Int. items: FG/PACK	LT: -10%	SS ↓	↑	↓	↓
<b>Service level</b>	FG	SL CW: -1.5%	SS ↑↑	↑↑	↑↑	-

The scenarios “Combined shipments” and “Lead time length” give insights in the effects of delivery frequency and speed on the safety stock product value. “Service level” aims to find out the type of relationship between service level targets and the safety stock product value. Although demand variability affects safety stocks, it is left out of the scope, because it is an exogenous effect. The sensitivity analysis is only conducted for October, because the directions are probably not time-dependent.

Below the scenarios and the outcomes are discussed in words. Appendix U depicts a visual overview *per method* of the SS DOS. As Figure 16 earlier showed the systematic and large differences between the three methods, it has been decided to show the scenario analysis outcomes in separate graphs *per method*, which makes changes better visible. Furthermore, the showed results for the LSC Method do only contain the four stages that are considered by the method.

**Combined shipments:** The base models assumed monthly shipments by sea freight. However, in practice, shipments for multiple orders are often combined. Therefore, the review period, which modelled the fixed shipment time between shipments, is reduced by 50%. For the LSC Method, the Order Size (months) at the most downstream step (Packaging) is reduced by 50%, because no review period is considered.

**Outcome:** It has been hypothesized that combined shipments lead to decreased safety stock levels, because one is replenishing more frequently. This change exactly occurred for LLamasoft, which is explained by the reduced review period term below the square root. However, the safety stock levels increased for ChainScope and the LSC Method. In the LSC Method, one observed that a reduction in the Order Size triggered an increase in the demand uncertainty. The result for ChainScope is also counter-intuitive and the assertion is that it is caused by the safety stock transformation, which prevents negative safety stocks. Table 8 supports this assertion, because the total investment decreases.

**Lead time length:** the lead time length should not significantly affect safety stocks, because it is modelled as known and deterministic. In agreement with stakeholders, it has still been decided to investigate *separately* the effects of a 10% lead time reduction for three internal and two external product types.

**Outcome:** A decrease in lead time duration did slightly decrease the safety stock product value for LLamasoft. For LLamasoft, the strongest decrease occurred for a reduction in the lead time of “All external items except API”. The movements for the LSC Method and the LSC Method after manual improvement were identical. It appeared that for the LSC Method the largest safety stock decrease could be obtained by a reduction in the BULK lead time. The largest reduction for the LSC Method after manual improvement could be obtained by decreasing the lead time for the most downstream stage, because the pipeline controller shifted all safety stocks to this most downstream stage. The effect of an API lead time change for the LSC Method is not considered, because the standard loss function table could not provide a safety factor.

For ChainScope, the largest safety stock product value reduction could be obtained by an API lead time reduction. In contrast to LLamasoft and the LSC Method, the outcomes of lead time length changes were apparently dependent on the product type for ChainScope. A lead time decrease did only cause a total increase in safety stock product value for BULK and PACK.

Those results are again counter-intuitive (Table 8) and the assertion is again that those results are caused by the safety stock transformation. When looking at the total investment change, this only explained the lead time reduction for FG/Pack. The explanation for the counter-intuitive behavior of BULK is that the critical path changed, which caused another allocation of safety stocks. Rosling’s theory namely implies that items with the longest lead time (in the same stage) receive the safety stocks. The lead times of TUB instead of BULK became the critical path, which led to reduced safety stocks for BULK and a steep increase for TUB.



Table 8, Detailed Investigation for the Counter-Intuitive Results

Unexpected Scenario outcomes	Hyp. Effect (PV)	SS PV in ChainScope	Total Investment in ChainScope
<b>Combined Shipments (50%)</b>	SS ↓	SS ↑	<b>Total investment ↓</b>
<b>LT: Int. items: FG/PACK (-10%)</b>	SS ↓	SS ↑	<b>Total investment ↓</b>
<b>LT: Int. items: BULK (-10%)</b>	SS ↓	SS ↑	<b>Total investment ↑</b>

**Service level:** As seen in Chapter 3.1.3, LSC achieved through flexibility measures a higher service level. However, higher service levels do not only increase the cost of flexibility, but also the required safety stock levels. Therefore, LLamasoft and ChainScope are run with a service level of 99%. In agreement with stakeholders, LSC's base model was already run with 99%, because historical data contained flexibility measures and LSC preferred a more stringent comparison to compensate for some of the method's simplifications.

**Outcome:** When the service level is increased, steep increases in safety stocks occurred for both LLamasoft and ChainScope. This behavior is expected, because demand fulfillment criteria are more stringent, which requires safety stocks to also fulfill relatively high demands.

#### **Hypothesis SRQ 2**

Based on the described results above and the graphical results in Appendix U, **hypothesis F)** is rejected. Although the different methods moved *generally* in the same direction and did change with different magnitudes, ChainScope moved in two cases in the opposite direction. However, it needs to be observed that two likely explanations are given for this unexpected behavior.

#### **4.1.3 Additional Quantitative Investigations**

To complement the previous analysis and add some nuances, some interesting phenomena have been investigated: the exclusion of yield in LLamasoft and different demand propagation methods in ChainScope and LLamasoft as well as the volatility in optimal safety stock levels due to storage limitations for ChainScope.

#### **The Influence of Yield and Demand Propagation Methods on Safety Stocks**

In order to assess the impact of yield on ChainScope's outcomes, the model is run for October with and without yield, which means that a yield of 1 is entered. This leads to substantial safety stock reductions on most product types, which helps to understand the large difference between LLamasoft and ChainScope. Furthermore, the LLamasoft model, which offers the possibility to insert yields, is run with and without yield as well. As Figure 17 shows, no difference in SS DOS occurred for LLamasoft. Nevertheless, the missing yield correction resulted in lower component demands in comparison to ChainScope's demand propagation. The demand propagation also differed slightly in its standard deviations. In order to conclude whether the demand propagation or the whole safety stock optimization method caused the safety stock differences, ChainScope's item level demand propagation *with yield* has been modelled in LLamasoft by a so-called *Facility Demand User Profile*. For the purpose of analysis, the average coefficients of variation per scenario and product type are plotted as well.

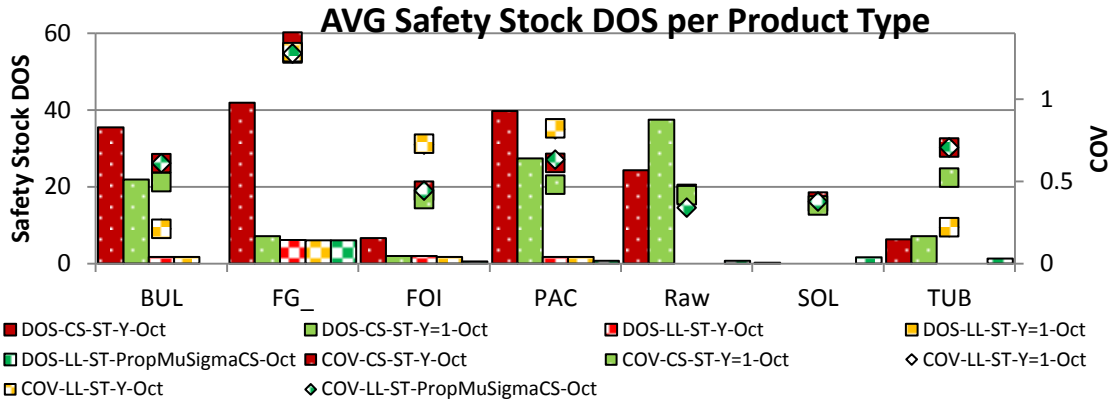


Figure 17, Average Safety Stock and Coefficient of Variation per Product Type

Explanation: “DOS”: Days of Supply, “CS”: ChainScope, “LL”: LLamasoft, “ST”: Storage constraints; “Y”: Yield, “Oct”: October, “COV”: Coefficient of Variation, “PropMuSigmaCS”: ChainScope’s demand propagation in LLamasoft

Figure 17 shows that the ChainScope model with yield has in total the highest safety stock DOS. The ChainScope model without yield shows significantly less overall safety stock DOS, but slightly more for Raw and TUB. The largest difference in SS DOS and automatically product value occurred for FGs. The large difference for ChainScope with and without yield can be explained, because the yield is modelled as an item-based random yield that follows a binomial distribution. Although this modelling can only be applied for relatively high yields, it still amplifies the uncertainty and therefore causes higher safety stock levels. A ChainScope model without yield reduces substantially the differences in safety stock product value with LLamasoft and leads to similar FG safety stock levels. When the LLamasoft model with ChainScope’s demand propagation is run, it resulted overall in significantly less SS DOS. Furthermore, LLamasoft allocates for the first time SS DOS to more upstream stages, such as Raw, SOL and TUB.

Additionally, Figure 1 in the Management Summary already showed the stacked overview of the total average SS DOS, which includes inventory constraints, for **i)** ChainScope with yield, **ii)** ChainScope without yield and **iii)** LLamasoft.

With respect to the **coefficient of variation**, one needs to realize that some average coefficients of variation exceeded 1.5 and are therefore not shown. Based on Figure 17, one can state that high respectively low coefficients of variation cannot be related to high respectively low safety stock DOS. For example, ChainScope (with yield) has clearly the highest average SS DOS, but it does not have the highest average coefficient of variation. The opposite also occurred: LLamasoft’s large coefficients of variation do not trigger high safety stocks. Furthermore, although one can observe that the coefficient of variation remained similar for ChainScope (with yield) and the one used in LLamasoft (*should also be the same!*), the safety stock allocations completely differed.

This leads to multiple insights: **First**, the effects of yield can affect, depending on the method, the safety stock allocation. **Second**, high or low safety stocks appeared to be more triggered by the method than by high or low average coefficients of variation. **Third**, demand propagation methods do cause differences in propagated item means and standard deviations, but other approximations/algorithms within LLamasoft cause the completely different safety stock allocation.

### Storage Space Restrictions to Deal with Frequent Product Changes and Perishability

As mentioned in Chapter 2.1.1, shelf life is limited and 30% of the products have yearly product changes. Detailed analysis shows that the modeling of frequent item changes and shelf life by limited stocks has a considerable impact on the safety stock allocations in the ChainScope model. Large decreases in the FG safety stock allocation and multiple minor increases in the component safety stock allocation occurred, when the model is unconstrained. A more detailed analysis on FG level showed that the large decrease is caused by a minority of items. The explanation is that some common components' safety stocks are restricted too much and therefore lead to a shift of safety stocks to the more downstream FG level. **This finding also helps to explain the large difference between ChainScope's base model and LLamasoft.** Future research should determine *on an item-by-item level* the appropriate inventory constraints, because the increased FG safety stock levels are expensive. For now, Figure 18 should be interpreted as the bandwidths in which the optimal solution is (according to ChainScope with yield). However, LSC should still try to reduce the yearly amount of product changes.

As LLamasoft's safety stock allocation is generally significantly lower than ChainScope's, the optimal results of LLamasoft were not affected by the inventory constraints. The current LSC model does not require any further investigation, because PACK and TUB are in this method excluded.

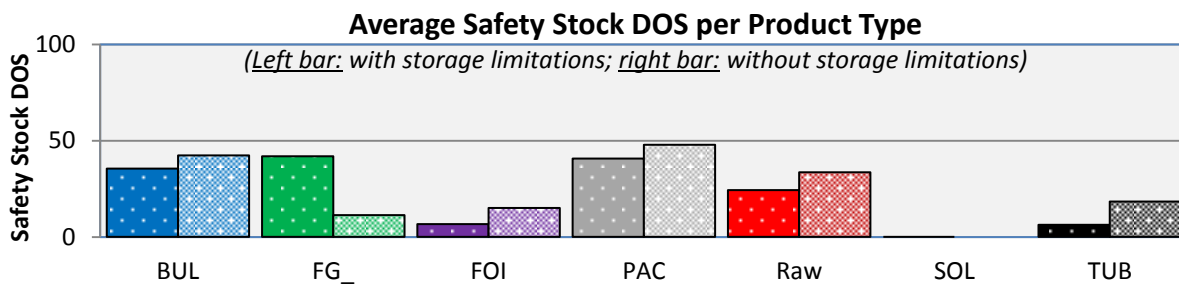


Figure 18, Average Safety Stock with and without Inventory Constraints per Product Type

### Feasibility of the Monthly Safety Stock Levels

Before system parameters are changed, it should be assessed whether the safety stock levels can be produced with the available capacities. A detailed evaluation is out of scope, because a decision about the preferred method is not yet taken and not the whole product portfolio is considered. After a final decision about the preferred method, LSC should assess whether an adaptation to the safety stock levels of the first period is feasible for the *complete portfolio* (Formula (51)). Then, LSC should check whether the recommended monthly stepwise changes can be achieved for the *complete portfolio* (Formula (52)).

$$PQ_0 = \widetilde{SS}_1 - SS_0 + D[0,1] \quad (51)$$

$$PQ_t = \widetilde{SS}_{t+1} - \widetilde{SS}_t + D[t, t + 1], t \geq 1 \text{ month} \quad (52)$$

## 4.2 Qualitative Comparison

Chapter 4.1 compared quantitatively the two multi-echelon methods and tools with the current LSC method. However, all methods and tools possess their qualitative advantages and disadvantages, which will be evaluated in the next paragraphs. Those qualitative and quantitative evaluations form the basis for the redesign in Chapter 5. First, Chapter 4.2.1 discusses some general advantages and disadvantages of advanced tools, such as ChainScope and LLamasoft. Then, Chapter 4.2.2, 4.2.3 and 4.2.4 focus on the specific benefits and drawbacks of ChainScope, LLamasoft and the LSC Method, which **answers SRQ 3.**

### 4.2.1 Advanced Tools

ChainScope and Llamasoft are considered as advanced tools, which have some similar pros and cons. Those are summarized, before the tool-specific benefits and drawbacks are discussed.

