Eindhoven University of Technology

MASTER

Multi-echelon inventory analysis
a case study of setting inventory targets and assessing the impact of uncertainty factors

Alatas, G.

Award date:
2017

Link to publication

Disclaimer
This document contains a student thesis (bachelor's or master's), as authored by a student at Eindhoven University of Technology. Student theses are made available in the TU/e repository upon obtaining the required degree. The grade received is not published on the document as presented in the repository. The required complexity or quality of research of student theses may vary by program, and the required minimum study period may vary in duration.

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 13. May. 2025

Eindhoven, 2017

Multi-echelon inventory analysis: A case study of setting inventory targets and assessing the impact of uncertainty factors

by

Georgios Alatas

MSc Mechanical Engineering

Student identity number 0929268

in partial fulfilment of the requirements for the degree of

Master of Science
in Operations Management and Logistics

University Supervisors:
dr. B. Huang, TU/e, OPAC
Prof. dr. A.G. de Kok, TU/e, OPAC

Company Supervisor:
R. Gut, Hilti A.G., Head of Materials Management BU Supply/Plants

TUE. School of Industrial Engineering.

Series Master Theses Operations Management and Logistics

2017 OML

Subject headings: inventory target setting, multi-echelon, safety stock, influence factors, Supply Chain Management, single-echelon approximations, Synchronized Base Stock.

I. Abstract

Aiming to minimize the tied-up capital related to inventory, Hilti has developed an inventory target setting rule, applied on every type of stationary storage locations. In line with the existing rule, the targets are generated on warehouse level through a process that involves internal benchmarking within turnover clusters and other business related empiric approaches. Acknowledging that this method ignores critical influence factors relevant to inventory management, such as the service level or supply and demand uncertainties, this project deals with formal approaches on how to accurately set inventory targets in a multi-echelon environment facing uncertainties. Using models that provide adequate empirical validity, the current performance of the items in scope is evaluated, then their stock levels are optimized. Comparing the optimized with the existing stocks, the target increase or reduction is obtained. Furthermore, through a sensitivity analysis of the influence factors, insight is provided to the company regarding the extent of their impact. Finally, the case study is used to perform a quantitative comparison between two inventory management paradigms, multi-echelon and single-echelon approximations.

II. Management summary

Dealing with a vast item portfolio distributed by more than 110 warehouses, retail stores and a van fleet worldwide, Hilti requires a significant expenditure in inventory capital to provide the required service level to the customer. In agreement with the Champion 2020 strategy, the efficiency of the supply chains should be increased by improving the stockpoints performance and, at the same time, reducing the inventory levels. As a means to tackle this objective, Hilti developed an inventory target setting rule, which determines targets on a warehouse level for all Hilti stock locations. The fact that all targets generated by the Hilti rule are either negative or zero, implies that management assumes that the total stocks of each warehouse is either superfluous or properly set. The components of the target setting can be seen in Figure I.

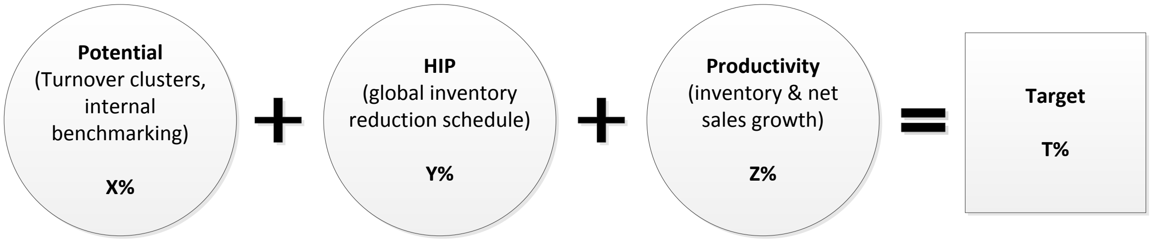


Figure 1.1 Hilti target setting components

In this thesis, we argue that rather than designing a reduction target setting process, it is more relevant to find the appropriate inventory management models and calculate the optimal inventory levels following formal and robust methodologies suggested by the existing literature, and calculate the optimal stock levels. Therefore, the assumption of superfluous inventories will be challenged and, instead, the proposition that inventories will be discussed. Any given inventory is comprised of the *Cycle Stock*, generated by lot sizes due to fixed order costs and packaging restrictions, and the *Safety Stock,* which buffers against the supply and demand uncertainties a supply chain faces. Given the stakeholders wish not to elaborate on the lot sizes, the focus of this study shifts upon the safety stock levels and how accurately they are calculated.

As revealed by the AS-IS analysis, large number of SKUs have their safety stock levels calculated using fixed coverage period methods. This also applies to items which are going through their maturity phase of their life-cycle, meaning that plenty of data are available, enabling statistical calculations over the demand and the lead time. Hence, safety stock levels are calculated without considering critical influence factors of the inventory, such as the demand and lead time deviations. Additionally, a significant portion of the safety stock is calculated without being tied to the performance target. The reason for that is that Hilti currently determines the safety stocks through a rather loosely structured range of calculation methods, which are variations of typical safety stock calculations methods seen in literature. As a matter of fact, without specific guidelines on which calculation method should be used on each application, it is common for employees to set safety stock levels based on intuition. The charts in Figure II-2 show that out of 86% of the SKUs of a central warehouse, for which planning is performed and safety stocks are maintained, 42% of the safety stock levels are calculated ignoring the service level and supply and demand uncertainties, while only 30% considers all of them.

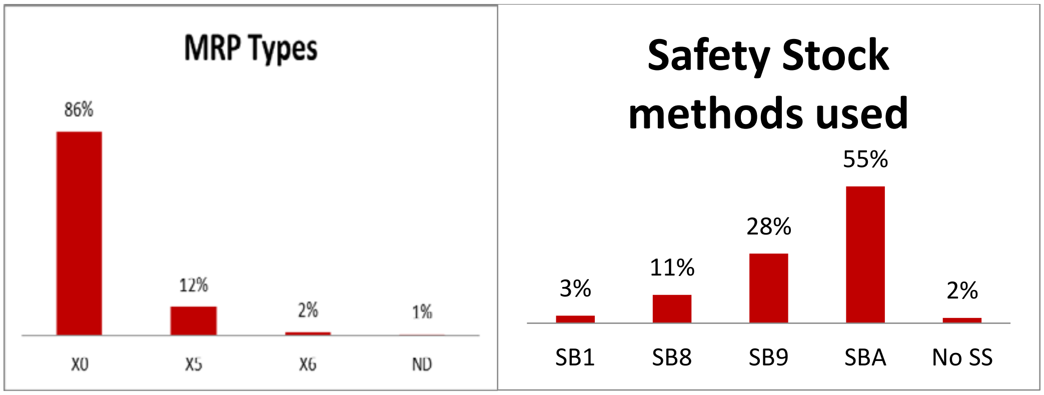


Figure 1.2 Percentage of planned SKUs and allocation of safety stock calculation methods

It was found that the inventory modelling approach that yields valid results and simulates the real-life operations with accuracy is the *Stochastic Service Modelling (SSM) with single-echelon approximations*. Evaluating the performance of the supply chains, it was shown that theoretical performance of the stockpoints was in many cases significantly higher or lower than the ambition target service level of 98%. Thus, the proposition that inventories are not superfluous, but inaccurate, was verified. Furthermore, the subsequent optimization of the stock levels revealed the correct inventory targets by comparing the optimal to the existing levels. The evaluation results can be seen in Table 1.

Table 1 Actual and evaluated performance of the stockpoints

Modeled **Actual**	**< 95%**	**95-98.5%**	**>98.5%**
< 95%	0980		
95-98.5%	6004, 4400	6000, 6135, 6140, 6805, 6815, 2100, 7500, 8110, 8150	0900, 8120, 8130
>98.5%	0550, 2600	6134, 3300, 8180	6120, 6145, 6150, 6160, 6820, 0506, 8140, 9150

With respect to the inventory influence factors, several optimization scenarios were created to provide insight on the sensitivity of the stock levels on them, along with the total impact of the factors on the inventory. The analysis showed that the largest impact on the stock levels is originating from the demand uncertainty. The lead time variability has also a significant effect and should not be neglected. In fact, the effect of the two uncertainty factors in the Power Tool supply chain is almost identical. Finally, the sensitivity analysis of the target service level provided a quantitative example of the radical increase in the required inventory investment when the target approaches levels close to 100%. An example of the influence factors impact on the Anchor supply chain can be seen in Figure 1.3.

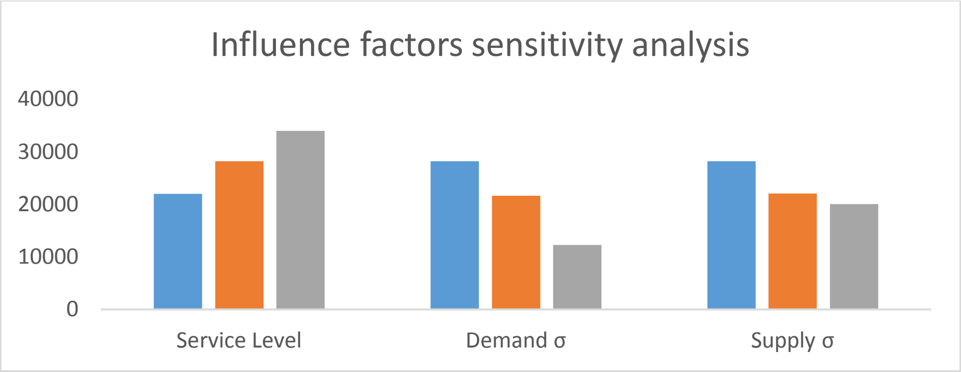
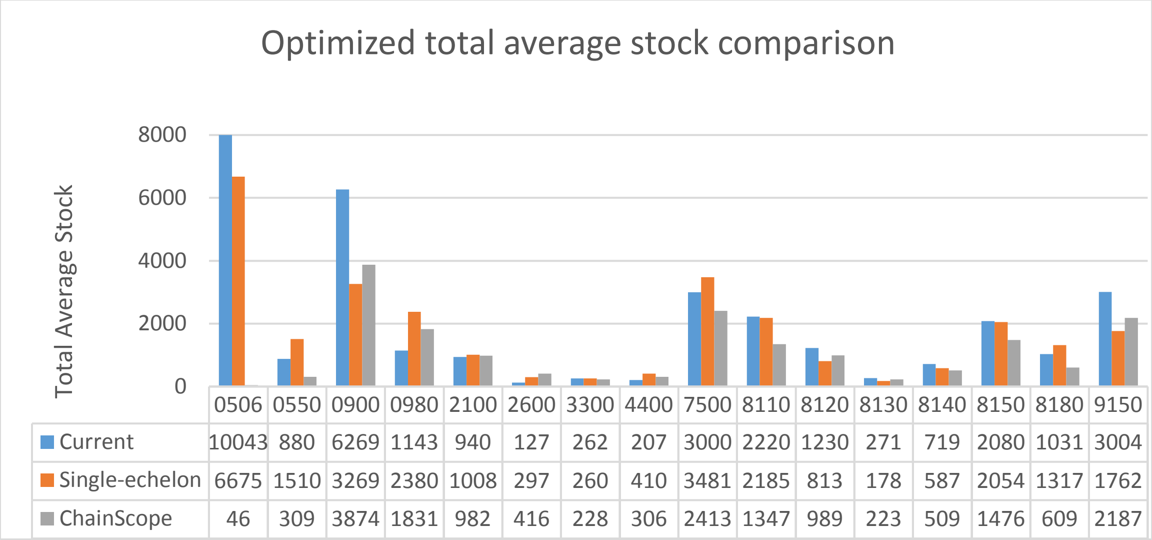


Figure 1.3 Sensitivity analysis of Anchor SC influence factors

The contribution of this master thesis to literature comes in the form of providing a case study where the single-echelon approximation approach of managing inventories in a multi-echelon environment is compared to multi-echelon control concept, namely the Synchronized Base Stock (SBS) technique. The outcome clearly points towards the higher efficiency of SBS. The advanced control concept of the SBS where all the stockpoints are simultaneously optimized and the physical stock is allocated according to information from the entire supply chain, is proved to be superior over the easy-to-implement single-echelon approximation approach. Concluding, Hilti is strongly recommended to consider the adoption of a multi-echelon inventory control concept for managing its supply chain operations. Results from the Anchor supply chain can be seen in Figure 1.4.