#### Pros

ChainScope respectively Llamasoft have an **academic basis** -*SBS policy* respectively *GS approach*- and are both **applied to real-life supply chains** for inventory optimization. The methods distinguish themselves by their **multi-echelon** approach. Furthermore, both methods possess a high level of **granularity**, which allows for safety stock setting for *all* items on an *item* level. This high level of granularity prevents unexpected interruptions through an exclusion of stages. A higher granularity is also desired, because lead times and standard deviations differ per item and because SAP requires item-level specifications. Finally, both tools offer the feature of user-specified item **inventory constraints**.

#### Cons

Those benefits do not come without a cost and one of the costs is the **license fee**. Although the tools conduct an optimization, they still require **capable employees**, who understand the logic, can model features, interpret the outcomes and keep track of the limitations, which affect the general applicability of the outcomes. Furthermore, it *was* **time consuming** to develop the base model due to ambiguous, non-mathematical definitions. Finally, it will cost some time to train the regular users at the sites to maintain the model's data quality, because of the item-level granularity and the frequent product changes at LSC. However, for the regular users the optimization only takes a couple of minutes.

### 4.2.2 ChainScope

The next two paragraphs discuss the specific pros and cons for ChainScope.

#### Pros

ChainScope is **empirically valid**, because the publicly available scientific method is validated multiple times for real-life supply chains. In fact, Uquillas (2010) validated it also within another division at LSC. Groenewout (2015) stated not only that ChainScope **outperforms MRP and APS**, it also mentioned the high responsiveness and stable order release quantities. In addition, SBS considers the mean and standard deviation instead of only the forecasted demand. This included **stochasticity**, which relies on a more realistic gamma distribution, makes the model more robust. ChainScope also offers an **evaluation mode** based on analytical expressions to validate the model, before one uses the optimization mode. At the same time, the tool is **concise and user friendly**, because it does not base its outcomes on user-specified inventory policies and inventory control parameters. It only requests as input the average inventory, which is the outcome of the complex interaction between inventory control parameters, human behavior and the environment. Although the tool cannot model the infinite forms of flexibility, it can show the **costs of flexibility**. Furthermore, ChainScope can deal with **item-based random yield**.

#### Cons

ChainScope's **item-level lead time** is not able to deal with varying batch sizes, which affect the lead time. ChainScope can neither deal with **very small BOM quantities** nor with **multi-period** models at once. Item-based yields cannot be larger than **1**, which is not necessarily true for process industries.

### 4.2.3 LLamasoft

Chapter 4.2.3 describes the pros and cons for both LLamasoft's simulation and optimization.

#### Pros Simulation

LLamasoft's simulation provides *theoretically* a feature to **validate** your model. It provides **built-in decision rules** and a lot of **detailed** modelling options, such as work center specifications for yield, lot sizes and resources. One promising built-in decision rule is a **forecast-based inventory policy –SS DOS-**, which is *dynamic* and *forward looking*.

#### Cons Simulation

Some of the modelling flexibility is offered by a **scripting functionality** of which tutorials were not available, the debugging mode does not function well and the system's performance appeared to become unstable. The remaining standard built-in decision rules are **insufficient** to model more complex and in practice used planning and capacity management processes (e.g. priority rules instead of FIFO). That leads to additional deviations, which make model acceptance difficult. This and run times of 25 minutes for 28 FGs make the model development **time consuming**. Unfortunately, LLamasoft does not offer the flexibility to conduct overnight many simulation runs within a parameter range. Furthermore, simulation and optimization do not rely on the same set of parameters, through which the optimization model can never be 100% validated with simulation.

#### Pros Optimization

LLamasoft relies on an **advanced demand pattern analysis**, which classifies demand, removes outliers, and applies different (safety stock) formulae based on variability, clumpiness, moving velocity (slow/fast) and intermittency characteristics. This should lead to a proposed distribution, which deviates less from the actual demand density function (Appendix V). Furthermore, LLamasoft can perform the **multi-period optimization** runs with different input parameters per period at once. Finally, LLamasoft adapts safety stock levels for **operating flexibility**, when this would be present at a stage.

#### Cons Optimization

Although the GS approach assumes 100% material through assumptions as **bounded demand** or **operating flexibility**, it is questionable how large the impact is of the operating flexibility assumption for relatively high service levels. Except from the bounded demand or operational flexibility assumptions of the GS approach and the lack of yield modeling, the major cons of LLamasoft's optimization are that it is a **large black box** with a lack of transparency and appeared in ChainScope's evaluation to be empirically invalid. Furthermore, it is unclear which formulae *per demand class* are used to determine the safety stocks from the coverage values. The academic basis from which they derived the threshold values for the demand class categorization, lead time demand distribution and recommended inventory control policy is also unclear (Appendix P). Due to this lack of transparency and freedom to adapt it, the impact on the results remains unclear. Furthermore, the optimization does not have the functionality to recommend the inventory control parameters for a "**SS DOS –Forecast**" **inventory policy**, because the optimization does not rely on any forecast information.

#### 4.2.4 LSC Method

The evaluation of the LSC Method does contain both the pipeline risk management approach and the safety stock calculation method. Those paragraphs form the basis for the **answer to SRQ 1**.

##### Pros

The current LSC method is a more *strategic* risk management tool that considers both supply and demand risks, which focuses on the main stages within the supply chain. The method follows the high-level steps identification, evaluation and implementation and appeared to be complete. Multidisciplinary groups of employees identify more operational risk than described in the literature and *quantify* the length and frequency of supply interruptions. After safety stock allocation, the LSC Method shows the remaining existing risk exposure and the outcomes form the input for the ERM cycle. In addition, the method's lower granularity requires less data preprocessing.

##### Cons

The current overall **pipeline risk management approach** could be improved by more SC collaboration with suppliers and country representatives during the risk brainstorming process. The brainstorm process should also rely more on historical data instead of solely rely on expert opinions. Furthermore, the approach does only adapt physical safety stocks instead of any scheduled margin keys.

The current **safety stock allocation** tool is **single echelon** and therefore by definition less appropriate for the analysis of multi-echelon systems. Although the forecast inaccuracy is positively correlated to the coefficient of variation, taking the forecast inaccuracy as a proxy for the coefficient of variation, which is translated to a standard deviation of the forecast, is doubtful. Ignoring this fact, it remains a questionable assumption whether the *FCIA* of the last stage is identical to the *FCIA* of the previous stages. More problematic, the method's implementation contained a misplaced bracket in the formula. This error is corrected in order to not disturb the comparison. Furthermore, LSC excludes the review period and assumes that the lead time variability is zero. LSC's concept of lead time does also deviate from the academic formula, where only the cycle time or replenishment lead time and the review period are considered. However, LSC stated that the Planned Lead Time concept should be used. Furthermore, it is questionable whether a weighted average is correct due to the differences in the produced quantities and the unit cycle times. Moreover the method is based on normality assumptions and the standard loss function. On an API level some demand uncertainties cannot be even calculated, because the standard loss function table does not provide those values. Those **input parameters** can lead to wrong safety factors and demand uncertainties and hence wrong safety stocks.

LSC's Method relies on a **non-stationary** yearly period. This is undesired, because the formulae are developed under the assumption of stable demand. In case the bucket length would be decreased, it raises the question whether a yearly risk assessment frequency is sufficient.

Furthermore, the method's **scope** does neither represent the end-to-end supply chain nor determine safety stocks for stages other than API, SOL, BULK and FG. The exclusion of less important stages can be explained, as long as those items are *real* commodities with 100% availability and short lead times. However, Simchi-Levi showed that ignored, low value items frequently caused the longest delays. LSC does currently set safety stocks for those product types independently of the risk management approach.

Finally, the **level of granularity** is too low to take the tool's output directly as input for SAP.

## 5. Redesign of Operational Risk Management Methodology

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Chapter 5 contains a generic, redesigned **integrated strategic and operational** risk management approach, which is based on a literature review, LSC's current risk management approach and the qualitative and quantitative evaluation of the LSC Method, LLamasoft and ChainScope. The starting point is the current approach, because those processes seemed to function well and everyone is familiar with them. Nevertheless, the redesign tried to solve the drawbacks by some small adjustments, additional steps or a complete replacement of some steps. For example, the demand uncertainty safety stock calculation is completely replaced by a multi-echelon approach.

The assertion is that the execution of those steps is time-feasible. Although it took roughly two months to develop the correct ChainScope model for the pilot study, it is expected that the development of some tooling and the connection with the current system takes 3 months. However, this depends on the scale of implementation. Due to the non-stationary environment, the number of items and the frequent product changes, a high level of automation is recommended. However, this goes relatively fast, because it is clear which data is exactly needed and where it can be found in the data warehouse.

An **overview of the redesigned integrated strategic and operational risk management methodology** is depicted in Figure 19. On the left side, it is indicated when an activity should take place and to which category it belongs. Then, on the right side, it is highlighted whether all products and pipelines should be included or not. For example, the "demand uncertainty safety stocks" are determined for all items together in order to benefit from the existing interdependencies.

As many steps are self-explanatory or already discussed, only a few steps are highlighted. Step 5 aims to gather a group of experts, which are representatives along the whole SC. The steps 15-18 contain "a" and "b". This difference is added to show that the processes are "quasi-parallel" instead of sequential. However, the execution of activity 19 can start, when the "a" activities are not yet completed. Step 16b converts the identified risk impact to an item level *after the workshop*. For example, one looks which products are affected by a breakdown of Machine X and one then assigns this impact to those set of items. In case an item is exposed to multiple supply risks, the maximum impact is taken as an item's "supply uncertainty safety stock". As the steps 17b-20 are already extensively described in Chapter 3, only the high-level steps are presented. Step 22 guarantees the production feasibility and offers the possibility for manual adjustments to parameters that could not be considered in the optimization model. Step 23 also highlights the possibility to translate some of the safety stocks to safety time by an adaptation of the scheduled margin keys. Then, pipeline controllers prepare a proposal, which management from headquarter, sites and countries need to approve. Then, local sites, such as SC GER and CW, are responsible for the safety stock setting process and implementation. A pipeline controller monitors monthly whether the norm levels are approximately met and report about the performance, such that corrective actions can be taken if necessary.

This procedure needs to be repeated at least yearly. In case many stock outs occur, the network or the capacity is significantly changed or an important product is launched, the process might be repeated. As the pipeline controllers cannot conduct all the activities themselves, they are responsible for the coordination and documents of the Pipeline Risk Management workshop.

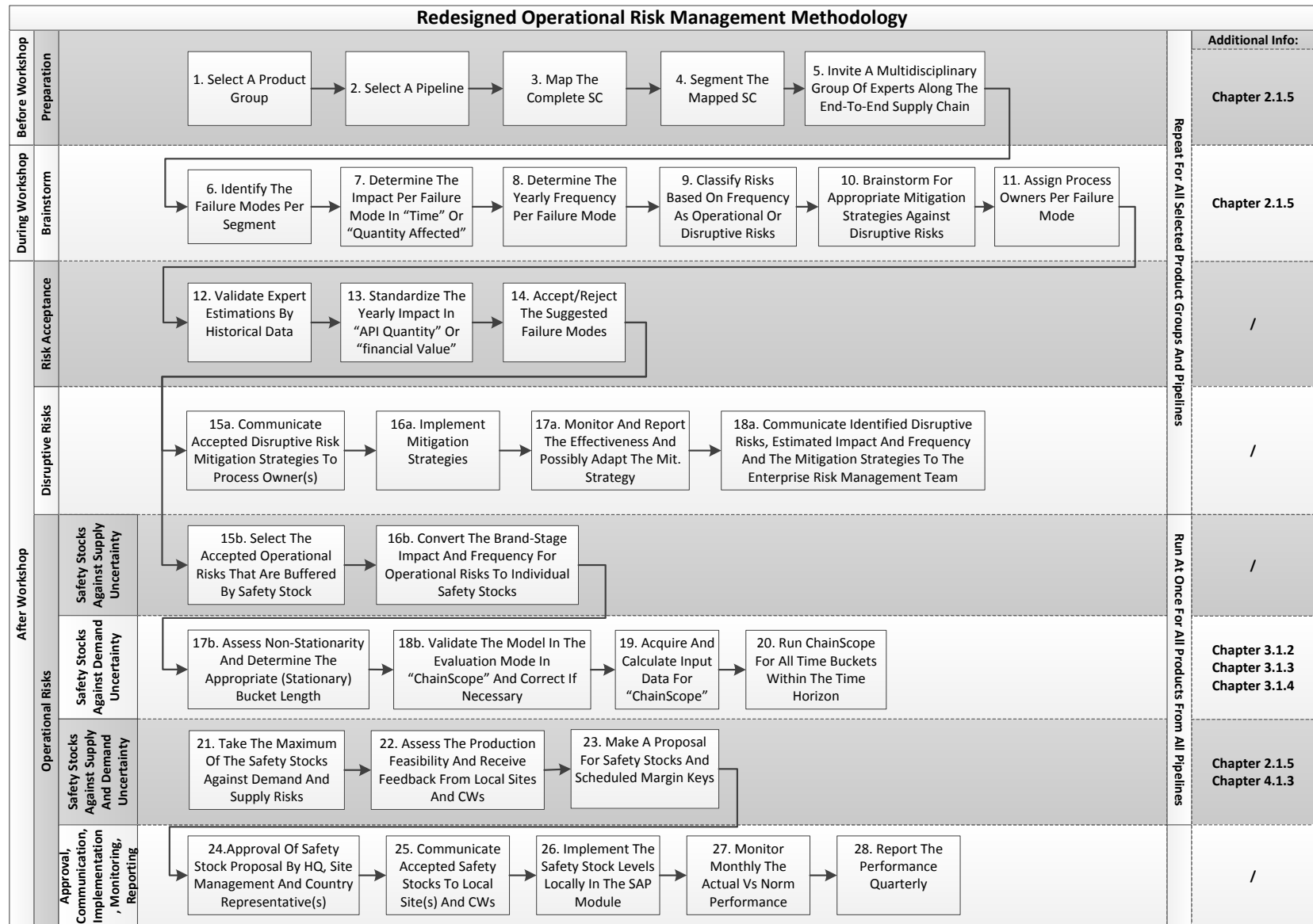


Figure 19, Redesigned Operational Risk Management Strategy



## 6. Recommendation

This recommendation is based on the previously answered sub research questions and separated into one **strategic (R1)**, one **tactical (R2)** and one more **operational (R3)** recommendation for implementation. Hence, both the question about the overall preferred risk management methodology (**overall RQ**), safety stock optimization method and implementation **are answered (SRQ 4+5)**.

### R1: Invest in more quantitative and advanced risk management methodologies

Simchi-Levi (2015) found that, according to *The SC and Risk Management Maturity Model*, mature companies (phase 3 and 4) outperformed immature companies (phase 1 and 2) on all surveyed operational and financial KPI's, such as delivery performance, cycle time and inventory days of supply. Chapter 2.1.6 showed that LSC can be categorized in stage 3 with only *basic, single-echelon* quantitative risk management strategies. The assertion is that LSC can improve its maturity by more quantitative and advanced risk management methodologies, which positively affect the operational and financial KPI's. For example, more advanced models can better set norms and therefore better support human decision makers, who can manually adjust the norms for soft constraints.

Therefore, the **first recommendation** is to invest in more quantitative and more advanced risk management methodologies.

### R2: Slightly extend the current approach and include multi-echelon safety stock optimization models

As discussed in Chapter 4.2.4: although the current pipeline risk management approach seemed to be complete and perfectly suited to identify process and supply risks, the LSC Method is undesired due to its single-echelon like approach, the stage-level granularity, the invalid stationarity assumption, the parameter usage as well as the lack of supplier and country involvement. Multi-echelon approaches take away those three first drawbacks, because **i)** they consider the relationships between items of different stages, **ii)** provide outcomes on an item level that can be directly implemented in SAP, and **iii)** can easily be run for different stationary periods, when the base model is developed. Although dynamic safety stock levels for this subset appeared to be less relevant (Chapter 4.1.1), it can be valuable for other more non-stationary product demands. However, the multi-echelon models are less suited to deal with individual risk events as those are identified in LSC's risk assessment workshop. Therefore, this part of LSC's current approach is maintained and slightly adapted, such that it becomes a higher granularity.

In Chapter 2.1.6 LSC is classified to stage 4 of the Inventory Professionalism Framework. Further improvement potential could be realized with stage 5, which differs from stage 4 mainly through the multi-echelon inventory optimization. Groenewout (2015) also emphasized that the application of sequential single-echelon logic enables the Bullwhip effect, because all stages keep inventory and the variability between stages is not reduced. This might reduce service levels and increase costs.

The quantitative analyses showed **–even with yields and inventory constraints–** lower safety stock product values for the two multi-echelon models in comparison to LSC's System Settings and Actual (which contained some safety stock against supply uncertainties). Especially after this successful pilot run, the first problems are solved, which makes horizontal and vertical extensions easier to achieve.

Therefore, the **second recommendation** is to apply the redesigned operational risk management approach (Figure 19), which is renewing through the multi-echelon demand uncertainty safety stock optimization and the increased level of granularity for the supply uncertainty safety stock.

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**R3: Apply ChainScope to benefit from a risk-free cost reduction and service level maintenance**

Recommendation 2 highlighted that a multi-echelon approach is recommended over a single-echelon approach. Although the LSC Method appeared to be less expensive than ChainScope's base case, the allocation among product types was completely different. As ChainScope is empirically valid and based on a more advanced logic, the assumption has been that the product type allocation is better and the risk exposure is therefore less, while still achieving the claimed service level. ChainScope is the recommended *multi-echelon* approach, because with LLamasoft's optimized inventory levels a service level drop from 97.5% to 57.5% is, according to ChainScope, at stake.

The quantitative analysis in Chapter 4.1 showed that ChainScope is expected to be less expensive than LSC's System Settings and the Actual carried safety stocks after correction for supply uncertainty safety stocks. As ChainScope is modelled without flexibility measures, with an item-based random yield, with inventory constraints and without scheduled margin keys, it proposed a higher safety stock product value. When LSC decides to continue the deployment of some flexibility measures, has a stable yield, and keeps using scheduled margin keys, the safety stock product value could be significantly reduced.

**This would make ChainScope less expensive than LSC's method.**

The qualitative advantages described in Chapter 4.2.2 are the empirical validity, the robustness thanks to the stochasticity, the concise and user-friendly interface and the possibility to model yield. Besides that, ChainScope/SBS is academically sound, applied in practice at Philips Electronics with inventory savings and maintenance of service levels, and not a black box, such as LLamasoft, with a questionable material availability assumption.

In terms of risk: it is relatively risk free that LSC's current safety stock product values reduce and it is unlikely -due to the relatively high safety stocks that are closer to the current levels- that the service level decreases.

Proponents of the LSC method might argue that ChainScope allocates large safety stock DOS to BULK, where pipeline controllers took safety stocks away on purpose. A combination of actions is recommended:

- Update the Scheduled Margin Key, which can be item specific, to model a *safety time*. Unforeseen demand increases can then still be produced with less safety stocks.
- Rerun the model without item-based random yield.
- Rerun ChainScope, as in Chapter 4.1.3, with additional storage limitations for BULK.

Although this recommendation is based on the quantitative and qualitative comparison, proponents of the LSC Method might also mention ChainScope's licensing costs. However, the interrelationships for a whole supply chain are too complex for human planners to oversee. As discussed, single-echelon safety stock determination does enable the Bullwhip effect, which might disaffect the service level and/or costs. In addition, other multi-echelon tools, such as LLamasoft, do also have a licensing cost. LSC benefits from large product volumes where small savings can lead to large savings thanks to multiple pipelines and multiple divisions. Additionally, Chapter 7 enumerates other factors that are excluded in this study, which should be considered in the final management decision.

Despite those possible arguments, the **third recommendation** is to deploy ChainScope, because it is empirically valid at LSC and expected to lead to a cost reduction in comparison to at least Actual and System Settings and to maintain a service level of 97.5% *without any flexibility measures*.

## 7. Implications for LSC and Academia

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Chapter 6 summarized the recommended integrated strategic and operational risk management approach based on the qualitative and quantitative evaluation. Some aspects were excluded from this study and should be considered by management in their final judgment: *desired risk exposure, inventory level targets, budgets for licensing, presence and level of operating flexibility (LLamasoft), expected workload of and available organizational resources to deploy a new method*. Therefore, Chapter 7.1 does not only outline the implications for LSC when a multi-echelon model is implemented, but also when management decides to maintain the current methodology. Therewith, Chapter 7.1 highlights the implementation aspects, **which answers SRQ 5** in more detail than the high-level recommendations in Chapter 6. Then, Chapter 7.2 proposes interesting future investigations for LSC. Finally, Chapter 7.3 states the project's contribution to the existing gaps in research and indicates future research activities.

### 7.1 Implications for LSC

Independent of the chosen method, LSC should vertically integrate the scope of the approach and benefit from the reduction of redundant stocks. Now the specific implications are described:

**In case ChainScope or LLamasoft is selected:** For extension and adaptation LSC can rely on the model conceptualization, the created Excel sheets, the existing models and the redesigned risk management approach. **First**, LSC should automate the data preparation, because automation is limited in this project. Only the necessary macros were created in Excel for the pilot study, because no decision was yet taken about the preferred method. **Second**, data should be updated, because product changes occur frequently. Furthermore, the historical demand data should be updated by new forecasts, because a detailed analysis showed that the monthly coefficient of variation is not stable per month over multiple years (Appendix W). That implies that LSC should be careful to implement this year's safety stocks for the US. **Third**, LSC should extend the scope of 28 US FG's to more pipelines and more key countries. **Fourth**, production feasibility for the whole portfolio needs to be checked by pipeline controllers, because peak safety stocks of multiple products might coincide in the same month. Pipeline controllers should also check whether some safety stocks can be reduced due to slack capacity or updated scheduled margin keys. **Fifth**, current brand-stage supply risks need to be translated to an item level. LSC should relate items to specific supply interruptions, such as a machine breakdown, and assign the defined safety stocks to the affected items. **Sixth**, the outcomes of the risk management approach and safety stock optimization need to be regularly updated within SAP's monthly dynamic safety stock module. As the coefficients of variation were not constant over the years, it is not recommended to use the same yearly dynamic profile for multiple years.

**For ChainScope specifically:** **First**, LSC should assess the safety stock transformation formula, which caused some unexpected results in the scenario analysis. **Second**, LSC should decide about an appropriate yield modeling technique: **i)** non-random yield, **ii)** item-level yield or **iii)** batch-yield modeling, because of the relatively high impact on safety stocks. **Third**, the inventory constraints need to be determined *item-by-item*, because it heavily affected the safety stock allocation among the product types. LSC should also continue to reduce the yearly amount of product changes, which is often out of SCM control.

**For LLamasoft's simulation specifically:** As standard built-in functions are not sufficient to model the in practice used decision rules (priority scheduling, SAP inventory policy), advanced rules need to be programmed. Simulation then might become a useful tool for model validation and supply uncertainty modeling.

**In case the not recommended current safety stock method is kept:** LSC can decide to improve the current approach and keep the current safety stock method due to management considerations. Then, LSC should consider the following: **First**, LSC should investigate the relationship between the forecast inaccuracy and the coefficient of variation of the forecast error and whether an identical value can be used for upstream stages. LSC should in addition reconsider the used lead time definition. Furthermore, LSC should consider the modeling of lead time variability and review periods. Finally, it should find a solution to deal with look-up values that cannot be found in the standard loss function table. **Second**, LSC should divide the year in stationary periods and apply the formulas only under stationary conditions. **Third**, LSC should develop a methodology to properly convert brand-stage safety stock levels to an item level. **Fourth**, LSC should reconsider the benefits and effort of more product type stages, because the quantitative analyses showed that ChainScope exploited all product types (e.g. PACK).

## 7.2 Future Investigations for LSC

Two interesting future investigations for LSC arose during the project. **First**, in Chapter 3.1.3 and Chapter 3.2.3 different flexibility measures were identified, which most likely increased both the costs and the service level. LSC should assess whether they do not rely *too often* on flexibility measures, because the measured service level was often above the target. LSC can compare the cost of the flexibility measures with the costs of additional safety stocks and/or the value of this increased service level. **Second**, LSC should strive for human independent service levels, because stock-outs are currently *estimated* by humans instead of automatically determined by systems (Chapter 3.1.3).

## 7.3 Contributions to Academia

This paragraph summarizes the contribution to academia, which **answers the academic question**:

**First gap:** Although this project assessed qualitatively and quantitatively the GS approach and the SBS policy in a non-stationary environment under supply, process and demand risks for a subset of a real-life convergent supply chain in a challenging batch/mix environment, the superiority debate is not yet settled after one case study. Multiple comparative case studies are required to claim a method's superiority for certain networks or environmental characteristics. However, the results showed the more conservative and more downstream safety stock allocation for convergent network structures according to the GS approach. According to ChainScope's evaluation, significant service level deviations (-40%) occurred for convergent networks and therewith explain LLamasoft's conservative safety stocks. Furthermore, it appeared that the *end-item average inventory* between LLamasoft and ChainScope a factor 2 differed and that downstream stages contributed the most to the service level decrease.

An additional investigation also showed the influence of yield and inventory constraints on ChainScope's optimal allocation. Future research should conduct a comparison between the original GS algorithms and LLamasoft. Only then one can conclude whether the GS approach or LLamasoft's heuristics caused the large differences in safety stock allocations. More fundamentally, it would be interesting to conduct a comparison study for a simplified network that is extended step-by-step to find the drivers of the differences, such as, for example cost ratios, network structures and yields.

**Second gap:** This project has proven again the empirical validity of ChainScope and reported about the difficulties of simulating the behavior of real-life supply chains, where humans often intervene. Table 9 highlights the common and tool-specific causes for deviations during the model validation. Moreover, I emphasize the need to support practitioners with a simulation tool, which does provide practically useful instead of simplified theoretical decision rules.