	0506	0550	0900	0980	2100	2600	3300	4400	7500	8110	8120	8130	8140	8150	8180	9150
■ Current	10043	880	6269	1143	940	127	262	207	3000	2220	1230	271	719	2080	1031	3004
■ Single-echelon	6675	1510	3269	2380	1008	297	260	410	3481	2185	813	178	587	2054	1317	1762
■ ChainScope	46	309	3874	1831	982	416	228	306	2413	1347	989	223	509	1476	609	2187

Figure 1.4 Optimized total average stock comparison in Anchor supply chain

III.Preface

I could easily argue that this Master Thesis project has been one of the most challenging experiences of my life, both mentally and physically. Beginning in Eindhoven in 2016 till its completion in Austria in 2017, this project was carried out in 6 different apartments and 3 different countries. Quite impressive a score, one that I could never have thought of when I took it up. All in all, it was a huge learning process which ultimately allowed me to jump-start my career in the field of Logistics.

I would like to thank my first supervisor, Boray Huang, who helped me find this project, even though he had to deal with being new to the Technical University of Eindhoven and the Netherlands. Special thanks to my second supervisor, Ton de Kok, for his valuable feedback, insights and support in every turning point of the project. Our interaction might have been short, but your comments were always cherished. Despite ending up with more questions after our exchanges, eventually I realized that every time you were pointing me towards the right direction. Finally, my deep appreciation to Ralph Gut who not only managed me all during this period, with all its ups and downs, but also showed me how to act as a proper professional. Last but not least, a big thanks to Rüdiger Kübler for placing his trust on me, paving the way for our subsequent collaboration.

Most importantly, a HUGE thank you to my family for their continuous support. None of this would ever be possible without your contribution. Thank you for letting me develop into who I am today. Credits also to all my friends in Greece, the Netherlands and the Feldkirch gang.

George Alatas

May 2017

IV. Table of Contents

V. List of figures

VI. List of tables

1 Introduction

Chapter 1 outlines the company and its activities as a player in the global construction equipment industry. Section 1.1 outlines the research model and sets the framework to tackle the project objectives. Section 1.2 provides basic information of the company's development and current activities, along with key economic figures. Section 1.3 describes the supply chain and how it is managed.

1.1 Research model

Aiming to do research with both rigor and relevance, the research model of Mitroff et al. (1974) is used to provide the necessary framework. Mitroff's model describes four interrelated steps: conceptualization, modeling, model solving and implementation. Leading the research through these steps will allow for the problem the company faces to be tackled and also, extend the academic literature. The four steps of Mitroff's model are explained below.

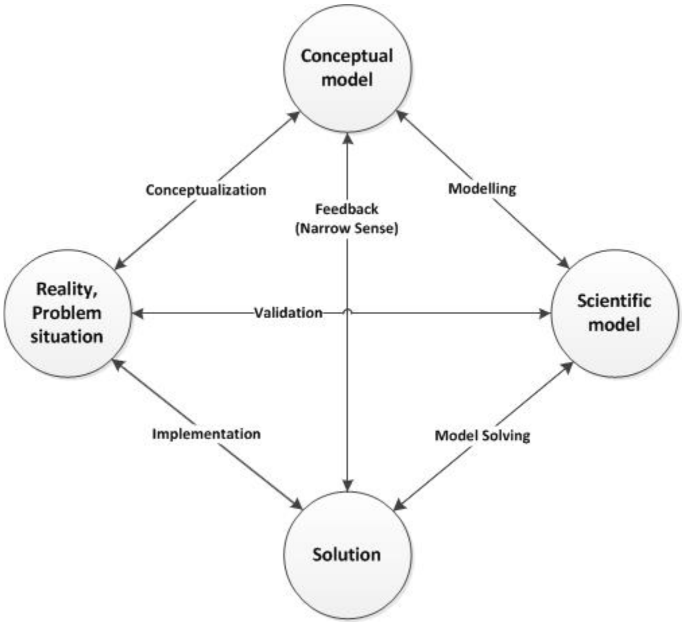


Figure 1.1 Research model by Mitroff et al. (1974)

1.1.1 Conceptualization

This is the first step of the research model. The conceptual model of the problem and system under consideration are developed. It is during this phase that the decision about which variables needs to be included in the model. The conceptual model description should use as much as possible concepts and terms that are accepted as standards published in the scientific operations management literature (Bertrand & Fransoo, 2002). The conceptual model of this Master Thesis consists of the determination of the necessary input parameters for the multi echelon safety stock model and the calculation of these parameters for the supply chains in scope. The conceptual model is thoroughly analyzed in chapter 5.

1.1.2 Modeling

The second phase is the specification of the scientific model of the problem under consideration. The scientific model has to be presented in formal, mathematical terms, such that either mathematical or numerical analysis is possible, or computer simulation can be carried out (Bertrand & Fransoo, 2002). According to Bertrand and Fransoo (2002), quantitative models are based on a set of variables that vary over a specific domain, while quantitative and causal relationships have been defined between these variables. The purpose of this phase is to develop the quantitative model. Central to the model is the definition of the variables and the interrelations between them. In the current research, the quantitative model is an inventory management optimization model, selected from the inventory management framework conducted in the conceptualization phase. Getting to further detail, the model describes the safety stock placement in a multi stage supply chain. The simulation will be utilized to determine the optimal safety stock allocation along the tiers of the supply chain and individual service levels of the stockpoints that collectively achieve the overall target.

The input parameters to be included in the model are described in chapter 5. The mathematical formulation of the quantitative model is presented in chapter 6. Afterwards, the necessary verification and validation of the model is carried out, effectively leading to the model solving phase.

1.1.3 Model solving

The model solving phase of the research requires the selection and use of a simulation software. Real-life supply chains with the size and complexities like those seen in the networks of Hilti, deem the formal mathematical analysis of the problem infeasible to be carried out. In such cases, computer simulations are often used instead of mathematical models (Bertrand & Fransoo, 2002). The particular solution method leads in general to results of inferior scientific quality comparing to using forma analysis, but, on the contrary, the quality of scientific relevance can be proved to be much higher.

The model solving phase of this research will lead to a number of optimization scenarios for each of the supply chains in scope. To begin with, a structural iterative process of optimization is developed to determine the optimal inventory levels that achieve the overall supply chain service level target under against minimal investment. An experimental design is created and the impact of the various influence factors on the fill rates and stock levels is determined. Finally, a sensitivity analysis is conducted to quantify and visualize inventory performance for a range of values of the influence factors. The optimization scenarios and the results generated are presented in chapter 7.

1.1.4 Implementation

The final phase of the research framework involves the implementation process of the results. However, the implementation phase of this Master Thesis will be restricted to providing quantitative insights and further recommendation to Hilti regarding the inventory target setting. Further discussion on the implementation is presented in Chapter 8.

1.2 Company description

1.2.1 Overview

In 1941, Martin and Eugene Hilti started a family enterprise, manufacturing mechanical components and commissioning parts and supplies, on a small scale, for the Swiss textile and German automotive industries, among few others. Their endeavor grew steadily since then, expanding its operations from a garage operated workshop to a market leader for professional fastening and demolition technology with global presence. Nowadays, known as HILTI AG (will be called HILTI in short from now on), the company is currently active in more than 120 countries worldwide, its human resource is about 23,000 employees and operates on its entire value chain including production, distribution and sales. HILTI provides a plethora of construction power tools and consumables, achieving a turnover of 4.4CHF billion and constantly increasing its market share, especially in the emerging markets where the higher growth figures can be spotted. HILTI offers full system solutions for the professionals in the construction and energy industry, with product range that includes Measuring Systems, Drilling and Demolition, Diamond Coring and Cutting, Cutting and Sanding, Screw Fastening Systems, Cordless Technology, Direct Fastening, Anchoring Systems, Firestop Systems, Installation Systems and Software. Ever increasing emphasis is given on innovation. In 2015, HILTI invested 5.5% of sales (240CHF million) in R&D projects, achieving the launch of 40 new products per year on average. Apart from manufacturing, HILTI also acts as a service provider, with Fleet Management (leasing service), Lifetime Service, Theft Protection System and Service Consultancy to name a few. HILTI, following a direct sales business model, generates the largest part of its turnover in Europe (not including East Europe) and America, with 47% and 24% total sales share respectively (according to the 2015 HILTI business report). A map showing global sales in 2015 (Figure 1.2) along with two pie charts depicting sales percentages over time (Figure 1.3) can be seen below.

Figure 1.2 Hilti global presence

HILTI at the moment is operating eight production plants around the globe, five for consumables and three for power tools manufacturing and assembly. One should not be mistaken, though, as the turnover from the external suppliers of HILTI is quadruple that of the production plants, 1CHF billion and 250CHF million, respectively. Production plants and suppliers either replenish the retailers directly or through the multi-stage distribution network of HILTI.

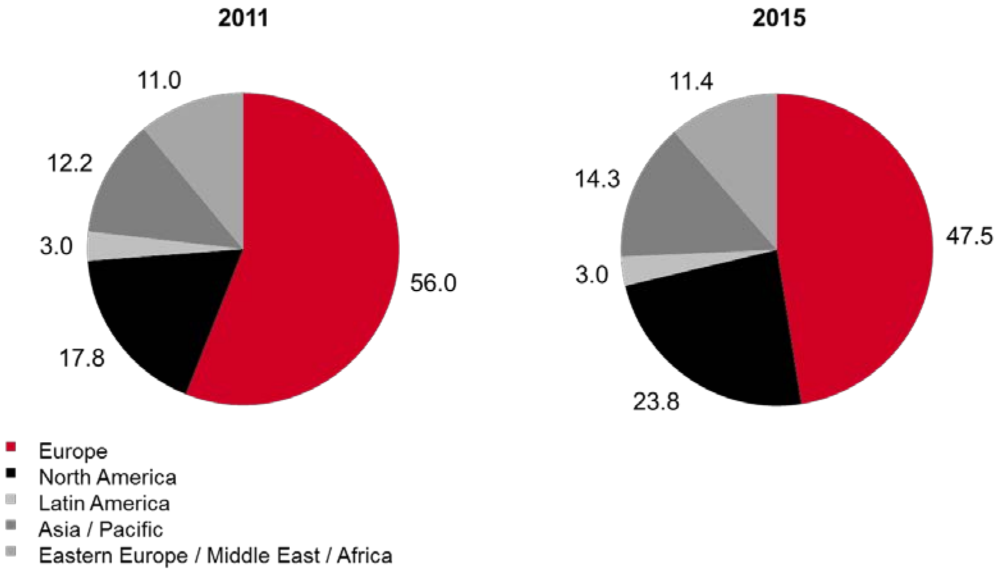


Figure 1.3 Global sales allocation

1.2.2 Organizational structure

The structure of HILTI is such that the customer is the most important unit of the company. The company's mission statement is "*We passionately create enthusiastic customers and build a better future*". To fulfill this mission, HILTI has created and developed its business structure aiming for efficient and productive governance, allowing cross-function communication, better monitoring and effective decision making. It is divided into four functional units, all located in Lichtenstein (HAG): Corporate Research & Technology, Business Units (BUs), Supply Chain and Corporate Units. An additional fifth functional unit entitled Market Organizations or Market Regions (MOs) exists which differs from the others as the MOs are separate legal entities tasked with marketing and sales responsibilities. Since 2003, the Martin Hilti Family Trust acts as the sole shareholder of the worldwide HILTI group, holding all the company's registered shares.

HILTI's management structure is a mixture of centralized and decentralized decision making. The centralized part comes in the form of the Business Unit philosophy, cross-functional entities tasked with managing the different business functions of the company across the globe. These Business Units are BU Anchors, BU Direct Fastening, BU Installation, BU Chemicals, BU Power Tools & Accessories, BU Diamond Systems, BU Measuring and Global Logistics. The first five BUs are sub-divisions of one of the main Business Areas (BAs) of HILTI, Fastening & Protection (F&P), with the other one being the Electric Tools & Accessories (ET&A), including the other three. The Global Logistics department is similar with the rest of the BUs in terms of hierarchy and structure, however, it acts independently. Meanwhile, HILTI's worldwide operations call for decentralized decision making as well. The Sales and Marketing functions, along with their respective support functions, are geographically divided into the Europe & North America and Emerging markets. The division derives from the percentages of turnover that were shown above in Figure 1.3. This combination of centralized and decentralized decision making system, coupled with well-defined areas of responsibilities and boundaries, allows for effective information and material flow, collaboration between different business areas, monitoring and control.

1.2.3 Hilti Global Logistics

1.2.3.1 The department and the trinity

Global Logistics act as the link between production and sales, controlling the flows of materials and the inventory positioning in the supply chain network. The goal of the Global Logistics at HILTI is to fulfil customer's needs with the highest efficiency. To achieve this goal, the aim is always to reduce the Net Working Capital (NWC), delivering productivity growth, operate in the "fit for scalability" fashion, increase customer satisfaction by realizing reliability and service level goals and introducing new and improved and additional services. The Global Logistics department is an independent entity within the organization. Its operations are divided into three main areas: Warehouse Management, Transport Management and Materials Management.

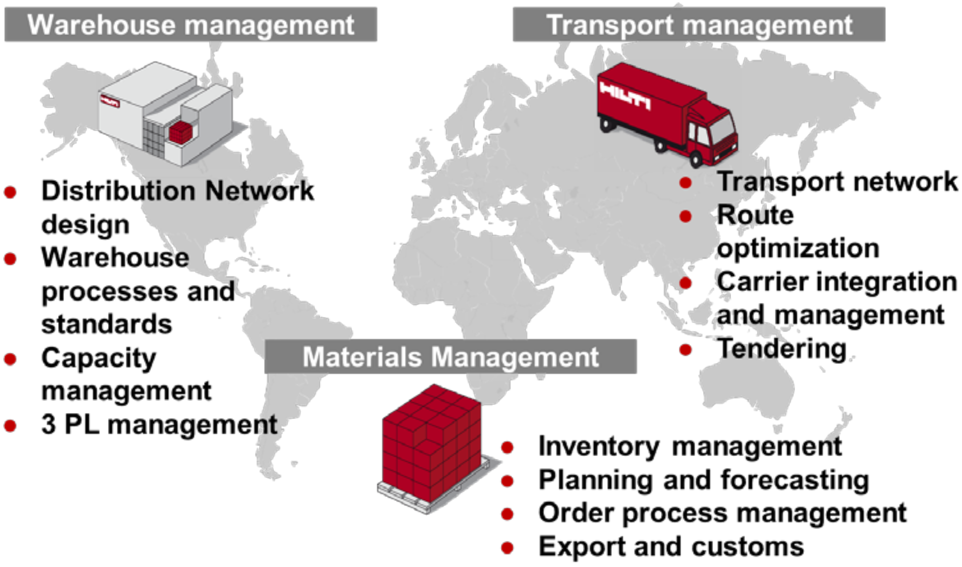


Figure 1.4 Hilti Global Logistics

Warehouse Management includes all the necessary functions and planning for the optimal performance of the warehouse network. On a strategic level, the design of the distribution network falls into this category. Market, capacity, costs, utilization and shipping data are collected and monitored on a regular basis to determine the optimal location, the capacity and whether to be owned and operated by HILTI for the inventory locations across the supply chain. One example of such network design planning was the closure of the Asia Logistics Center RDC, promoting direct replenishment of the warehouses lower in the stream. Apart from the network design, setting the standards and optimizing the warehouse operations and processes is a key responsibility. HILTI has observed that the lack of global standards on the main processes, such as the pick & pack and inbound/outbound handling can have a serious impact on delivery reliability, and thus, customer satisfaction.

Transport Management focuses on transportation and distribution processes. Strategic goals involve the optimization of the transport network by following global developments related to routes and shipping methods. On a tactical basis, experts are negotiating the tendering and contract terms with the 3PLs and shipping operators according to changes on order volume and delivery frequency. The renegotiation of the contract terms usually takes place two times per year. Carrier integration and management planning takes place both on tactical and operational level, ensuring optimal carrier utilization and routing, seeking to reduce transport costs while reducing lead time variability.

1.2.3.2 Global Logistics Materials Management

The third area of Global Logistics, Materials Management, is the most related to this project. Its functions involve inventory management, production planning and sales forecasting, order process management, the export and customs operations.

Managing the inventory levels is a delicate and multi-discipline task for a company dealing with large material volumes and sales orders. Adjustments have immediate impact on the customer satisfaction by affecting product availability and service level, but also on the company's finances, as well. With increased NWC, additional funds are occupied that could otherwise be used for investments, short term cash liquidity or free cash flows (Brealey, Myers, & Allen, 2011). Meanwhile, production of higher amounts of stock than needed, leads to larger quantities turning obsolete in the future and thus, cutting potential from profit.

In order to maintain high product availability in the most efficient way, it is important for HILTI to not only run, but also constantly improve, demand forecasting and supply planning operations. Both are conducted through APO. Forecasting involves all cross-department activities attempting to predict incoming demand in the most accurate way. Planning enables the information transfer from the lower to the upper stages of the supply chain and makes sure that materials flow from the upper to the lower stages, so that HILTI's performance goals are met. Ultimately, demand from all planning levels is matched either by a planned production order, an external procurement order or an internal replenishment order. Forecast is done on Central Warehouse level and on corporate level for non-integrated markets.

Essential for demand forecasting is sales history collection. The sales data account for the total consumption of a product, both Sales Orders and Internal movements, which are stored in monthly "cubes" for aggregation. For increased accuracy, it is the confirmed quantity that is accounted, not the one originally requested by the customer. In each region, demand data are collected at the retailer stage and consolidated at the upper stage, where the forecast for the whole region along with the warehouse is done. In a sequential fashion, demand data of every stage, including the lower stages in their area of jurisdiction, is propagated and consolidated upstream, ending up in the Corporate Forecast taking place at the headquarters.

Demand forecasting as conducted by Hilti up to date, incorporates seasonality patterns for several SKUs for which data is available and furthermore, adjusts planning by also considering promotional activities. However, demand correlation between products is not yet regarded but its integration is in progress.

The Global Logistics department also includes experts on Export and Customs operations. The former are responsible for securing a smooth process flow form order entry to shipment completion from the headquarters, and maintaining constant communication flow between all parties involved. Tasks involve various processes in preparing and modifying order processes and order status inquiries, transport handling, after market and occasional special processes. The Customs team objective is to optimize customs cost while complying with the legal framework. Key processes include provision of custom processes and data for cross-border transports, adequate documentation and argumentation to manage Country of Origin and fulfilment of international foreign trade requirements to tactically enable and support HILTI Business and avoid unnecessary risks.

1.3 Supply chain description

Chapter 2 presents the current setup of the supply chain of Hilti. Section 3.1 and section 3.2 outline the supply chain starting from the most upstream towards its most downstream stage. Section 3.3 explains how the chain is controlled and coordinated. Section 3.4 deals with product classifications and inventory types. Finally, section 3.5 describes the uncertainty factors faced by the company.

1.3.1 The supply chain from end to end

HILTI recognized this importance soon enough and over the years developed a highly competitive supply chain network. Supply Chain operations can be spotted spanning across its whole organizational structure, from involving members of the Executive Board responsible for strategic decisions, throughout the BUs with sourcing and manufacturing and the Supply Chain unit with the Global Logistics, to the decision centers at the MOs with sourcing and logistics.

The Supply network of HILTI is a multi-echelon chain reaching a maximum of 5 stages per the region. From up to downstream these stages are:

1. the Production Plants (PPs) and Suppliers
2. the HAG WH headquarters warehouses
3. the MO Regional Distribution Centers (RDCs) or Central Warehouses (CWs)
4. the Distribution Centers (DCs)
5. the HILTI Centers (HCs), the Pro Shops (PSs), the van fleet (V) and Territory Salesmen (TS), and the Repair Centers (RCs).

Customer demand is served directly from stages 3, 4 and 5, with the latter representing only the 20% of the demand. The RDCs, CWs and DCs see the largest part of demand through on site visits by customers, phone and online orders. It should be noticed, that, even though the DCs are also replenishing the downstream stage, they are considered retailers as well.

As expected, HILTI's distribution process is complex, accounting for more than 40 different types of goods issue for inbound and outbound orders. The reason behind this is optimizations which consider all kind of information and details, such as various shipping and customs costs per geographic regions, order lead times and container utilization given the shipping method, replenishment policies based on which stage of the supply chain an inventory location represents and so on. Nevertheless, for the sake of simplicity, the above procedures can be grouped into three major categories of material flow to the MOs: 1. directly from a production plant or allied supplier, 2. Through the HAG main warehouses and logistic centers in the Rhine valley or 3. Via one of the two Transshipping Points, one in the Rhine valley and one in Shanghai, where replenishment orders are consolidated before shipping. Figure 1.5 depicts a schematic representation of the material flow in the supply network. Emphasis is given to the difference between Make-to-Stock (MTS) and Make-to-Order (MTO) products. Products following the MTS policy are nearly every SKU that falls into the category of consumables or spare parts and are produced in-house. For these SKUs, production planning generates a stock of finished goods (FG) at the production site that is subsequently pushed directly to the MOs or through the HQ warehouse. MTO products are either power tools that, according to forecast, are assembled and shipped without being stored, or chemicals and other items labeled as “dangerous goods”.