Table 9, Common and Specific Reasons for Deviations during Validation

Tool	Identified Reasons	Example(s)
<b>ChainScope and LLamasoft (common)</b>	Human interventions affect norm values	Humans steer lead times by: 1) rescheduling and priority orders, 2) reduction of SMKB, SMKA, goods issue and goods receiving times, 3) the combination of shipments, and 4) air instead of sea freight
	Data reliability	Historical data, estimations, deviation between SAP and Actual
<b>ChainScope</b>	Methodological	Stochastic demands with limited inventory can never reach a 100% service level
	Other definitions	The amount of lost sales is estimated by humans instead of counted
<b>LLamasoft Simulation</b>	Other limitations	Built-in decision rule functionalities in the tool

**Third gap:** Furthermore, the project partially contributed to the lack of described safety stock optimization *procedures* by a detailed description of the input parameters and a procedure to deal with non-stationarity. Those publicly available descriptions are useful for practitioners from all industries who start with multi-echelon safety stock optimization.

**In addition to those gaps,** the quantitative comparison and the scenario analysis accepted and rejected some of the formulated hypotheses, which can form the basis for new research projects in order to understand the “Why?”(Table 10). Furthermore, it is especially interesting to investigate the safety stock transformation method within ChainScope, which caused a rejection of scenario 1 and 2.

Table 10, Hypotheses Testing

Sub Hypotheses	Outcome
<b>A)</b> Multi-echelon models allocate <b>less</b> safety stock than LSC’s single echelon method	Rejected
<b>B)</b> LLamasoft’s safety allocation in assembly networks is <b>more conservative</b> –which refers to less safety stocks- than ChainScope’s	Accepted
<b>C)</b> Relative differences between LLamasoft and ChainScope <b>decrease</b> in terms of safety stock value in comparison to safety stock days of supply	Accepted
<b>D)</b> ChainScope’s and LLamasoft’s safety stock allocations in contrast to LSC’s are <b>dynamic over time</b>	Accepted
<b>E)</b> ChainScope’s, LLamasoft’s and LSC’s safety stock allocations show <u>always</u> a <b>similar direction</b> , but a <b>different magnitude</b> for different scenarios	Rejected
1. Reduced review periods do <u>always</u> <b>decrease</b> safety stock levels	Rejected
2. Reduced lead times do <u>always</u> <b>decrease</b> safety stock levels	Rejected
3. Higher service levels do <u>always</u> <b>increase</b> safety stock levels heavily	Accepted

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Appendix A - Top Business Risks 2015

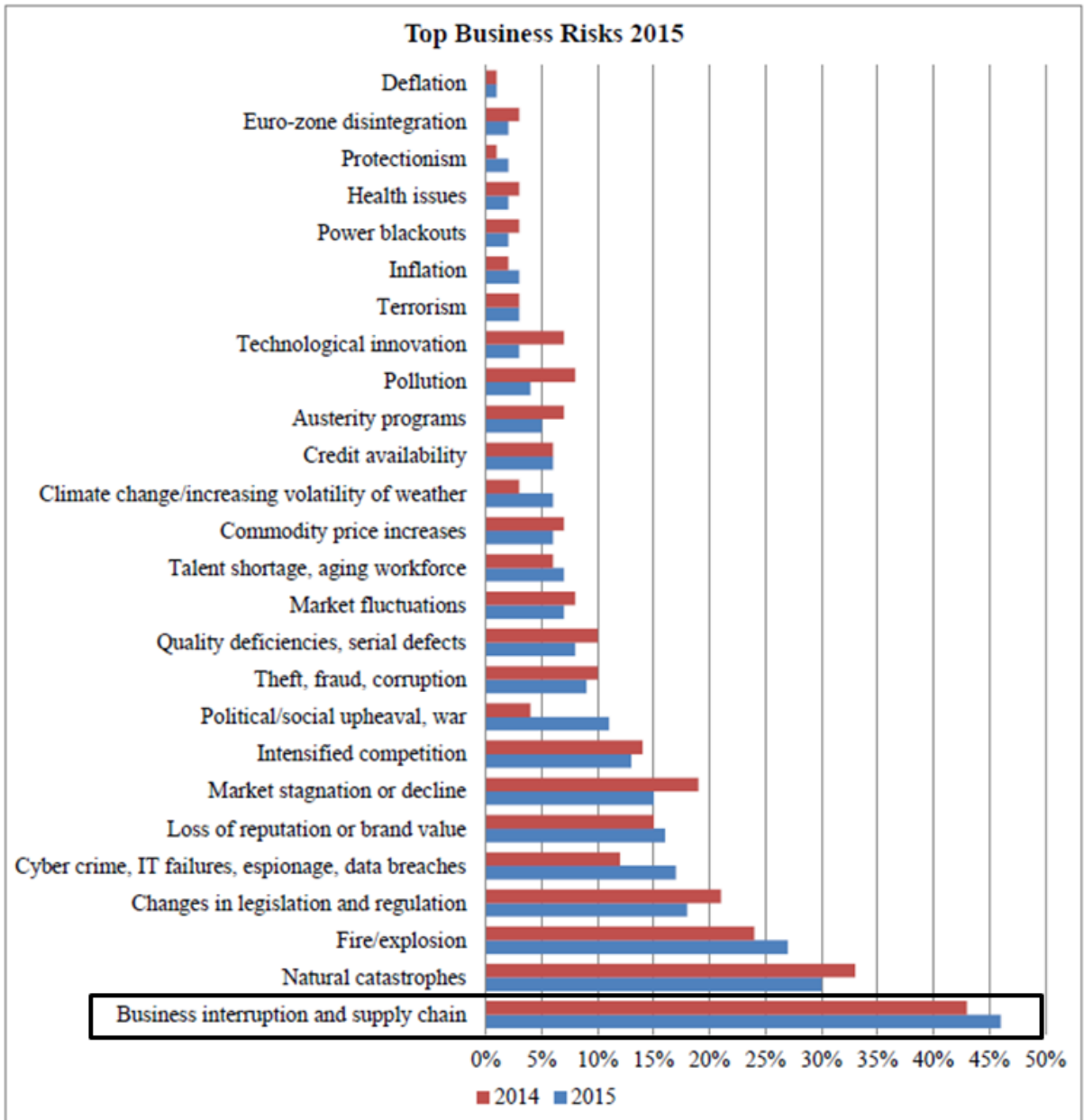


Figure 20, Top Business Risks 2015 – (Lachner, 2015, p. 25)

Appendix B - DuPont Chart

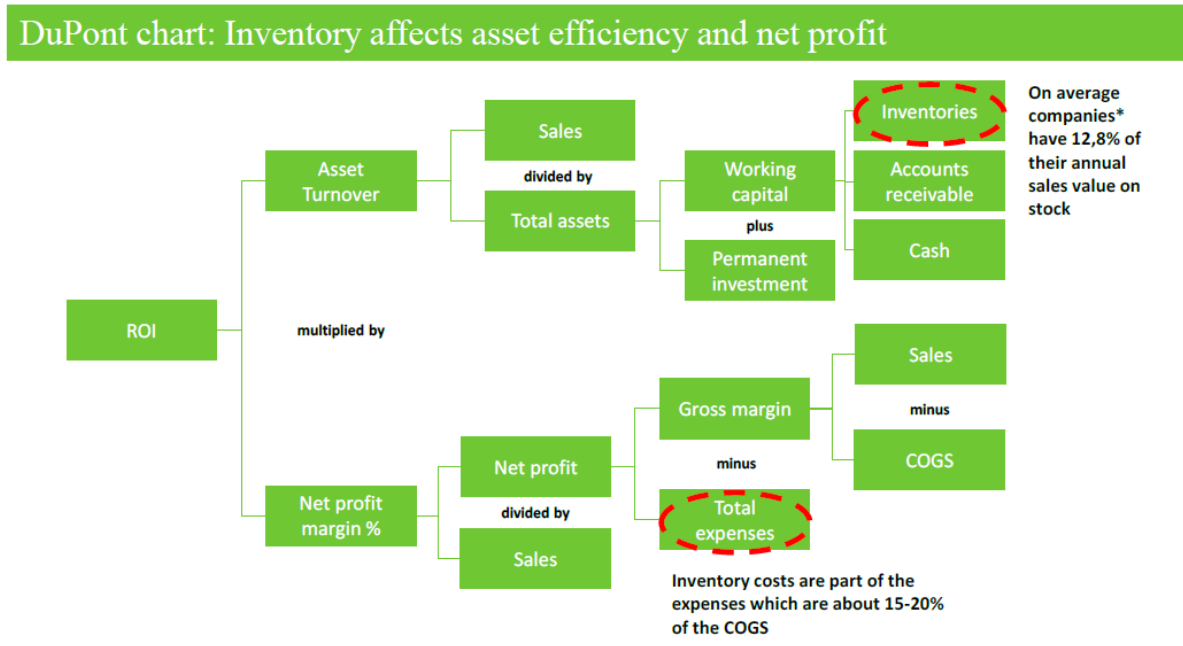


Figure 21, DuPont Chart: From Inventory to Working Capital to ROI - (Groenewout, 2015, p. 5)

Appendix C - Demand and Variability Patterns of Three Products

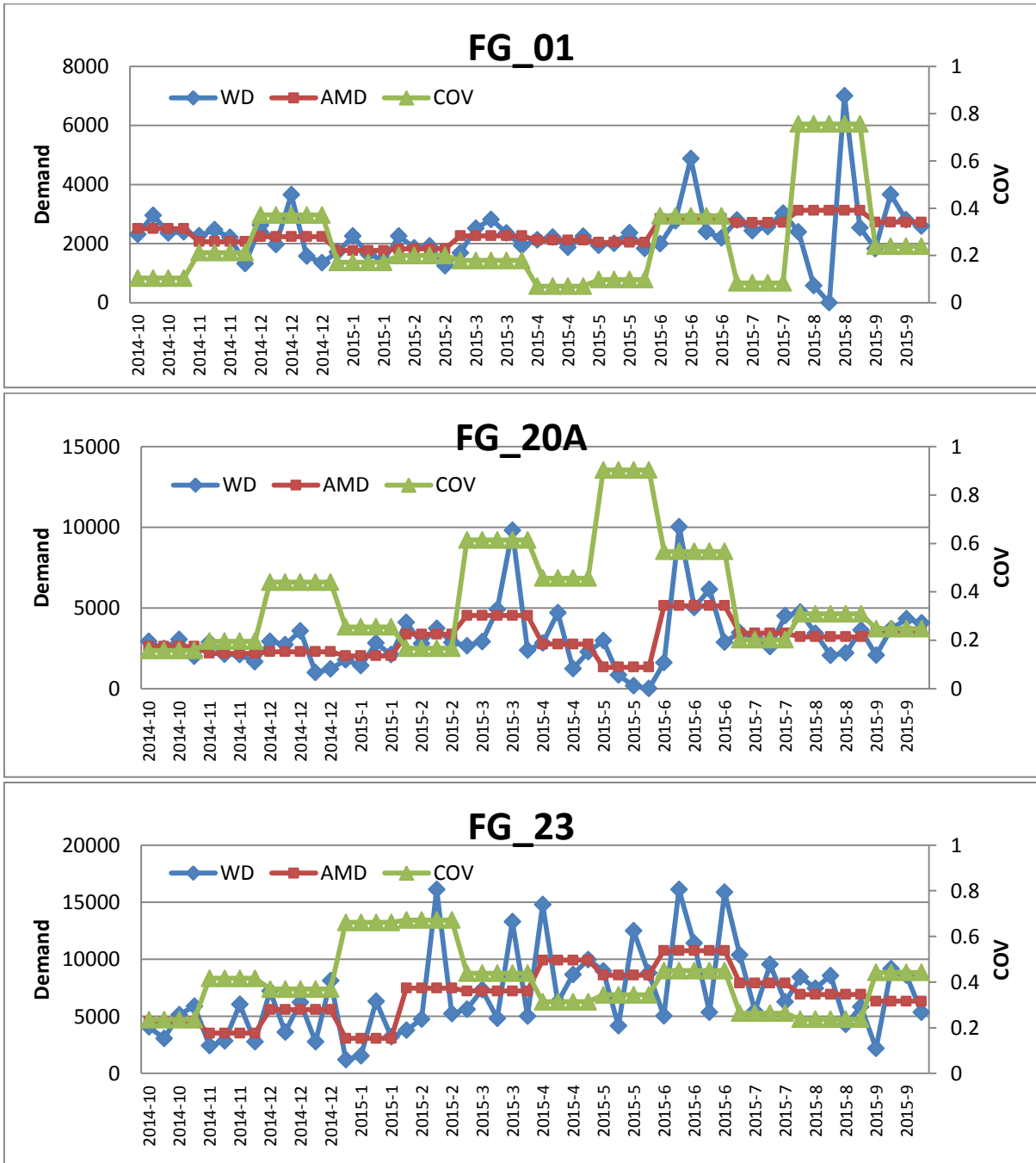


Figure 22, Demand and Variability Patterns for Three Products

**Explanation:** WD: Weekly Demand, AMD: Average Monthly Demand and COV: Coefficient of Variation

## Appendix D - LSC's Brand-Stage Safety Stock Allocation Philosophy

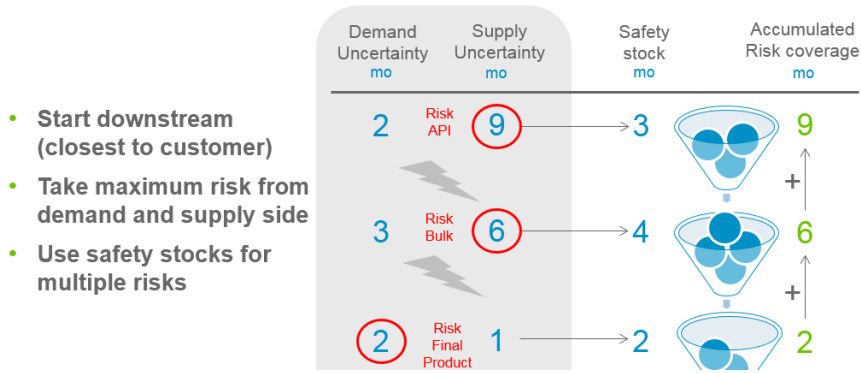


Figure 23, LSC's Brand-Stage Safety Stock Allocation Philosophy

## Appendix E - Risk Matrix

		Risk Matrix		
Very probable	Probability at least moderate	Probability at least moderate		
	Low Impact	Impact at least medium		
Moderate	Low probability	Low probability		
	Low impact	Impact at least medium		
Very unlikely		No impact	Medium	Catastrophic