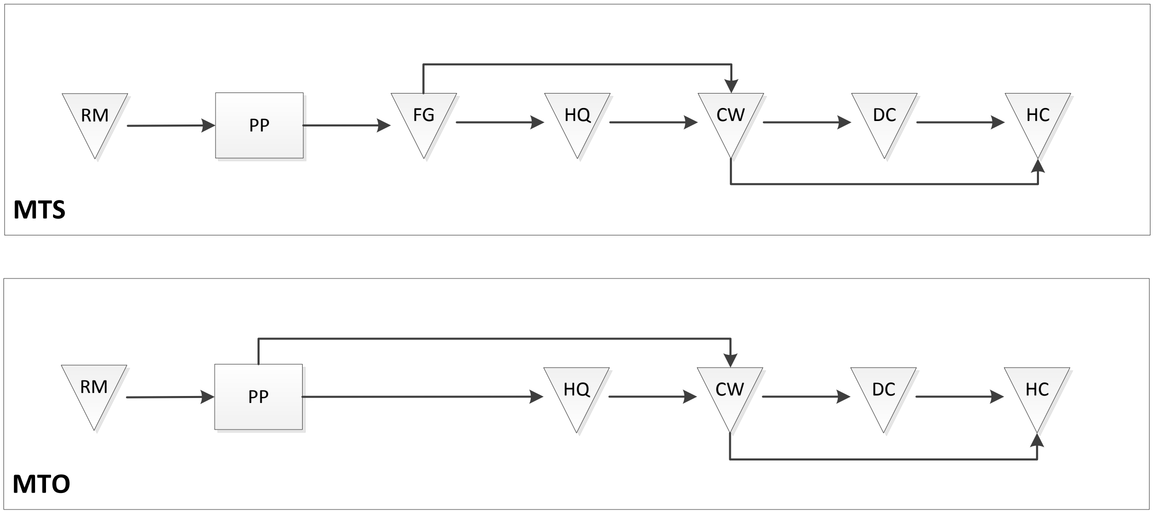


Figure 1.5 Material flows

1.3.2 The Supply Chain in numbers

Key figures indicating the size and extent of the supply chain operations are:

- ✓ 380 suppliers of raw materials
- ✓ 900 suppliers directly supplying the Central Warehouses and Distribution Centers
- ✓ 8 production plants
- ✓ 6 headquarters warehouses
- ✓ 80 MO Central Warehouses and Distribution Centers
- ✓ 120 Repair Centers
- ✓ 1500 HILTI Centers and Pro Shops
- ✓ 7000 vans and territory salesmen

It should be noted that HILTI does not operate itself all the inventory locations and, furthermore, owns even less. According to 2014 data, HILTI owns 20% of the total 110 warehouse locations globally and operates a 65% of them. The percentage of warehousing operations that is outsourced to third party logistics providers (3PL) is defined by previously developed network design strategy and currently, a consolidation plan is being implemented so that to reduce the amount of 3PLs.

The allocation of stock around the various inventory locations in HILTI's supply chain is roughly: 74% at CWs/DCs/RDCs, 16% at HCs/PSs and 9% in VAN. In regions where demand rate is constant or follows predictable patterns that comply with the forecasts, inventory is being held downstream, at the later stages of the supply chain to achieve better service level and delivery reliability. In other cases, inventory is pooled in upper stages of the stream, so that to avoid unnecessary overstocking and obsolescence generation due to demand volatility.

1.3.3 Supply chain control and coordination

Responsible for the coordination of production and replenishment processes are the Material Managers of the Global Logistics department in conjunction with Material Managers from the various BUs and MOs. The BUs provide run the materials planning for the raw materials procurement and the stock levels up to the stage of Central Warehouses in the MOs. The MOs side oversees material requirements from the Central Warehouses and downstream replenishment to the DCs, HCs, TSCs, RCs and moving/consignment stock. The commonality seen in the areas of responsibility between the two is established for better coordination and target setting.

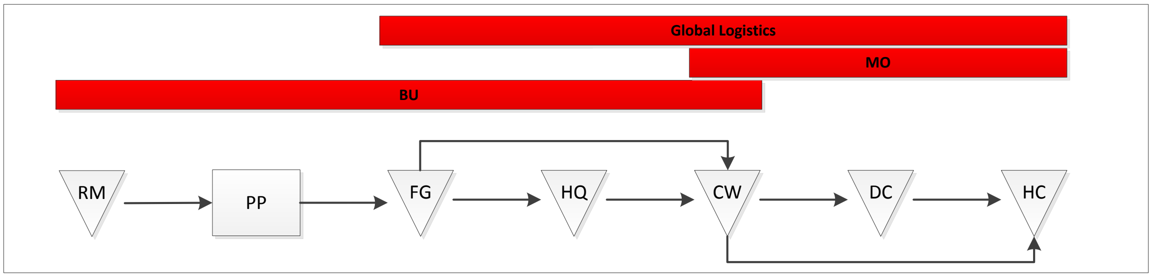


Figure 1.6 Inventory management responsibilities

The planning and control process for plants and warehouses is based on the MRP II process. The MRP II process generates *net requirements,* which are the actual amounts of each item needed each period. The *net requirement* considers the planned inventory on-hand, planned order receipts and planned order release, and calculates the quantity that needs to be ordered accordingly.

$$Net\ Requirement_t = OH_t + IT_t - D_t^{fc} - SS$$

$OH_t: planned\ on - hand\ inventory\ at\ period\ t$

$IT_t: planned\ inventory\ in\ transit\ at\ period\ t$

$D_t^{fc}: forecasted\ demand\ up\ to\ period\ t$

$SS: Safety\ Stock$

Hilti has two information systems working together: SAP-APO, an advanced planning and scheduling system (APS), and SAP-R/3, an execution system. Every weekend APO makes a long-term plan per item for the upcoming 18 months. Additionally, the long-term forecast is made on the highest level possible. For Hilti, this could be the total volume of a BU or in some cases on product family level. The current long horizon forecast per individual item leads to an unrealistic plan, because it is too detailed (Hopp & Spearman, 2008). APO also runs every night to make a short-term plan for the upcoming 12 weeks. This planning is based on item forecasts created by the MOs, the current stock and safety stock and the outstanding orders. This information is sent daily to the Production Plants and Distribution Centers, so that net requirements are generated and planned orders are created (van Wanrooij, 2012).

The lot sizes of the replenishment order quantities are fixed. The calculated quantity is derived from an adjusted Economic Order Quantity (EOQ) formula which considers the number of products per different packaging method (packet, carton, pallet layer, full pallet etc.), the MRP and the demand cluster type and is also truncated between minimum and maximum days of coverage values. The safety stock calculation methods are based on modified versions of standard formulas seen on literature and textbooks, or in other cases rules of thumb and will be explained in section 2.4.

1.3.4 Products and inventory

1.3.4.1 Product classification

Hilti has a vast product portfolio of more than a hundred thousand SKUs in total, covering an assortment of different product families like power tools, consumables and spare parts. For easier product management and control over the supply chain, all products are labeled according to profile types indicating their contribution to turnover (TABCD), order frequency (QRS) and order amount variability (UVW).

The TABCD profile indicates the contribution of the product to the total turnover. End-products are sorted in decreasing order, based on their turnover, and then the relative contribution per products is calculated and cumulated. The result is the following classification:

- T: *50% of total turnover*
- A: *30% of total turnover*
- B: *15% of total turnover*
- C: *4% of total turnover*
- D: *1% of total turnover*

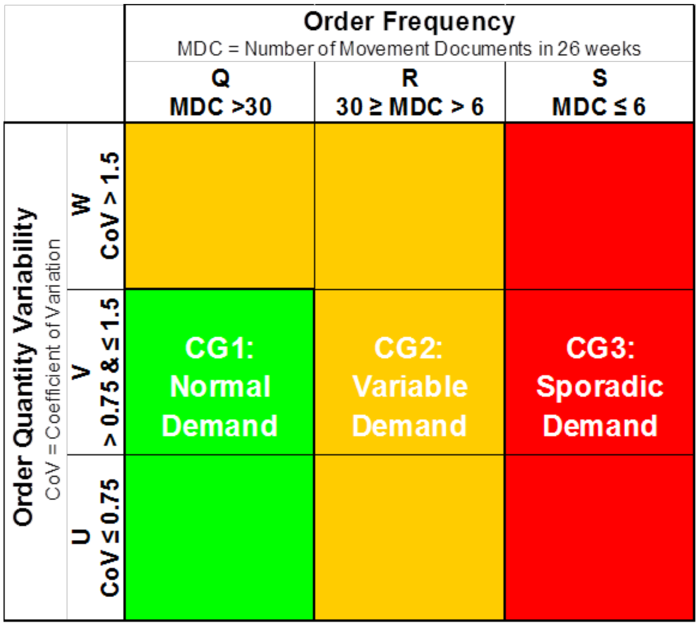
The QRS profile indicates the order frequency of a product by calculating the number of order lines per 26 weeks on global scale. Three categories are created:

- Q: *# order lines > 30*
- R: *6 ≤ # order lines ≤ 30*
- S: *# order lines ≤ 6*

The UVW profile indicates the order amount variability of a product by calculating the quantities' coefficient of variation. The coefficient of variation (CV) is defined as the standard deviation divided by the average demand, based on the global weekly demand over a period of 26 weeks. The following classes are formed:

- U: *CV ≤ 0.75*
- V: *0.75 ≤ CV ≤ 1.5*
- W: *CV > 1.5*

Based on the profile categories that were described above, the Global Logistics department has created a strategic segmentation map that sorts the end-products in demand clusters. These clusters are normal, variable and sporadic demand, as shown in Figure 1.7 Demand cluster matrix. A biannual consumption-based classification update ensures items remain classified as the right cluster group (van Wanrooij, 2012).



Order Quantity Variability CoV = Coefficient of Variation	Order Frequency MDC = Number of Movement Documents in 26 weeks Q MDC >30	R 30 ≥ MDC > 6	S MDC ≤ 6
W CoV > 1.5	🟨	🟨	🟥
V > 0.75 & ≤ 1.5	🟩 CG1: Normal Demand	🟨 CG2: Variable Demand	🟥 CG3: Sporadic Demand
U CoV ≤ 0.75	🟩	🟨	🟥

Figure 1.7 Demand cluster matrix

1.3.4.2 Inventory types

HILTI distinguishes its inventory into 3 types: cycle stock, safety stock and over stock. Cycle stock is the result of the common practice to produce in batches due to ordering and setup/fixed order costs. Reasons for batch replenishments are achieving economies of scale, quantity discounts in purchase price or freight cost and technological restrictions such as the fixed size of a processing tank. Cycle stock reflects the level of demand that HILTI expects to face during given lead/setup times.

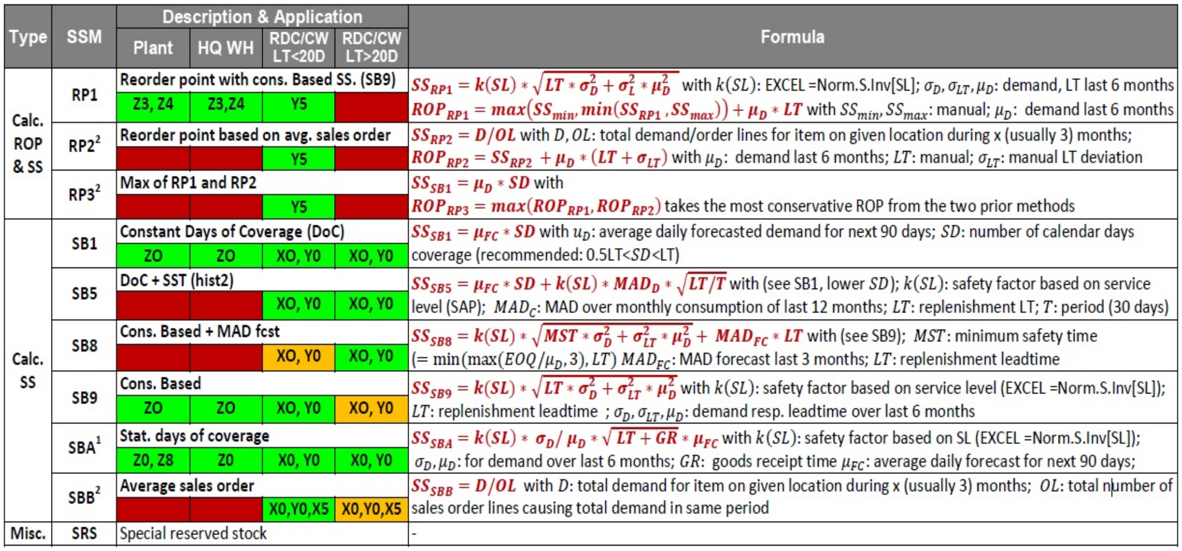
Given the uncertainties in supply and demand it is inevitable that a safety stock will be needed. Safety stock is the amount of inventory kept on hand, on the average, to allow for variations in demand and supply (Axsäter, 2015). The investment in safety stock is directly related to the desired service level and is of major importance in this master thesis project.

Over stock is the excess inventory that is generated due to over-forecasting, lot sizes, poor event management etc. High amounts of over stock along with poor inventory management often lead to high amounts of obsolescence and profit loss, considering the relative short life-cycles and the presence of cannibalization. Furthermore, despite fixed capacity not accounted as a restricting factor, significant amounts of over stock can prove detrimental to material flow and falsely raise discussions over investing in extra capacity. In essence, any inventory beyond the cycle stock and calculated safety stock, is overstock.

1.3.4.3 Safety stock calculation methods

Safety stock is kept for the majority of product types of Hilti, for which ensuring high service levels is important and the demand curve may show large deviations. Products that are made/produced/assembled to order, such as chemicals, are skipped from safety stock calculations. Influence factors that impact the safety stock levels are the level of demand and its variation, expected forecast errors, supply and delivery volatility, the level of service promised to the end customer, lead times, seasonality and the life cycle phase of the product. Safety stock calculations are a mix of literature based approaches with a few adjustments to tackle situational issues. The input data for the calculations can be statistical, forecast or order history, depending on the product and location. A list of the calculation methods can be seen in Table 2.

Table 2 Safety stock calculation methods



Type	SSM	Description & Application				Formula
		Plant	HQ WH	RDC/CW LT<20D	RDC/CW LT>20D	
Calc. ROP & SS	RP1	Reorder point with cons. Based SS. (SB9)				$SS_{RP1} = k(SL) * \sqrt{LT * \sigma_D^2 + \sigma_L^2 * \mu_D^2}$ with $k(SL)$: EXCEL =Norm.S.Inv[SL]; $\sigma_D, \sigma_{LT}, \mu_D$: demand, LT last 6 months $ROP_{RP1} = max(SS_{min}, min(SS_{RP1}, SS_{max})) + \mu_D * LT$ with SS_{min}, SS_{max}: manual; μ_D: demand last 6 months
		🟩 Z3, Z4	🟩 Z3,Z4	🟩 Y5	🟥	
	RP2[2]	Reorder point based on avg. sales order				$SS_{RP2} = D/OL$ with D, OL: total demand/order lines for item on given location during x (usually 3) months; $ROP_{RP2} = SS_{RP2} + \mu_D * (LT + \sigma_{LT})$ with μ_D: demand last 6 months; LT: manual; σ_{LT}: manual LT deviation
		🟥	🟥	🟩 Y5	🟥	
	RP3[2]	Max of RP1 and RP2				$SS_{SB1} = \mu_D * SD$ with $ROP_{RP3} = max(ROP_{RP1}, ROP_{RP2})$ takes the most conservative ROP from the two prior methods
		🟥	🟥	🟩 Y5	🟥	
Calc. SS	SB1	Constant Days of Coverage (DoC)				$SS_{SB1} = \mu_{FC} * SD$ with u_D: average daily forecasted demand for next 90 days; SD: number of calendar days coverage (recommended: 0.5LT<SD<LT)
		🟩 ZO	🟩 ZO	🟩 XO, Y0	🟩 XO, Y0	
	SB5	DoC + SST (hist2)				$SS_{SB5} = \mu_{FC} * SD + k(SL) * MAD_D * \sqrt{LT/T}$ with (see SB1, lower SD); $k(SL)$: safety factor based on service level (SAP); MAD_C: MAD over monthly consumption of last 12 months; LT: replenishment LT; T: period (30 days)
		🟥	🟥	🟩 XO, Y0	🟩 XO, Y0	
	SB8	Cons. Based + MAD fcst				$SS_{SB8} = k(SL) * \sqrt{MST * \sigma_D^2 + \sigma_{LT}^2 * \mu_D^2} + MAD_{FC} * LT$ with (see SB9); MST: minimum safety time (= $\min(\max(EOQ/\mu_D, 3), LT)$ MAD_{FC}: MAD forecast last 3 months; LT: replenishment leadtime
		🟥	🟥	🟧 XO, Y0	🟩 XO, Y0	
	SB9	Cons. Based				$SS_{SB9} = k(SL) * \sqrt{LT * \sigma_D^2 + \sigma_{LT}^2 * \mu_D^2}$ with $k(SL)$: safety factor based on service level (EXCEL =Norm.S.Inv[SL]); LT: replenishment leadtime ; $\sigma_D, \sigma_{LT}, \mu_D$: demand resp. leadtime over last 6 months
		🟩 ZO	🟩 ZO	🟩 XO, Y0	🟧 XO, Y0	
	SBA[1]	Stat. days of coverage				$SS_{SBA} = k(SL) * \sigma_D / \mu_D * \sqrt{LT + GR} * \mu_{FC}$ with $k(SL)$: safety factor based on SL (EXCEL =Norm.S.Inv[SL]); σ_D, μ_D: for demand over last 6 months; GR: goods receipt time μ_{FC}: average daily forecast for next 90 days;
		🟩 Z0, Z8	🟩 Z0	🟩 X0, Y0	🟩 X0, Y0	
	SBB[2]	Average sales order				$SS_{SBB} = D/OL$ with D: total demand for item on given location during x (usually 3) months; OL: total number of sales order lines causing total demand in same period
		🟥	🟥	🟩 X0,Y0,X5	🟧 X0,Y0,X5	
Misc.	SRS	Special reserved stock				-

As was mentioned before, safety stock calculations use input data of different origins. According to the life cycle phase of a product, some of this data may be inaccurate or non-existent. An overview of the appropriate safety stock and re-order point calculation can be seen in Figure 1.8.

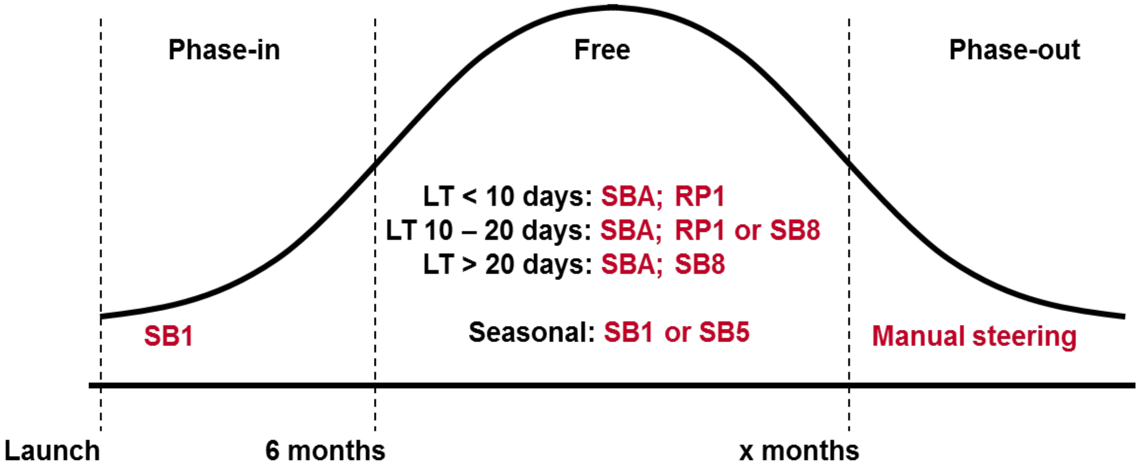


Figure 1.8 Safety stock and re-order point method during life-cycle

At this point it is worth commenting on the safety stock calculation methods presented in Table 2. First remark is that there are no strictly defined criteria. One may see that items going through their free life-cycle phase or several different MRP types, there more than one methods suggested. This leads in many cases to abuses of the calculation methods. For instance, it is very typical to see large numbers of SKUs with enough order lines history, sufficient to generate adequate statistical data, or planned items with forecasted demand, to have their safety stock calculated as fixed days of coverage, ignoring all other components. An example of the calculation methods over the items' portfolio in a central warehouse can be seen in Figure 1.9. A third remark would be that, while the performance ambition targets of the company are expressed as the percentage of items delivered without delay, the safety factors in the statistical methodologies shown above are determined considering the probability of not stocking out just before a replenishment arrives. A final remark refers to the consistency of the safety stock calculation methods with the uncertainties they were designed to buffer against. The forecast error is considered only in SB5 and SB8 and only as a linear deviation per day. SB8 also considers the lead time deviation but instead of the lead time mean, the *Minimum Safety Days* component is used. Even the most recently designed method, the SBA, calculates the safety stock level adjusted by the consumption, it ignores, however, the forecast error and uses only the actual demand deviation. For all the above reasons, it is advised that the safety stocks are to some certain extent inaccurate.

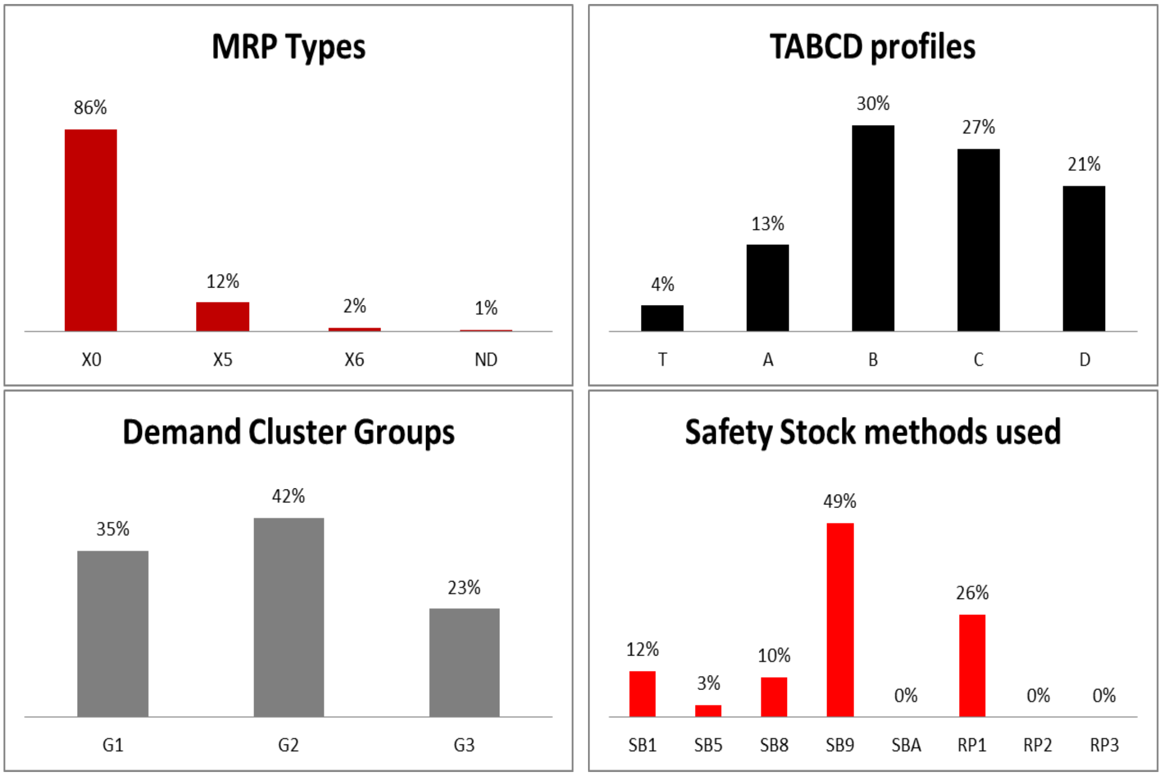


Figure 1.9 AS-IS statistics at CW Adliswil, CH

It should be noted here that the safety stock calculations presented above are not binding rules but act more than guidelines for different scenarios. Hilti Material Managers can still manually override the quantities automatically generated through APO and influence the quantities with manual inputs or by selecting different service level targets. All these facts make the gap between Hilti processes and

1.3.5 Uncertainty factors influencing inventory levels

An actual supply chain faces uncertainties that originate from its two ends, supply and demand. The existence of these unavoidable uncertainties is the main reason that a company is forced to maintain stock to achieve undisrupted production and distribution or achieve the desired target service levels.