Figure 24, Risk Matrix – (Hallikas et al., 2004, p.53)

Appendix F - Key Supply, Process and Demand Risk Definitions

Table 11, Key Supply, Process and Demand Risk Definitions

		Risk categorization							
My aggregation	Risk category:	Risk triggers:	Davis (1993)	Chen & Paulraj (2003)	Wagner & Bode (2008)	Tummala & Schoenherr (2011)	Manuj & Menter (2008)	Tang & Tomlin (2008)	Chopra & Sodhi (2004)
SUPPLY	Supplier / Supply / Supply Side / Supply (procurement) risks/ Procurement	1) Low on-time performance; High average lateness; and a high degree of inconsistency; 2) Low quality; low timeliness; and less stringent inspection requirements; 3) Poor logistics performance of suppliers (delivery dependability, order fill capacity); supplier quality problems; sudden default of a supplier; poor logistics performance of logistics service providers; capacity fluctuations or shortages on supply market; 4) Low quality of service (including responsiveness and delivery performance); many supplier fulfillment errors; selection of wrong partners; high capacity utilization supply source; poor quality or process yield at supply source; supplier bankruptcy; disadvantageous rate of exchange; percentage of a key component or raw material procured from a single source; 5) Disruption of supply, inventory, schedules, and technology access; price escalation; quality issues; technology uncertainty; product complexity; frequency of material design changes; 6) High supply cost; low supply quality; and little supply commitment; 7) Exchange rate risk, percentage of key component or raw material procured from a single source; industrywide capacity utilization; long-term vs short-term contracts;	1	2	3	4	5	6	7
	Transportation / Delay	1) Much Paperwork and scheduling; port strikes; delay at port due to port capacity; late deliveries; higher costs of transportation; 2) Excessive handling due to border crossings or change in transportation mode; port capacity and congestion; custom clearances at ports; transportation breakdowns; 3) High capacity utilization at supply source; inflexibility of supply source; poor quality or yield at supply source; excessive handling due to border crossing or to change in transportation modes;				1,2			3
	Process	1) Low quality; little time; and capacity risks associated with in-bound and out-bound logistics and in-house operations;							1
	Manufacturing / Manufacturing (process) breakdown / Operational	1) Poor process performance; frequent machinebreakdown; bad supply chain performance; 2) Poor quality (ANSI or other compliance standards); low process yields; frequent design changes 3) Breakdown of operations; inadequate manufacturing or processing capability; high levels of process variation; changes in technology; changes in operating exposure;	1			2		3	
DEMAND	Physical plant	1) Lack of capacity flexibility; high cost of capacity;				1			1
	Customer/ demand / Demand Side / Demand / Forecast	1) Many forecasting errors; many irregular orders; 2) High fluctuations and variations in demand; 3) Unanticipated or very volatile customer demand; insufficient or distorted information from customers about order quantities; 4) Order fulfillment orders; inaccurate forecasts due to longer lead time; high product variety; swing demands; seasonality; short life cycles; small customer base; information distortion due to sales promotions and incentives; lack of SC visibility; exaggeration of demand during product shortage; 5) New product introductions; variations in demand (fads, seasonality, and new product introduction by competitors); chaos in the system (Bullwhip effect on demand distortion and amplification); 6) Inaccurate forecasts due to long lead times; seasonality; product variety; short life cycles; small customer base; Bullwhip effect or information distortion due to sales promotions, incentives, lack of supply-chain visibility and exaggeration of demand in times of product shortage	1	2	3	4	5	X	6
	Behavioral	1) More partners in a supply under a limited level of visibility, communication, coordination;							1

Explanation: The indicated numbers show which author(s) distinguished the risk category as well as their proposed definition.

## Appendix G - Place of Risk Occurrences in a Supply Chain

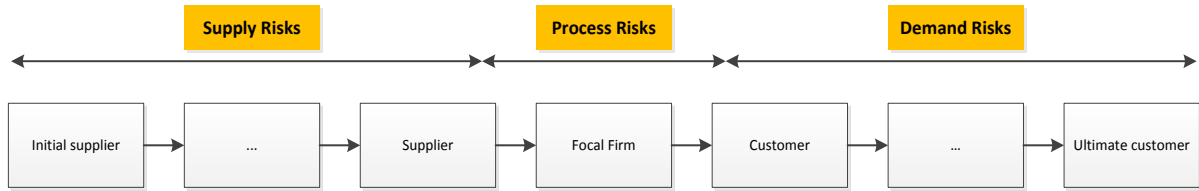


Figure 25, Risks in a Supply Chain – Adapted from: (Mentzer, 2001; Tang & Tomlin, 2008)

## Appendix H - Preferred and Combined SC Risk Management Methodology

The orange arcs indicate the additions from Tummala & Schoenherr (2011) and connect them to the right step in the process of Manuj & Mentzer (2008).

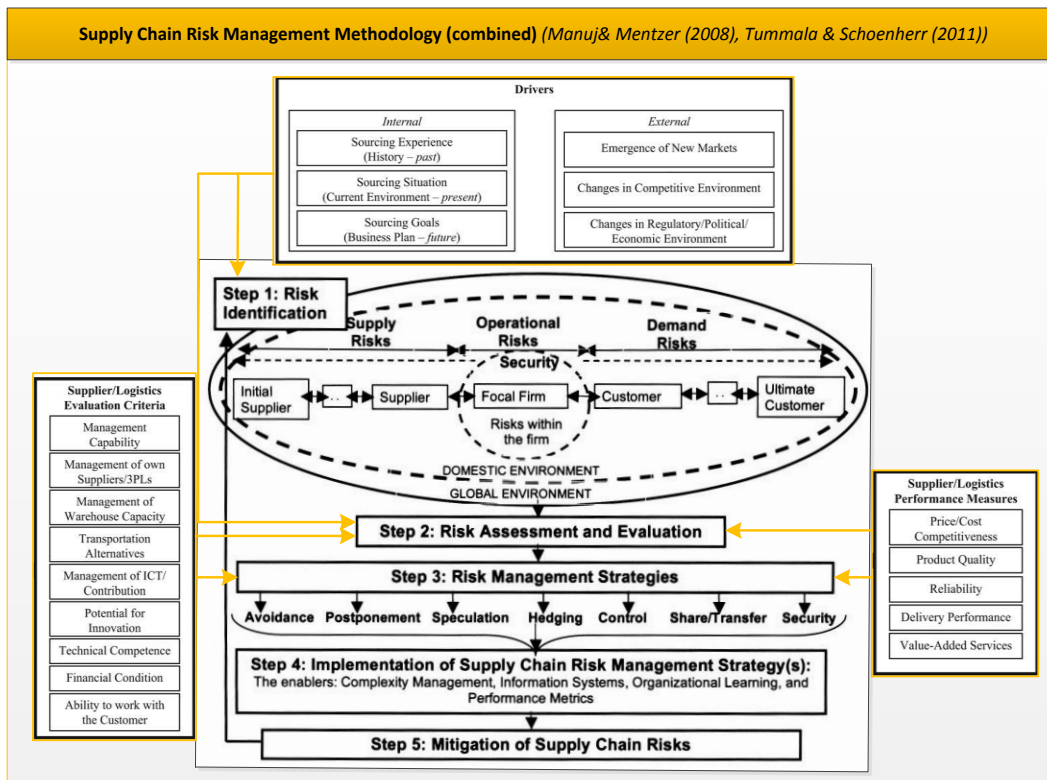


Figure 26, SCRMM – Adapted from: (Manuj & Mentzer, 2008; Tummala & Schoenherr, 2011)

**1. Risk identification:** Tummula & Schoenherr (2011) emphasized that a thorough understanding of the consequences and the affected domains/functions is important as well as the interconnectedness of risks to formulate the right mitigation strategy. They advised to focus on the existing internal and external forces, which reduce performance, and assets that could be disaffected. Possible techniques to carry out this analysis are supply chain mapping, checklists, event tree analysis, failure mode and effect analysis and Ishikawa cause-and-effect diagrams. Those results can subsequently be summarized into a so-called risk profile.

**2. Risk assessment and evaluation:** the risks that are critical for the supply chain are extracted from the risk profile table. Then, the consequences (potential losses), risk probability and risk impact are qualitatively or quantitatively described. Evaluation criteria and performance measures can serve as a reference to assign the right numbers and assess the likelihood. Then, (multidisciplinary) teams classify the risks as acceptable, tolerable or unacceptable. Acceptable risk do not require action, while unacceptable risks require action; it is worth to spend time and resources to reduce the risk.

**3. Risk mitigation strategy selection:** There are several general risk management strategies, which a company can apply. A company can *avoid* risks when the risk is unacceptable (e.g. do not enter African markets). Companies can also *postpone* activities, such as assembly, manufacturing or packaging, to remain more flexible. Furthermore, companies can *speculate*, when they expect higher prices or more customer demand. *Hedging* strives to reduce the risk and a company can hedge by diversification (e.g. multiple suppliers) or by buying forwards. Companies can also decide to *control* the risk by, for example, vertical integration. Opposite to this, companies can also *transfer* risks by offshoring certain non-crucial activities (Manuj & Mentzer, 2008). Jüttner et al. (2003) indicated that *co-operation* can be used as a mitigation strategy as well: supply chain partners can, for example, increase supply chain visibility and share risk-related information. Irrespective of the mitigation strategy, the risk mitigation strategy needs to be in alignment with the type of supply chain (Efficient SC, Responsive SC, Risk hedging SC, Agile SC) according to Manuj & Mentzer (2008).

Especially safety stock appears to be a good strategy to deal with operational risks, such as supply, process and demand risks.

**Alternative mitigation strategies** for safety stock and safety time, which are both efficient and resilient, are shown in Figure 27. According to Tang (2005), firms should try to implement robust supply chain strategies, which are characterized by two properties: **efficient** to manage operational risk and **resilient** to sustain the operations during disruptions and recover quickly.

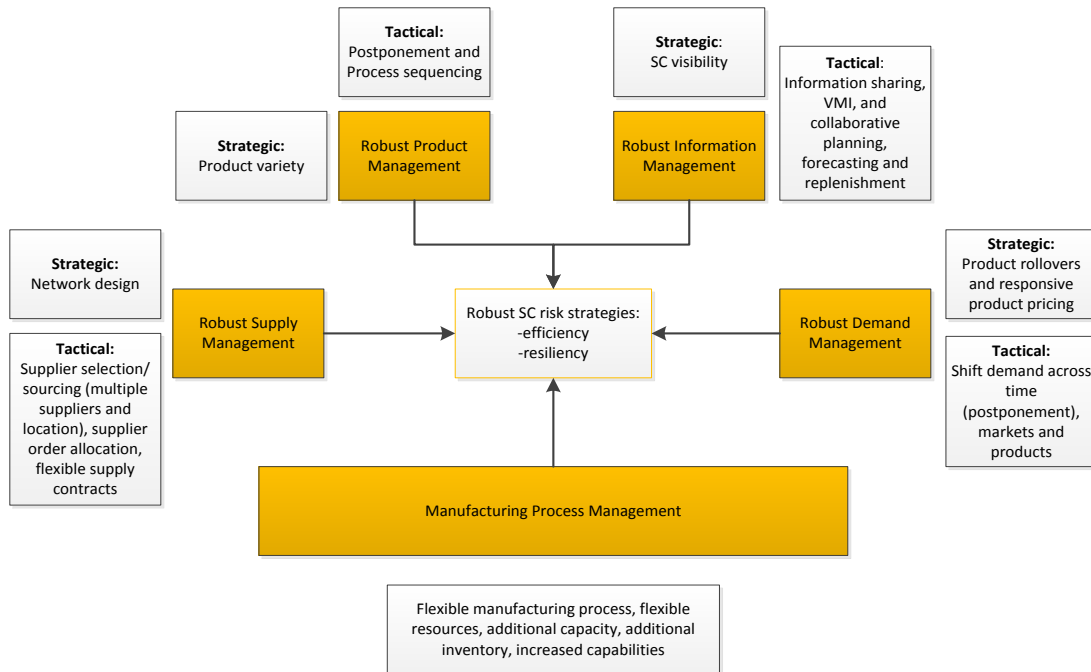


Figure 27, Robust SCs – Adapted from: (Tang, 2006; Chopra & Sodhi, 2004; Tang & Tomlin, 2008)

**4. Implementation of SC risk management strategies:** the success of implementation does not only depend on organizational learning, information systems and performance metrics, but also on personal characteristics, such as: discipline, commitment, creativity, leadership and superior execution skills (Freedman, 2003).