1.3.5.1 Demand uncertainties

On the other end, a retailer faces demand which by nature is stochastic apart from few exceptions like fixed quantity contracts. In a stochastic environment, actual demand fluctuates around the mean of the demand distribution. Assuming the mean of the underlying demand pattern is known, this fluctuation constitutes *demand uncertainty*. Nonetheless, the true mean of the demand distribution may not be stationary through time, due to seasonality, promotion or transitioning between life-cycle phases. Demand variability over time includes both demand uncertainty and the variation due to the shifting mean. The difference between the mean of the forecast and the mean of the actual demand distribution for a given point in time is called *forecast bias.* According to the sign, the forecast can be either positive (over-forecasting, over-estimating the actual demand) and or negative. The forecast bias in conjunction with the demand uncertainty, determine the magnitude of the *forecast error* (Enns, 2002)*.*

1.3.5.2 Supply uncertainties

Supply uncertainties involve internal processes of the supply chain, such as lead time variability, fluctuating yield rates or quality variability, to name a few. Variability of yield rates and production quality affect solely the production processes of the supply chain. Yield fluctuations can be spotted in the production of chemical while quality issues leading to batch rejections are also present in production of consumables such as nails, screws and anchors. Variability of lead times is present due to unexpected disruptions in the distribution network or other transport related issues, but most importantly due to inventory shortages. Backlogging and early deliveries of raw materials, components and finished goods from either allied suppliers or upstream stockpoints of the supply chain, cause actual delivery times to deviate from the planned ones, thus creating understock or overstock instances.

2 Project description

Chapter 2 provides details on the motivation for the project and discusses relevant concepts found in literature. In section 2.1 the problem is defined. Section 2.2 defines the scope of the analysis. Section 2.3 discusses the selection of an appropriate inventory management framework and section 2.4 explains relevant safety stock setting topics. Section 2.5 formulates the research questions and objectives based on the problem definition and modelling approach.

2.1 Problem definition

The project was initiated by a coordination of the Global Logistics Materials Management and Control & Business Development departments. Key stakeholders of the company are the head Managers of the two departments, along with the head Material Managers of the two largest market organizations, HNA (Hilti North America) and LEC (Logistics Europe Central). Contributions were also made by the head Material Managers of the 3 BUs with the major contribution to turnover, PT&A (Power Tools & Accessories), Anchors, and Diamond.

The project objective as set by the stakeholders is to provide a scientifically robust framework supporting the inventory target setting procedure. The current target setting rule was established to help the company achieve its strategic goals, namely best in class service levels and productivity, while at the same time minimizing the necessary capital investment. However, that rule is an empiric approach, incorporating rules of thumb and “gut feeling”, in other words is not based on a robust scientific model following literature. This created instances were conflict sparked between management teams of MOs, BUs and HQ, due to misalignment on incentives. The underlying reason is the target setting rule was a purely top down approach that sets internal benchmarks and made comparison not on item, but on stockpoint level. On top of that, it considered only the lead time and turnover of a stockpoint, but ignored any other inventory influence factor or more formal approaches of inventory optimization.

Consequently, the reduction targets that local managements were called to apply ended up putting considerate pressure on operations or even being infeasible. On the contrary, there were other locations with superfluous inventories which, paradoxically for the same reasons, were left unattended. It should be noted, that the company does not wish any redesign intervention in the supply chain or the way it is being controlled, but only a design that addresses the target setting process itself, calculates “optimal” stock levels and pinpoint the uncertainty factors that need to be considered and with what priority. True inventory optimization is impossible to achieve due to the given systems complexity (Stenius, Karaarslan, Marklund, & de Kok, 2015), therefore, the solution will be comprised of optimized results under current conditions and effective approximations.

Second part of the project is to study the effect of the various influence factors on the stock levels. By influence factors, the company refers to the uncertainties the supply chain faces and drive the setting of the stock levels, the service levels and how they should be set to maximize the efficiency of stock and the components of the lead time. The fact that Hilti is active in a number of regions which are sourced from different locations and capitalizes over markets with different characteristics, makes the need for quantitative insights on the influence factors per region even more essential. Ultimately, Hilti is aiming for a design that pinpoints the uncertainty factors that need to be considered and with what priority, according to their impact on the stock levels. Summarizing, the problem definition is formulated as follows:

Design a model with which the optimal stock levels of stockpoints in the various regions can be obtained, in order to support the inventory target setting process and obtain inventory targets. The design should take into account the inventory influence factors of each region and eventually rank them according to their impact on the inventory.

2.2 Scope

For the sake of conducting an analysis that is feasible to complete into the given time frame, the scope of the research needs to be as small as possible, solid and clearly defined. Yet, it is mandatory that it is one that can be expanded and generalized after the modeling and model solving phases are completed. The scope is defined by a number of dimensions that directly affect the content and extent of the research. These dimensions, sorted by priority, are

1. the items that will be included in the model design
2. the main markets to focus
3. the stages of the supply chain and types of stockpoints to be analyzed
4. the material flows that will be considered

A list of criteria will be outlined for each of the dimensions which, when explained, will lead to the final determination of the scope.

2.2.1 Criteria

First dimension to consider in limiting the scope is the product selection. Filtering the product range of HILTI will begin with initially selecting the BUs, then going deeper to product groups and finally end up with picking specific SKUs. The selection process considers two parameters, importance and generalizability. Importance of a BU comes in terms of number of products and contribution to turnover, which is a critical requirement for the model to generate results with the desired impact. Generalizability means that the SKUs selected effectively represent the product profiles/business areas of the company along with the turnover and demand volatility profiles. The profile classifications of end-products were explained in chapter 1.3.4.1.

Second dimension under consideration for determining the scope is the markets. Having narrowed down the scope of possible SKUs to analyze, the markets in which they are active should be identified. It is necessary to select markets because there can be different item codes for a single product, specifying certain modifications to match the features of each market. For example, a power tool that is sold in the US is different with that of the same type sold in the US due to the difference in the power cord, thus, ending up with a different item code. Concurrently, the data needs to be adequately diverse for the model to generate results and insights that could be afterwards generalized. As a consequence, the supply chains in scope should transcend the boundaries of a single MO. To increase the impact of the model results it was also advised to pick markets in which the largest portions of the total turnover of HILTI is generated.

The 3rd and 4th dimensions are interrelated and deduced from the supply chain operations in the market regions that will be included in the scope. The stages of the supply chain that will be analyzed will be determined according to the requirements of the stakeholders at HILTI, in terms of the inventory levels of what stock locations and warehouse types they deem necessary that are optimized and reduction targets are created for. Limitation may exist, though, not only from a data point of view, but also considering how meaningful it is to determine reduction targets for a specific stage. For example, during one of the interviews, the necessity of applying reduction targets to Hilti Centers was questioned. The argument was based on the fact that HCs function a lot more than retailers, where an image of abundance may be more important from a marketing perspective, rather than a logistics center.

Regarding the material flows within the given markets, routes that are used scarcely, resulting in volumes being transferred sporadically will be ignored for the sake of effective modelling. Normally, each stockpoint is replenished by a single upstream position in the distribution network. However, the actual structure is not strictly arborescent as demand reaches further upstream than the retailers and occasional lateral transshipments may occur, along with other types of inter-company sales, return shipments etcetera

2.2.2 Scope definition

According to the dimensions and respecting the criteria that were outlined above, the scope of the project will be defined.

The main turnover-generating markets in scope are those of northern and central Europe and North America. The market choice is such that includes regions with the highest turnover generation, so that the results from the model design have a high impact, but also are quite diverse. Their distribution network is different since in the US there is the extra tier between the RDC/CW stage and the HCs, to cover for the vast space of the market. What is more, there is also diversity in lead times and order frequency since there are daily truck deliveries for the stock locations in Europe, while shipments to the US CWs are consolidated and transported through ocean freight carriers From there, truck deliveries are used for the DCs and HCs replenishment but ultimately, the difference in lead times with Europe is significant.

The types of stockpoints that will be analyzed are the FG stocks of the Production Plants, the HQ warehouses, the RDCs/CWs and the DCs, each one representing a different echelon. The Van, Travelling Salesmen and consignment stock are out of the scope as the company does not wish to include them in the target setting process. Furthermore, the retailers will be left out of the scope of the analysis, as well. The reason behind this is that, firstly, there are no statistical and performance measurement data kept from the retailers' operations and, secondly, performance measurement is not tied with the inventory management. Local managements empirically specify for the retailers a fixed amount of minimum and maximum coverage days. Additionally, van Wanrooij (2012) in her master thesis project that also took place at Hilti, showed that the HCs are in their majority uncontrollable stockpoints because of the high coefficient of variation seen.

The selection of the SKUs that will be used in the modelling phase of the project will be determined according to the criteria that were mentioned above. The product portfolio will include SKUs coming from the higher turnover profiles of HILTI (T or A) of the markets under consideration. Attempting to cover as much of the span of Hilti's operations, a Power Tool, a consumable and a spare part are chosen. Using as input a product sample which includes diverse products with high contribution to turnover will enable the simulation to provide quantitative insights of high value on the matter of safety stock allocation influence factors impact.

A summary of the scope can be seen below in Table 3 and Figure 2.1.

Table 3 Materials in scope

Product	Type	Markets
2029228	Power Tool	LW1
2101918	Anchor	LEC, LE1, LE2, LE4, META

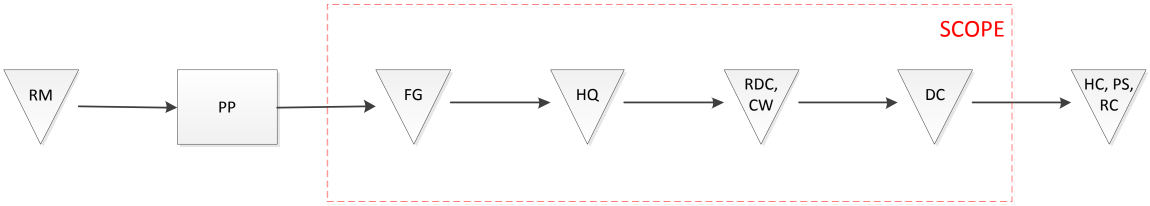


Figure 2.1 Supply chain stages and stockpoints in scope

2.3 Inventory management framework

As a means to tackle the problem defined in section 2.1, the appropriate inventory management method has to be determined. Despite the ample amount of different types of stock encountered in literature, this work will focus only on the ones that are relevant to the supply chain under examination, safety stock, cycle stock and obsolescence (overstock). A short overview of the optimization methods adopted with regard to each type of stock mentioned can be seen below in Table 4. For further analysis, the reader is prompted to go through the Literature Review part of this Master Thesis.

Within the context of this project, there is limited potential to optimize the cycle stock, as it was agreed to accept the batch quantities and lot sizes as fixed. Moreover, reduction of lead times by either shortening delivery times or increasing delivery frequency would require renegotiation with the 3PLs and is not directly applicable. Therefore, main focus of this Master Thesis will be the optimization of the Safety Stock.

Table 4 Inventory management framework

Research	Safety Stock	Cycle stock	Obsolescence	Optimization approach
Simpson (1958)	X			Optimal combination of service times
Minner (1998)	X			Various service measures
Silver et al. (1998)	X			Single echelon models
Axsater (2000)	X	X		Single echelon iterative techniques
Graves, Willems (2000)	X			Guaranteed service SSP
Boulaksil (2009)	X			Multi echelon models
Osman, Demirli (2012)	X			Fill rates optimization in SSP with supply & demand uncertainties
De Kok (1990)	X	X		Service criteria & rationing policy
De Kok, Fransoo (2003)	X	X		Synchronized Base Stock, material-feasible order releases
Teunter et al. (2011)			X	Link forecasting with obsolescence

The summary of the current situation at Hilti under analysis within the context of this Master Thesis project, is depicted by multi-item, multi-echelon distribution networks where stochastic demand arrives up to the third supply chain stage and the replenishment lead times are uncertain. The lot sizes are fixed, subject to packaging restrictions between the various stages. The replenishment process of the stockpoints follows the MRP II process which generates *net requirements*, from which planned orders are determined. Given that and also considering that the focus of the study is the safety stock levels, appropriate modelling approaches will be selected, so as the underlying assumptions of each provide a good fit with the existing Hilti set up and achieve valid results.

2.4 Safety stock relevant concepts

During the AS-IS analysis in the early stages of the project three important aspects were identified as key influence factors affecting the processes within the supply chains: Supply Uncertainty, Demand Uncertainty and the Target Service Level. In an ideal setup, supply and demand would be deterministic, allowing for the exact required quantities to be right on time where they are needed, without having to consider lot sizing and economies of scale, holding costs, excess stock etc. In most of the real-life scenarios, however, that can be encountered all around the industry, stochasticity, uncertainties and the existence of different costs generated by running operations lead to the necessity of maintaining stocks. What is more, the practical difficulty of calculating accurately the costs of unmet demand and penalty costs restrain managements of using analytical methods for the calculation of optimal service levels. Since shortage costs are often hard to determine in practice, service measures are used as operational surrogates. Hence, it is common practice to use a pre-defined Target Service Level and plan according to that. It is inevitable, though, that due to the uncertainty factors present that stockouts will occur. A stock out may cause lost sales, emergency shipments, or loss of goodwill. Therefore, safety stocks should be kept to increase the service levels. Traditionally, safety stocks are determined in advance based on models from inventory theory (Silver et al. 1998).

The existence of uncertainties renders inventory control using deterministic assumptions incapable of achieving performance targets. Thus, countermeasures have to be taken, in order to buffer effectively against stochasticity. Such measures against uncertainties can have been summarized as safety stock, safety lead time, safety capacity, and operational flexibility (Guide & Srivastava, 2000). The last concept is situation specific and hard to quantify and is, thus, not taken into account explicitly. Hopp and Spearman (2011) did also only distinguish inventory, capacity and time as a method to buffer against variability. 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. The management at Hilti showed more interest in investigating the safety stock allocation, so as to compare levels resulting from the analysis with the one of the currently used reduction target logic. Hence, there is not direct relevance to safety lead time. Safety stock in units, though, is rather straightforward to be converted to safety time coverage.
Safety stock is, according to Silver et al. (1998), the net stock just before replenishment a replenishment arrives. Hence, safety stock is the buffer inventory and, from another perspective, the capital investment made, that is placed to eliminate the effect of variations in the lead time demand. Such variations can be the results of supply delays and disruptions or higher than forecasted customer demand. As was discussed in Chapter 5, even the most accurate demand forecast techniques cannot predict in full the stochasticity of customer behavior. Safety stock appears to be a particularly good hedge, when it is for cheap, imperishable commodities (Chopra & Sodhi, 2004).

In an ideal environment, the costs due to understock could be accurately calculated, thus, leading to determining the cost-optimal target service level that balances inventory holding costs and backorder/lost sales costs. In the case of lost sales, the understock is straightforwardly calculated as the lost profit. On the other hand, when backorders are considered, the determination of understock becomes hard and oftentimes inaccurate. The problem arises because the frequently encountered measures to cover for backordered demand are simply postponed deliveries or otherwise emergency shipments. The associated costs can be very situational and usually impossible to measure. Such examples can be the extra holding costs generated from unnecessary stock due to the additional lot sizes to cover the backlog or the intangible costs relevant to customer dissatisfaction. Since shortage costs are often hard to determine in practice, service measures are used as operational surrogates (Diks, De Kok, & Lagodimos , 1995).

A typical calculation for the safety stock of an individual location in the presence of demand and lead time stochasticity is provided by Eppen & Martin (1988). The quantity under the square root expressed the variance of the lead time demand, assuming that demand and lead time are normally distributed.

$$SS = k * \sqrt{\sigma_D^2 * LT + \sigma_{LT}^2 * \mu_D^2}$$

The safety factor *k* for the above calculation is determined from the type of service level measurement considered. When the no-stockout probability is used, the safety factor is calculated as the inverse of the normal distribution for percentile of required coverage. If the fill rate is considered, then the safety factor is determined by the standard loss function *G(k),* which expresses the expected amount of shortage per cycle. (De Kok A. , Analysis of stock control models for one location with one product, 2002). Both derivations assume that demand is normally distributed. The calculation of the latter is more cumbersome, but as mentioned in the notes of De Kok (2002), when the parameters of the right-hand side of the equation are known, the value of left-hand side can be considered as a constant *C* and the safety factor can be determined from a table. Alternatively, there are also numerical calculations, such as the one discussed by Silver, Pyke & Peterson (1998). Additional derivations under gamma distributed demand can be found in the notes of De Kok (2002).

$$k_a = \Phi^{-1}(P_1)$$

$$G(k_\beta) = \frac{(1-P_2)Q}{\sqrt{\sigma_D^2 LT + \sigma_{LT}^2 \mu_D^2}}$$

In section 5.2, it is mentioned that the service level ambitions of Hilti match the fill rate measurement target. Contrary to that, it is worth mentioning that the current methodologies of Hilti for setting safety stocks, use as safety factor k_a. Although this approach is more simple to derive, there is the drawback that the order size *Q* is not considered. As one may notice in the above formula of $G(k_\beta)$, it increases in size as Q is increasing. However, from the standard loss function table we see that $G(k_\beta)$ and k_β are inversely proportional, meaning that with larger order sizes, the safety stock levels needed to achieve the same service target drops. The impact of this choice will be discussed in the following chapters.

2.4.1 Basic multi-echelon analysis concepts

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. As a distribution system, where the clear majority of material flows take place between a single source point and multiple recipients, the Hilti networks within scope fall into the divergent network category. However, it must be noted that due to the duality of the role of the warehouses, meeting both customer demand and replenishing downstream locations, the structure is not purely arborescent. This fact prevents from directly applying approaches such as that from van Donselaar & Wijngaard (1987) or De Kok (1990) and De Kok et al. (1994), where common notion is that all available stock is pushed to the retailers, close to the customer. In addition to its indirect effect on the service level for customers at the retailers, a stockout at the central warehouse with a dual role has a direct effect on the service level for the local customers. The safety stock decision at the central warehouse thus depends on replenishment demand from remote warehouses as well as direct customer demand at the central warehouse. However, there is no theory or analytical solution available in the current literature to determine the inventory policies for this alternate supply chain structure (Cattani, Jacobs, & Schoenfelder, 2011).

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 F. According to De Kok and Fransoo (2003), those echelon stocks can be recursively calculated.

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

$$Yi(t) = X_i(t) + O_i(t), \forall i \in E$$

$$Xi(t) = J_i(t) + \sum_{j \in V_i} Y_j(t) \;, \forall i \in I$$

$$Yi(t) = Xi(t) + Oi(t), \forall i \in I$$

$Xi(t)$: $Echelon\ on\ hand\ stock\ for\ item\ i\ at\ time\ t$
$Yi(t)$: $Echelon\ inventory\ position\ for\ item\ i\ at\ time\ t$
$Oi(t)$: $Cumulative\ outstanding\ orders\ for\ item\ i\ at\ time\ t$
$Ji(t)$: $Local\ on\ hand\ stock\ for\ item\ i\ at\ time\ t$
E: $Set\ of\ end\ items$
I: $Set\ of\ intermediate\ items$

2.4.2 The Supply Chain Operations Planning problem

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

Main difference between the two is that 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. This research will focus on stochastic demand models and specifically on the *Stochastic Service* approach.

2.4.3 Stochastic Service and the Synchronized Base Stock policy

Stochastic Service methods check at any 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, S, 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, which is both tractable and empirically valid. More information about SBS and modeling with ChainScope can be found in Chapter 3.

2.4.4 Single-echelon approximations

Multi-echelon inventory systems are often controlled as a network of single-echelon inventory systems for simplicity of managerial authority, organizational control and performance monitoring (Hausman & Erkip, 1994). Under independent single-echelon inventory control policies, the stockpoints of each stage are responsible for their own stocking policies, independent of each other and their replenishing plants. Once all the locations have determined their policies, their combined operation creates a demand process for orders placed in the upstream stockpoint.

Vast existing literature suggests that, if all information is available centrally and all management concerns are reflected in the system objective function, then the optimal multi-echelon policy will always produce results that dominate single-echelon policies. However, when managerial and organizational issues are concerned, this might not be true and the impact might be less severe. Lee and Whang (1992) ague that it is common to observe independently operating management levels whose performance is evaluated independently as well. Hence, the undeniable theoretical benefits of multi-echelon policies may be offset by managerial and organizational considerations.

2.5 Research questions

High end goal of the Global Logistics at Hilti is the distribution network achieving the target service level with the maximum efficiency possible. Hence, first step is to find which are the appropriate inventory models which tackle the problem of safety stock placement in a multi-echelon environment. Studying models which fit in the existing set u at Hilti, empirically valid results can be generated and compared with the actual reported ones. Having determined the modelling approaches and checking their validity, the theoretical performance evaluation of each approach will be calculated, along with optimal stock levels that bring the supply chains to the target performance under existing conditions. Moreover, it is essential to conceptualize and quantify the various influence factors described in section 1.3.5. Hence, several optimization scenarios will be devised to determine the impact of the influence factors on the stock levels. Summarizing, the following research questions are formulated:

1. *Which models yield empirically valid results?*
2. *What is the relative evaluated performance of the models comparing to that of the actual the supply chains?*
3. *What are the optimal stock levels to achieve the target service level under minimum inventory investment using single-echelon models?*
4. *What are the optimal stock levels to achieve the target service level under minimum inventory investment using multi-echelon models?*
5. *What is the impact of the uncertainty factors on the stock levels using single-echelon models?*
6. *What is the impact of the uncertainty factors on the stock levels under multi-echelon analysis?*
7. *What is the accuracy of the current inventory reduction target setting rule?*

3 Inventory modeling

Chapter 3 discusses the process of setting inventory targets and the two paradigms of inventory modeling, which will be used to analyze the supply chains. Section 3.1 describes the two SC networks in scope. Section 3.2 explains the basic input parameters of the models. Section 3.3 discusses the current reduction target logic employed by Hilti, then presents a formal approach of inventory target setting. Sections 3.4 & 3.5 presents the two modelling approaches and section 3.6 discusses their validity.

3.1 Supply chains in scope

In Chapter 4 the scope of the project was defined to include one power tool, one anchor and one spare part. The diversity these SKUs bring to the portfolio to be analyzed allow for generating insights of high value and generalizability. The SKUs are not only diverse in nature, but also in the supply chain networks employed for their distribution and the markets they address. The power tool is mainly distributed in the European markets, implying short lead times due to proximity to the production plant and further, rather steady high volume of order lines. The anchor, on the other hand, is distributed to markets across the Atlantic with long lead times and different consumption rates between the regions LW1 and LW2. Finally, the spare part supply network is universal, addressing almost every region Hilti is active at, and, what is more, shows different demand patterns comparing to the other two products due to the nature of repair and maintenance operations. Its supply chain also includes spare parts DCs and RCs.