**5. Mitigation of SC risks:** even after creating appropriate risk management strategies, risks can still occur. Therefore, a company needs to be prepared and create a risk mitigation plan, when an unexpected loss due to an unexpected event occurs.



## Appendix I - General Multi-Echelon Network Structure

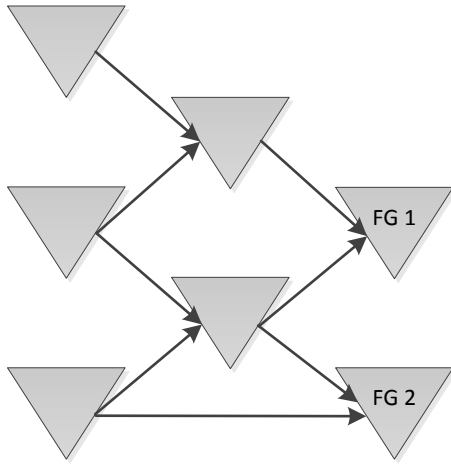


Figure 28, General Multi-Echelon Network

## Appendix J - Echelon Concept

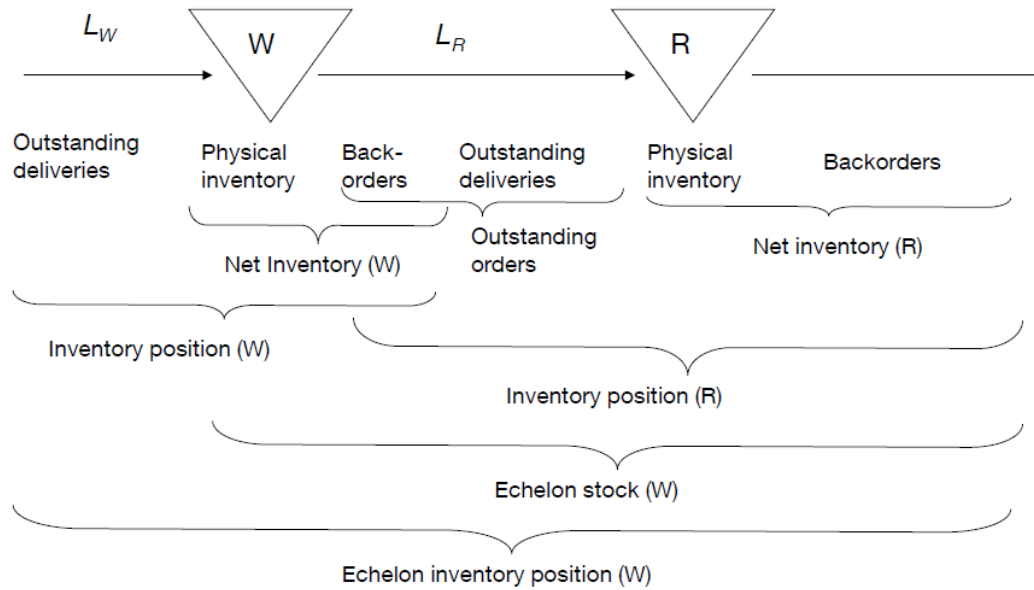


Figure 29, Echelon Concept for Retailer R and Warehouse W - (Minner, 2015, p. 181)

## Appendix K - Key Multi-Echelon Papers Sorted per Research Paradigm

Table 12, Overview of Key Multi-Echelon Papers Sorted per Research Paradigm

Overview of key papers for multi-echelon inventory systems				
Strategic Safety Stock Setting	Structure	Inv. Policy	Optimal vs Heuristic	Special characteristics
<b>(I) Stochastic Service approach</b>				
<b>Scarf and Clark (1960)</b>	Serial	(R,S)	Optimal	
<b>Shang and Song (2003)</b>	Serial	(R,S)	Heuristic	N-stages
<b>Rosling (1989)</b>	Convergent	(R,S)	Heuristic	Pure convergent systems
<b>Chen (2000)</b>	Serial	(s,nQ)	Optimal	
<b>Diks and De Kok (1999)</b>	Divergent	(R,S)	Heuristic	
<b>De Kok and Visschers (1999)</b>	Convergent	Adapted (R,S)	Heuristic	General convergent systems
<b>Dogru et al. (2008)</b>	Serial	(R,s,Q)	Optimal	
<b>(II) Synchronized Base Stock (SBS) policies</b>				
<b>De Kok and Fransoo (2003), De Kok et al. (2005)</b>	Convergent	SBS	Heuristic	General network
<b>Other policy:</b>				
<b>Boulaksil et al. (2009)</b>				Deterministic math programming based on APS
<b>(III) Guaranteed Service Time approach</b>				
<b>Graves and Willems (2000),</b>	Stationary	(R,S)	Demand forecast uncertainty	
<b>Minner (1997), Inderfurth and Minner (1998)</b>	Stationary	(R,S)	Demand forecast uncertainty	Normally distributed demand; alpha and gamma service level
<b>Graves and Willems (2002)</b>	Non-stationary	(R,S)	Demand forecast uncertainty	
<b>Humair and Willems (2006)</b>	Stationary	(R,S)	Demand forecast uncertainty	Clusters of commonality
<b>Sitompul and Aghezzaf (2006)</b>	Stationary	(R,S)	Demand forecast uncertainty	Included capacity restrictions by tabulated correction factor
<b>Schoenmeyr and Graves (2009)</b>	Stationary	(R,S)	Demand forecast uncertainty	Evolving forecasts for pure assembly systems
<b>Humair and Willems (2011)</b>	Stationary	(R,S)	Demand forecast uncertainty	Variable stage times and non-nested review periods
<b>Humair et al. (2013)</b>				Qualitative logic for stochastic lead times of Humair and Willems (2011)

## Appendix L – Cause-and-Effect diagram

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Although the project motivation included the problem area, a feasible and high impact root problem needed to be identified by means of a cause-and-effect diagram. Ideally, the identified cause is in the middle of the cause-and-effect diagram, because real root causes, such as budget or organizational behavior, are hard to change in a short time.

On the highest level, LSC searches for the optimal trade-off between the amount of locked working capital in safety stocks and risk exposure. High locked working capital increases the inventory holding costs and can increase the scrapping costs due to a limited shelf life and product changes. Low locked working capital can lead to backorders or even lost sales. **Although the two branches in Figure 30 are almost similar, causes that are specific for a too high risk exposure are underlined.**

On a lower level in the cause-and-effect diagram, the amount of safety stock is not only determined by the risk management methodology, but also by the subsequent communication to and acceptance by SC GER and the capacities, supply availabilities and production campaigns. Those sub branches are shortly discussed below:

1. **Risk management methodology:** The risk management methodology consists of the “risk selection process” and the subsequent calculation of the safety stocks. When, for example, the probabilities and the impact are overestimated, the safety stock will be too high. It is hard to estimate probabilities and impact, when risks are unknown. Alternatively, the risk selection process can also go wrong, because of behavioral or organizational processes. For example, when the team is not multidisciplinary and/or the involved persons are risk averse.

When the risks are selected, the right safety stock levels need to be determined. When the safety stock method does, for example, only take into account demand uncertainties and no supply-side uncertainties, the safety stock will not be correct. Also, the level of aggregation (single-echelon vs multi-echelon) determines the correctness of the safety stock calculation.

2. **Alignment SC GER:** Subsequently, the safety stock outcomes need to be communicated and aligned with SC GER. The environment changes continuously and the risk management workshop is currently scheduled once a year. Moreover, corrective actions require coordination and cost time to implement. Finally, risk-averse people take more rigorous actions than were communicated and vice versa.
3. **Production SC GER:** Finally, when SC GER receives the information, the safety stock level needs to be produced and “put aside”. However, there is already a planned production schedule with necessary production campaigns. In addition, it can happen that there is a supply unavailability of components.
4. **Lack of SC collaboration:** When more collaboration in the supply chain takes place, more information can be shared. This reduces amplifications and reduces the required safety stock.

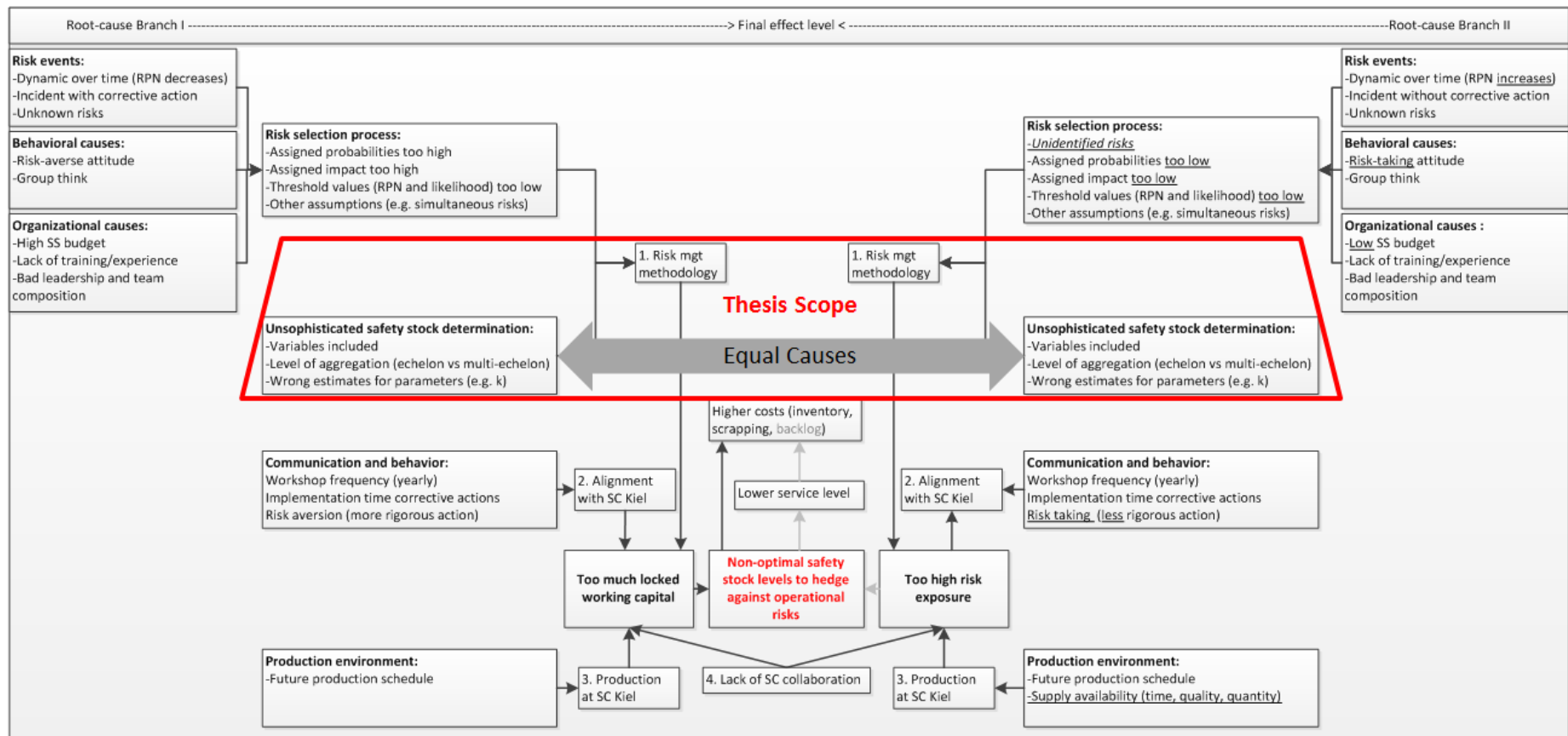


Figure 30, Cause-and-Effect Diagram

Note: Although the two branches in Figure 30 are roughly similar, causes that are specific for a too high risk exposure are underlined.

## Appendix M - Graphical Overview of Llamasoft's and ChainScope's Input Parameters

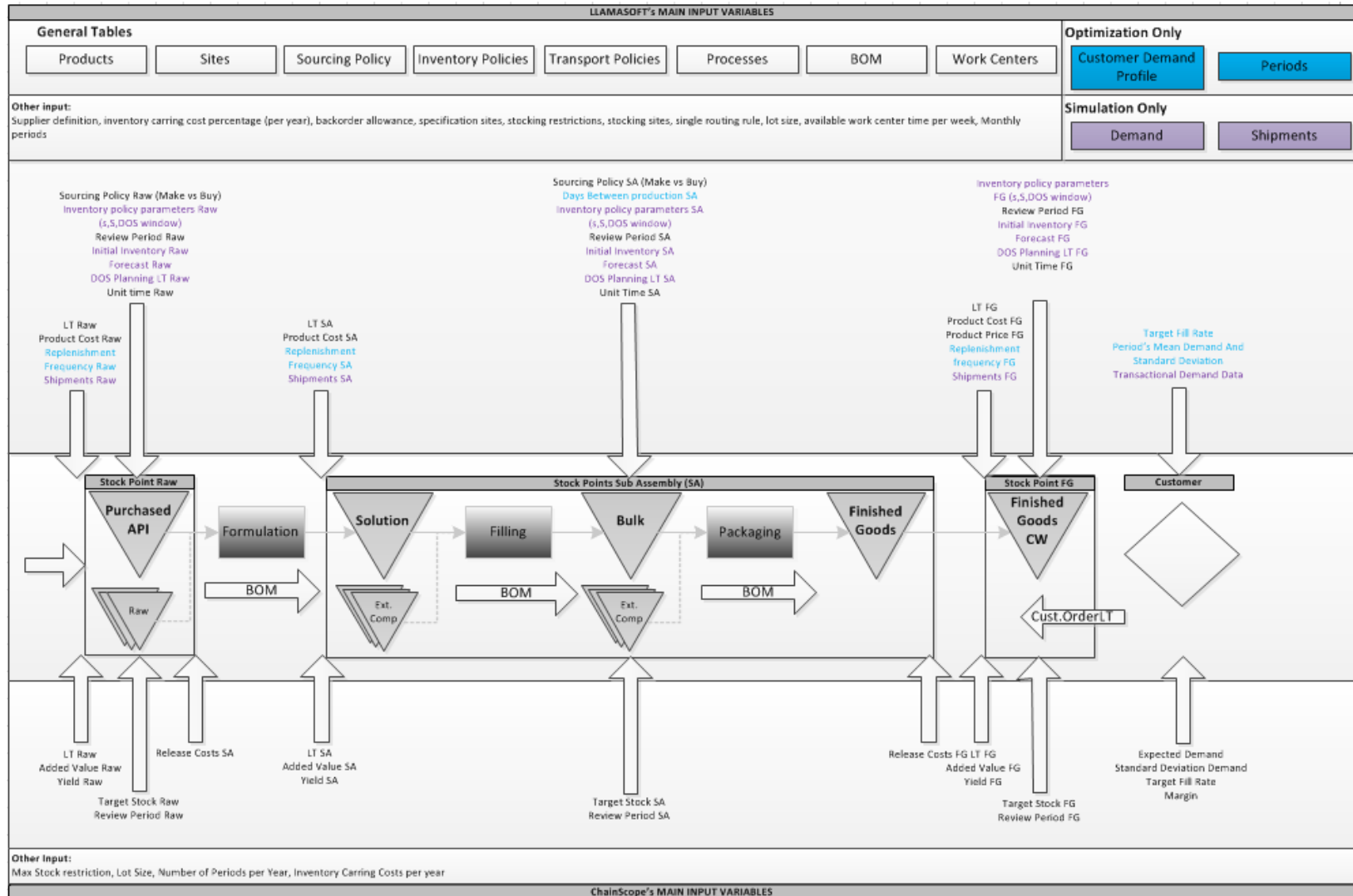


Figure 31, Overview of Llamasoft's and ChainScope's Input - Adapted from: (De Kok, 2008)

## Appendix N - Artificial Hierarchy in ChainScope

Assume that:  $(L_f, L_S, L_{SC}, L_C) = (1, 1, 2, 4)$ :

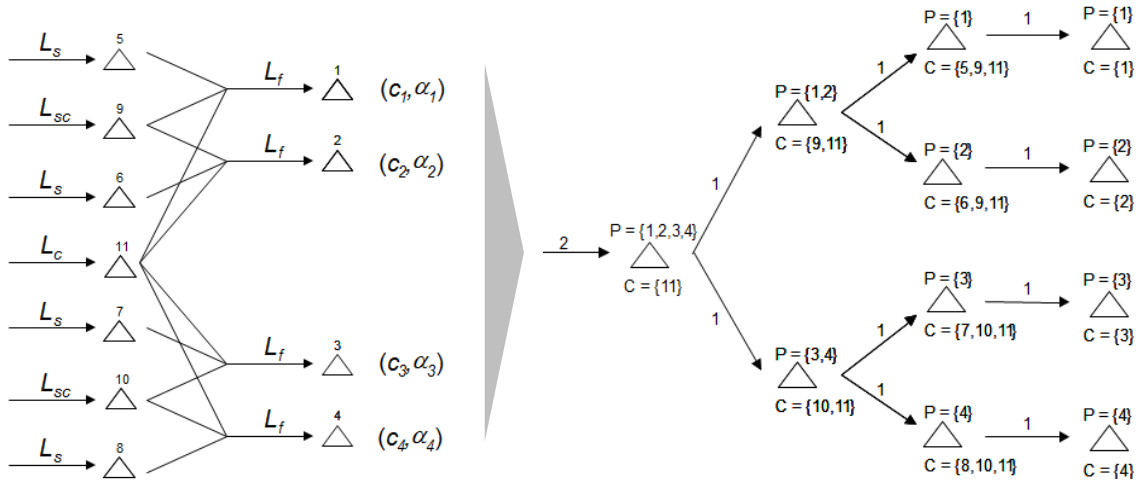


Figure 32, Artificial Hierarchy based on Lead Times and BOM - (De Kok, 2011, pp. 18,19)

## Appendix O - Concave Safety Stock Optimization Objective Function

SB: Safety Stock ("Sicherheitsbestand")

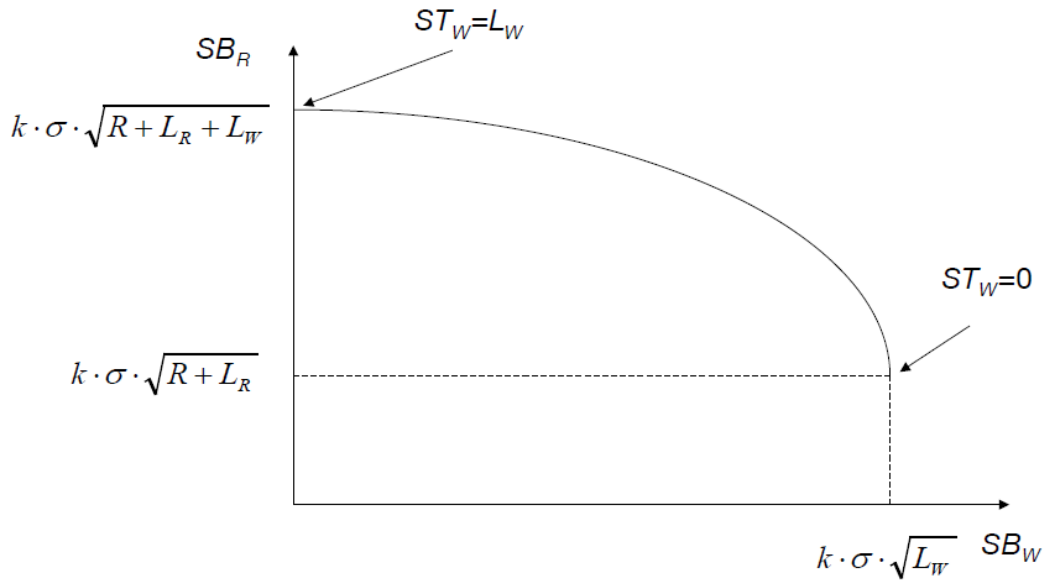


Figure 33, Concave Safety Stock Optimization Objective Function - (Minner, 2015, p. 50)

## Appendix P - Llamasoft's Safety Stock Optimization Heuristics

Threshold	Statistics used	Default Value	Minimum Value
Demand Frequency	Demand Count NOTE: Do not set this value less than 2. Demand Analysis will fail if there is insufficient Demand Frequency.	3	>= 2
Intermittency	Inter-Demand Interval Mean	1.32	>= 1
Dispersion	Non-Zero Demand CV2	0.49	> 0
Outlier	Non-Zero Demand Std Dev	10	> 0
Variability	Non-Zero Demand Std Dev	4	> 0
Clumpiness	Non-Zero Demand Std Dev	0.1	> 0

Figure 34, Threshold Values - (Llamasoft, 2015)

Demand Class	LTD Distribution	Inventory Policy
Extremely Slow	N/A	N/A
Smooth	Normal	R,Q
Erratic	Mixture of Distributions	s,S
Slow-LowVariable (batch size = 1)	Poisson/Mixture of Distributions	Base Stock
Slow-LowVariable (batch size > 1)	Poisson/Mixture of Distributions	R,Q
Slow-HighlyVariable	Poisson/Mixture of Distributions	s,S
Lumpy (batch size = 1)	Negative Binomial	T,S
Lumpy (batch size > 1)	Negative Binomial	R,Q
Extremely Small	N/A	N/A
Extremely Variable	Depends on the original class	Depends on the original class

Figure 35, Lead Time Distributions and Inventory Policies per Demand Class – (Llamasoft, 2015)

## Appendix Q - GS Coverage Calculation and Safety Stock Curve

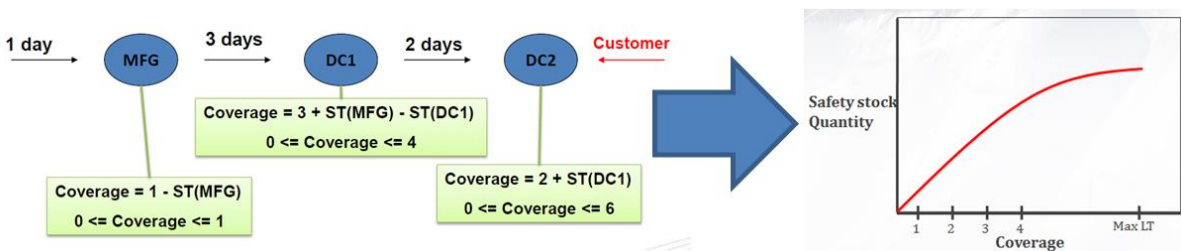


Figure 36, GS Coverage Calculation and Safety Stock Curve –Adapted from: (Llamasoft, 2015)

## Appendix R - Simulation Results for 28 Finished Goods

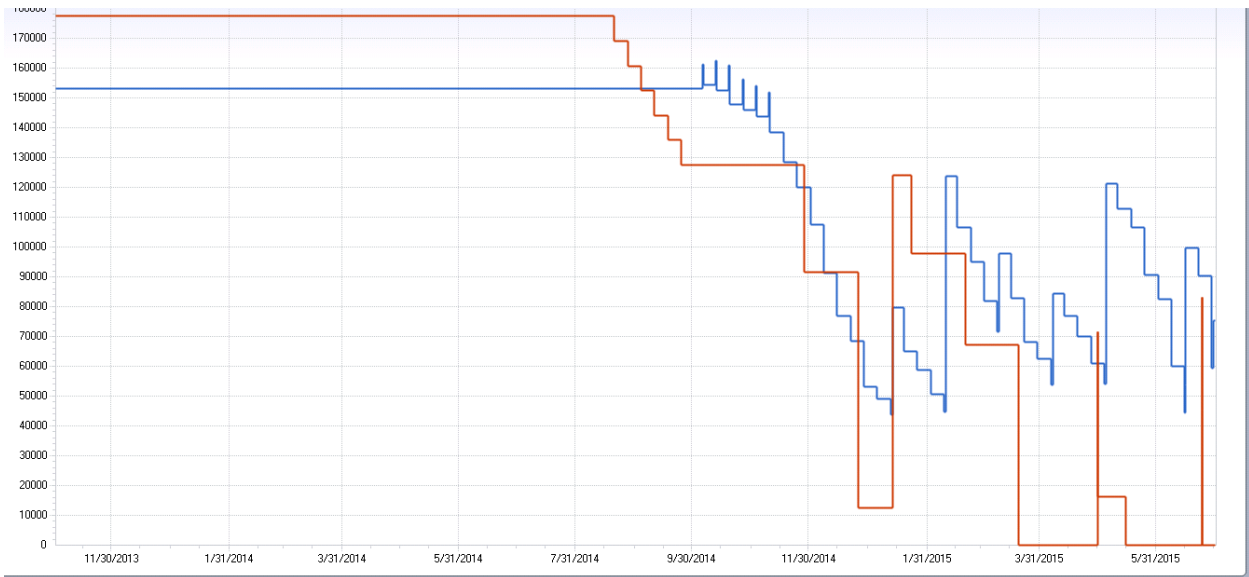


Figure 37, Simulation Results with all 28 FGs

Explanation: The **red line** represents the inventory for PRODUCT XX at SC GER. The **blue line** represents the inventory level at the country warehouse (CW).



## Appendix S - LLamasoft's Optimized Inventory in ChainScope

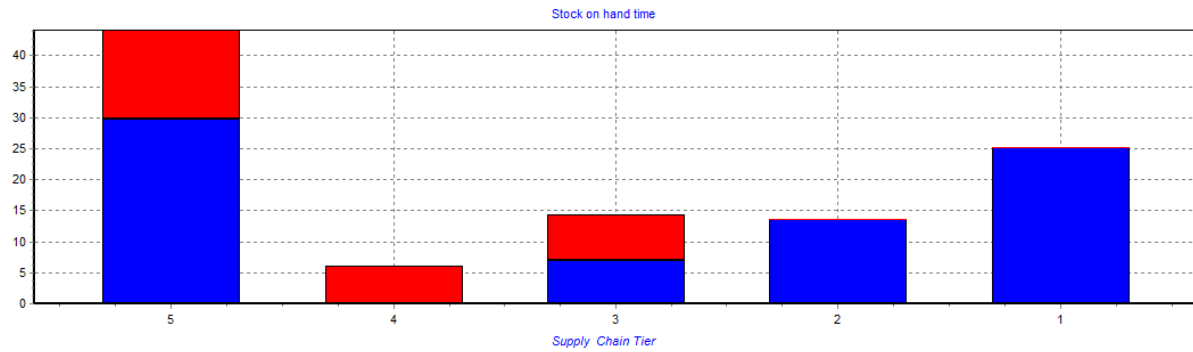


Figure 38, LLamasoft's Optimized Inventory Levels in ChainScope (57.5%)

## Appendix T - Graphical Overview of Theoretical Actual Safety Stock

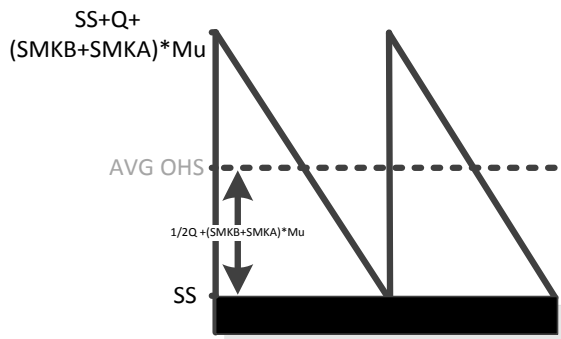


Figure 39, Graphical Overview of Derived Actual Safety Stocks

## Appendix U - Scenario Outcomes in SS DOS for ChainScope, LLamasoft and LSC Method

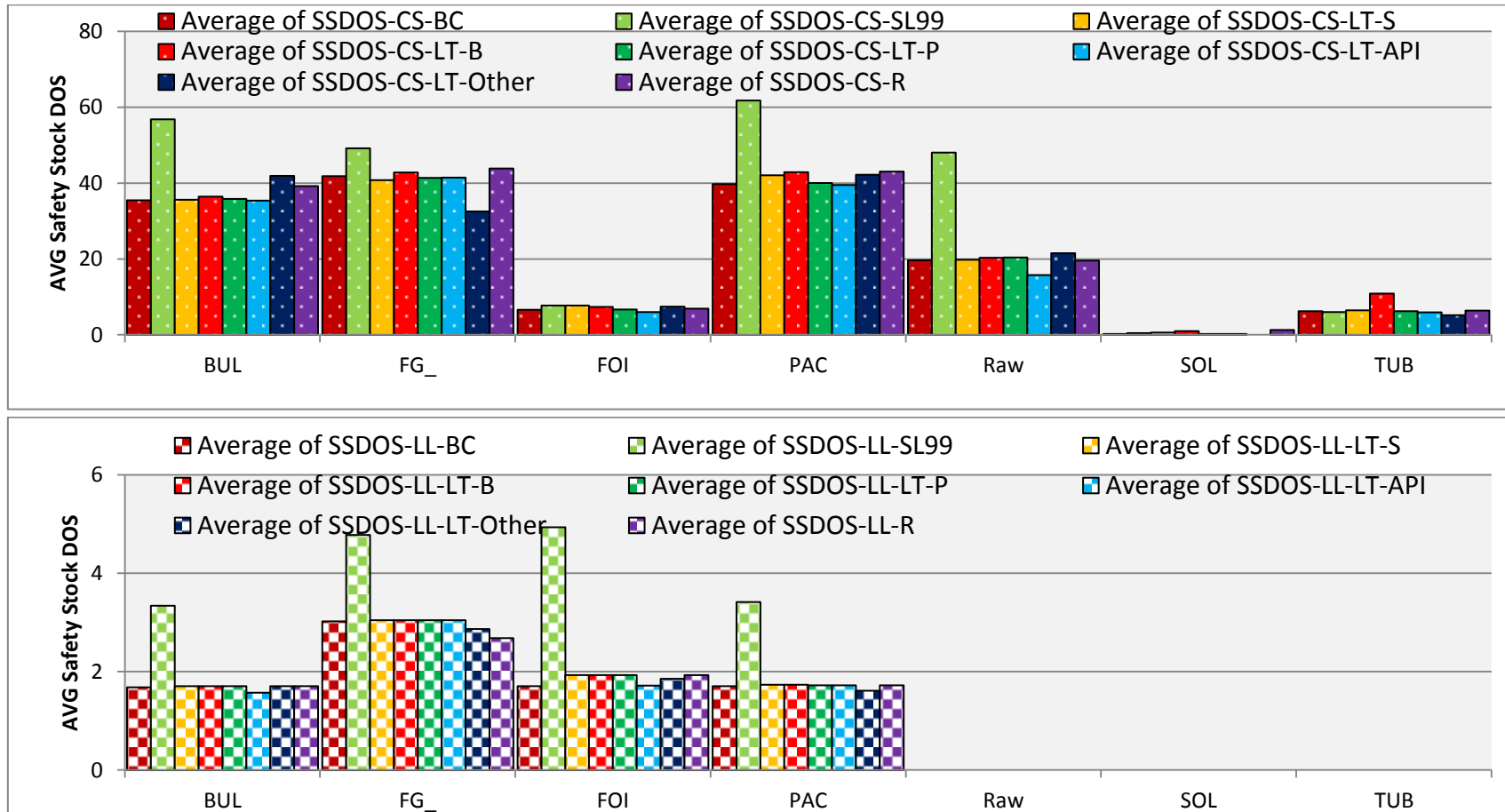


Figure 40, Scenario Outcomes for ChainScope (CS) and LLamasoft (LL)

**Explanation:** “SS DOS” indicates the safety stock days of supply measure. “CS” refers to the ChainScope. “LL” refers to LLamasoft. “BC” refers to Base Case. “SL99” refers to a 99% service level. “LT” indicates a 10% lead time reduction and “B”, “S”, “P”, “API”, “Other” indicate the stage: BULK, SOL, PACKAGING FG, API and All other external items. “R” refers to a 50% review period decrease.

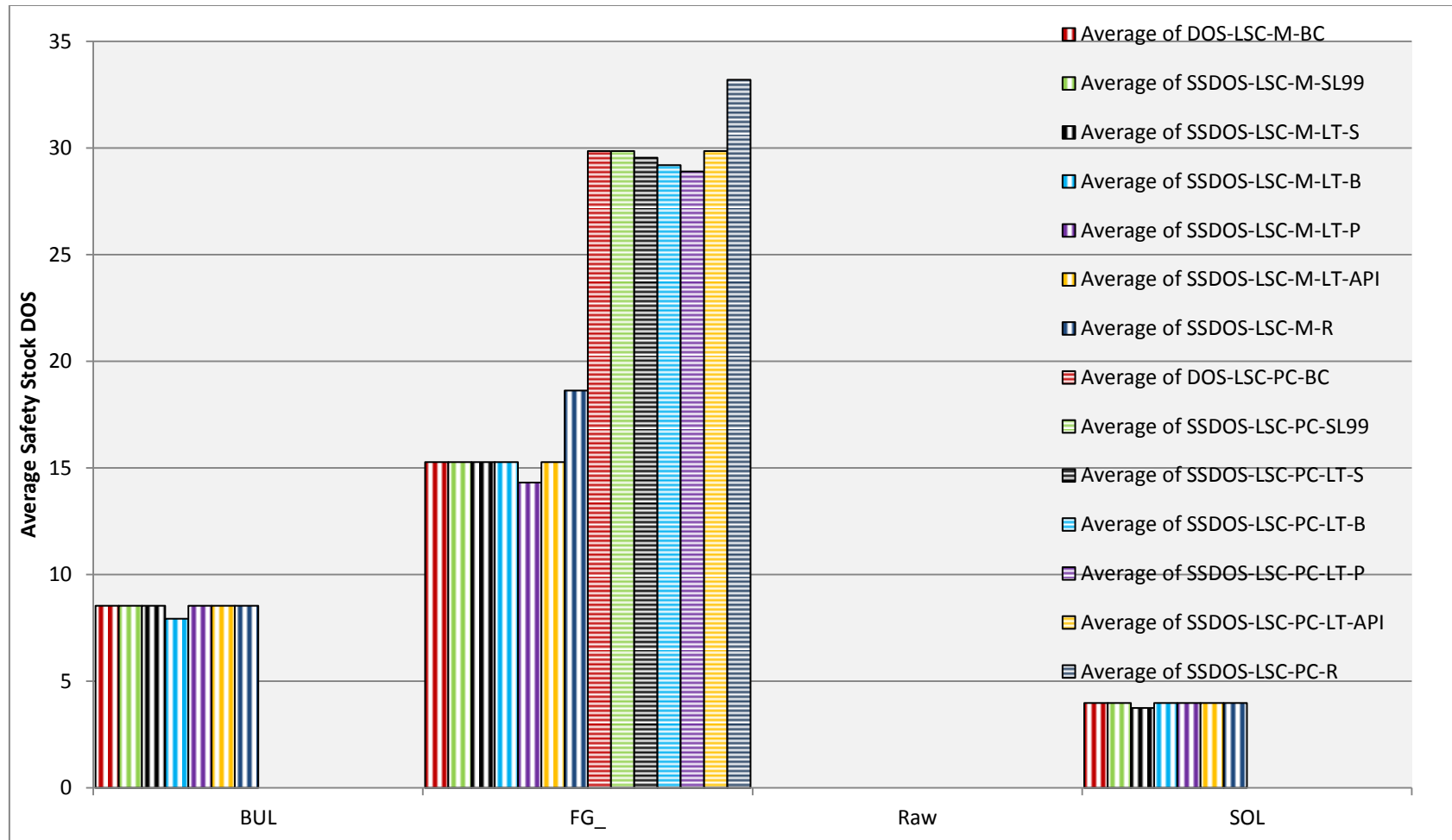


Figure 41, Scenario Outcomes for both LSC's Methods

**Explanation:** "SS DOS" indicates the safety stock days of supply measure. "LSC-M" refers to the regular LSC Method. "LSC-PC" refers to the regular method after Pipeline Controller improvements. "BC" refers to Base Case. "SL99" refers to a 99% service level. "LT" indicates a 10% lead time reduction and "B", "S", "P", "API" indicate the stage: BULK, SOL, PACKAGING FG or API. "R" refers to a 50% review period decrease.

## Appendix V - LLamasoft's Density Function

The better-fitting curves made possible by AI+IO technology result in right-sized inventory.

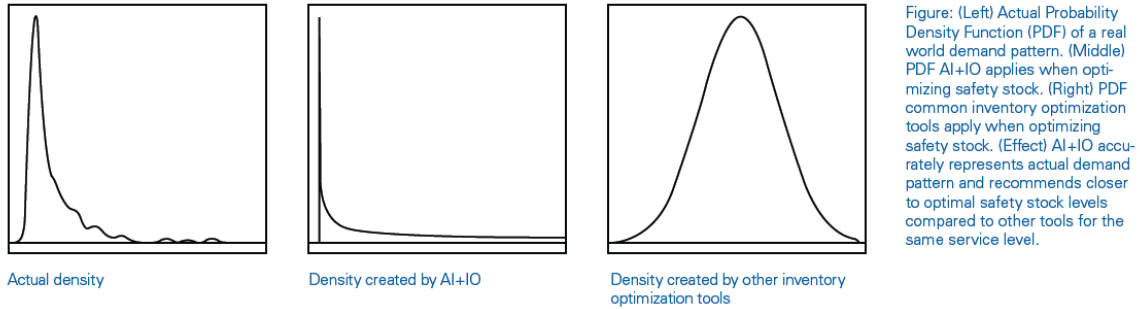


Figure 42, LLamasoft's Density Function Estimation - (LLamasoft, 2015)

## Appendix W - Stability of Coefficients of Variation over Multiple Years

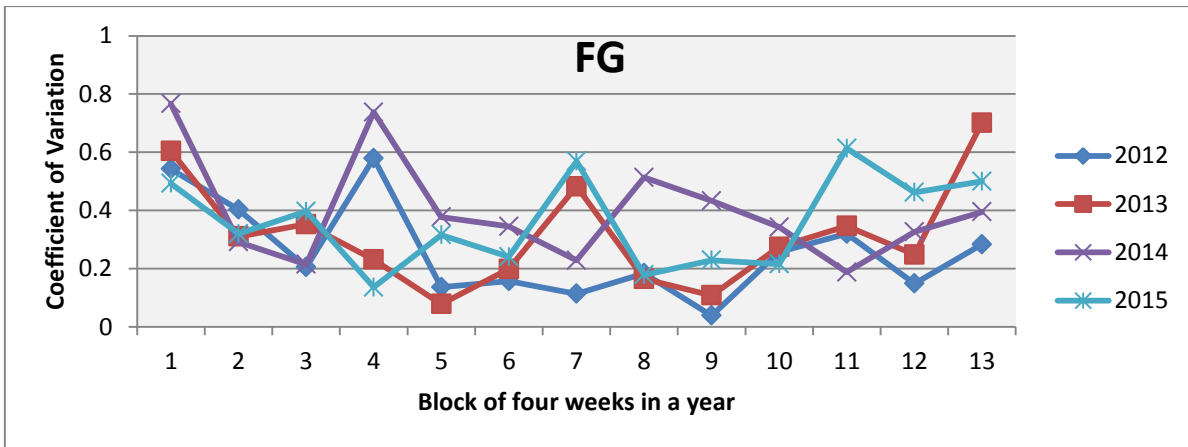


Figure 43, Overview of a Product's Coefficient of Variation