Hilti power tools are assembled in production plant 4 (P4) in Austria. The factory is the primary production site of power tools for the global operations of Hilti and works under a strict Just in Time, Assemble-To-Order (MTO) policy. This means that the plant does not maintain a stock of finished power tools, but only initiates production based on anticipated demand and ships the products directly to MOs, if the demand volume is sufficient to support direct shipments and an efficient route is available. Otherwise, shipments are consolidated in one of the HQ warehouses and then shipped from there to the MOs. Recipients are always CWs which subsequently replenish the stocks of the HCs in their vicinity.

The anchor in scope is produced in production plant 6 (P6) in Germany. P6 operates under a Make-To-Stock (MTS) policy. Production planning maintains stock in the plant and from that stock all downstream locations are replenished. In the same fashion with the distribution of the power tool, discussed in the previous paragraph, shipments reach the MO CWs either directly or via consolidation at the HQ warehouses. In contrast with the European markets, the supply networks in LW1 and LW2 incorporate an additional stage between CWs and HCs, the DCs, in order to better cover demand over vast geographical regions and create more efficient replenishment lines.

The spare part is produced also in P4. From there, produced volumes are transferred to an HQ warehouse for storage and distribution to MOs begins from there. Recipients of the HQ shipments are in their majority CWs and DCs, which in turn, replenish the downstream HCs and RCs.

Hilti's distribution planning dictates that there is a unique combination of product-route-location, meaning that each product is delivered a downstream location following a fixed route. Additionally, transshipments are rare. However, analyzing delivery lines data for the SKUs in scope, order lines of the same item reaching a stockpoint from secondary locations than the designated ones were found. In most of the cases, these order lines pertain to shipments from the HQ warehouses to CWs, but due to the low volumes and frequency of the shipments this material flows will be ignored to make the model simpler. Detailed schematic representations of the supply chains can be found in Appendix A.

3.2 Setting inventory targets

3.2.1 Current inventory reduction target determination logic at Hilti

As briefly discussed in Chapter 4, Hilti employs a rule that each year calculates what should be the percentage reduction of the average inventory level for each warehouse and retailer. The logic behind it is that each year, the capital investment is smaller but the company KPIs are improved. Its implementation generated positive results in overall due to the superfluous stocks that were kept to achieve the ambition performance targets. It did come to the management's attention, though, that the approach was flawed and created operational issues and frictions between management teams. In short, the inventory reduction targets are determined by three components:

1. *Potential improvement* is determined by comparing the stock levels of each location within turnover cluster groups, with that of the top performers which is used as internal benchmark. Inventory performance is calculated the ration of days-on-hand stock over the generated turnover. The cluster groups are set based on empirically observing the turnover data and dividing the data points in a reasonable manner and the classification differs between warehouses and retailers. The *potential* component calculation for the warehouses also considers the lead time difference with that of the European warehouses benchmark.

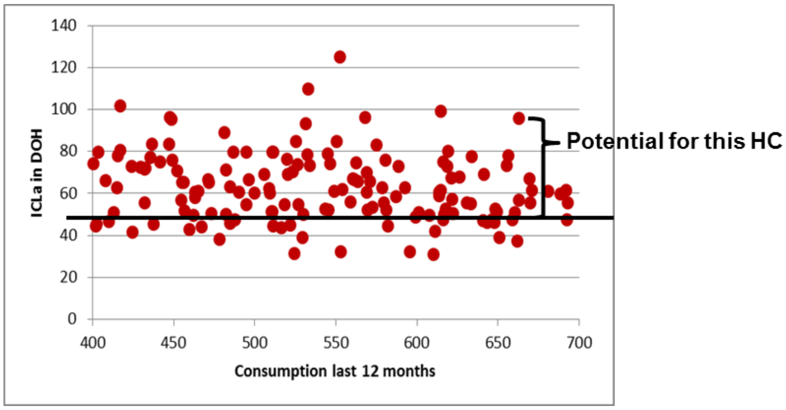


Figure 3.1 Calculation of potential for a Hilti Center

2. The *productivity* component is calculated through an empirical formula, using as inputs the sales growth and the inventory levels. It is an empirical calculation, adjusted over the years, to generate feasible reduction targets, lately setting the minimum to 2.5%.
3. The third component is a flat reduction factor applied universally to all warehouses inventories, based on the impact that the ongoing sales and production integration

planning project. The derivation of this component is empirically estimated and ranges from 1% to 4%.

As one may easily notice, various implications may rise from the application of this target setting logic. Calculating of potential for instance, not only uses arbitrarily set cluster groups, but also compares stockpoints which support different SKU portfolios and face customer demand of varying volatility. The same applies for the productivity component as an empirical derivation and the third, flat reduction factor, over a large number of warehouses, situated in different stages of the value stream and facing different levels of uncertainties. Therefore, the target setting process misses critical inputs necessary to optimize the inventories of the company stock locations, is rather inaccurate and does not allow for tapping the full cost-saving potential.

In the remainder of the chapter, selected methods of inventory optimization will be presented, out of the vast literature existing on the topic, that specifically match the current design of the supply chains of Hilti and their operations. The methodologies are divided into two main groups: single-echelon modeling (section 3.3) and multi-echelon modeling (section 3.5).

3.2.2 Formal inventory target setting and inventory control

When analyzing an inventory system, efficient management of the stock level requires four inputs: demand data, supply information, target service level and an appropriate inventory management framework.

There are two common approaches to characterize the parameters of demand that populated the calculations of safety stocks and average inventories. The first approach relies entirely on the actual historical demand data to calculate means and variances. This approach works well demand is rather stationary or any type of forecasting technique used generates results less accurate than simply following demand history. The second approach uses the forecast and actual demand history to calculate how the forecast deviates from the actual demand. The demand curves of many product families have attributes such as seasonality or life-cycles which affect the average demand levels. Thus, in these cases, using demand parameters generated with the second approach is the appropriate way (Willems & Manary, 2008). Forecasts are rarely 100% accurate, though. Consequently, it is also necessary to estimate the forecast error, which may be represented by the standard deviation or the so-called Mean Absolute Deviation (MAD) (Axsäter, 2015).

Analysis of the supply data is equivalently important for the determination of optimal stock levels. In the context of a distribution network, the relevant supply information consists of lead time data and the lot sizing. Under deterministic conditions, where demand is known and fixed and supply is steady and without disruptions, optimal stock levels are easily calculated by simply setting a reorder point that reflects the demand during lead time and using a lot-sizing technique, for instance the Economic Order Quantity (EOQ) that balances order and holding costs. In almost all cases of supply chain operations, though, there is always a certain degree of uncertainty caused by stochastic variations.

Of course, forecast demand is not enough to determine an effective inventory policy; uncertainty in demand and supply also need to be incorporated in the analysis. In practice, this is typically done by decomposing the problem into two parts: The first is identifying an inventory policy that balances holding and fixed costs assuming forecast demand over a given planning horizon, see Stenger (1994). The second is determining safety stock levels and incorporating these in the inventory level that should be maintained at the beginning of each period (Graves & Willems, 2003).

Simply put, inventory targets are derived by setting optimal safety stocks, reorder points and lot sizes. These three inputs determine the average inventory per replenishment cycle. It is important to highlight that these figures can only be calculated on item level by statistically analyzing data collected relevant to each item. Widely applied methods such as benchmarking inventory performance are hapless, as they attempt comparisons between unequal settings. The calculation of the safety stocks should consider both the uncertainty factors, the desired service level and the service level target, in order to effectively buffer against them and make the performance targets achievable under minimum capital investment.

The analysis presented in the remainder of the chapter is divided in two main sections: single-echelon modeling, where the system considered is comprised of one stock location at a time that is described and optimized, and multi-echelon modeling, where the optimal parameters are derived collectively for all the locations existing in the material flow stream.

3.3 Input parameters

Part of the conceptualization phase of the project is to specify and explain all the relevant input parameters of the inventory models. For each of the parameters a description will be provided, along with argumentation on its importance, how the values are calculated and, finally, how they will be used in the model. Detailed tables with all the values of the parameters used in the models can be found in the Appendix.

3.3.1 General variables

Order quantities

The order quantities are derived from the latest calculation of the EOQ that took place in August. The calculation of the lot sizes follows the typical EOQ method to balance ordering and holding cost but, on top of that, further adjusts them using an algorithm that also takes into consideration the MRP type, the demand cluster and the various packaging sizes. These lot sizes are held fixed through the simulation runs and used as MRP planning parameters. An actual replenishment order can only be released as an integer multiple of the given lot size. This analysis will not discuss the possibility of using alternative methods for the calculation of the optimal lot size according to the stakeholders' suggestions.

Lead times

The production and delivery lead times are used as parameters for the planning process. All the lead times are stochastic, apart from the batch production time of the Anchor at Plant 6 which is considered fixed. The necessary data for the actual lead times were extracted from the business warehouse data system of Hilti, based on which mean values and deviations were calculated.

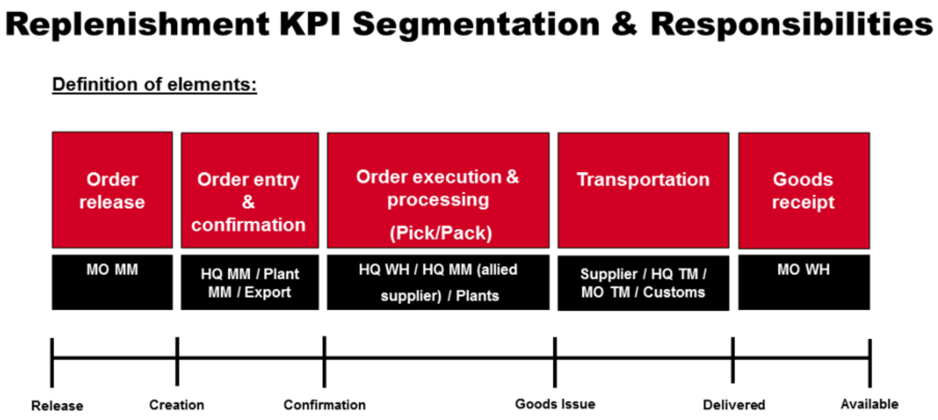


Figure 3.2 Replenishment Lead Time components

The total Replenishment Lead Time (RLT) of a stockpoint is comprised of many components, as seen in Figure 3.2. These include the time it takes for an order to be created after it is released, the time till confirmation, the time for the goods to be issued and the outbound is ready to be shipped in the source stockpoint, the pure transportation time and the item required for the shipment to be received and booked by the destination stockpoint. In other words, the RLT data generate for each stockpoint a mean and a standard deviation which include delays caused by limited upstream availability. Considering these stochastic delays is a key input for the SISE approximation. A table with the lead time parameters of all the location is presented in Appendix C.

<u>Cost structure</u>

Hilti products are sold worldwide with a price according to the currency and the total cost incurred according to the market organization. Thus, the same retail prices of the same SKU could highly vary from market to market. It is, therefore, preferred to express the product value according to the COGS price in order to better monitor the allocation of stock along the supply chain. However, the actual COGS values of the SKUs which are used in the models is confidential information for Hilti, so, it will remain concealed throughout this report.

As the materials flow from one stockpoint to another, the operations taking place, such as transportation, inbound and outbound handling, are adding value to the initial COGS price of the item. Transportation and handling differ between routes and warehouse types. Adding these values provide the basis for the calculation of the inventory holding costs, which at Hilti are calculated as 12% of the current item value. A table with all relevant costs for the two SKUs in scope is shown in Appendix E.

<u>Service level</u>

The service level is the main driver for keeping stocks in the supply chain. In both practice and academia, the two most usually measurements of performance are the *no-stockout probability* (P3 service) and the *fill rate* (P2 service). In short, P1 measures the percentage of periods that the net inventory does not drop to negative levels or, equivalently, the percentage of time that a stockpoint spends with positive net inventory. On the other hand, P2 brings in a unit perspective, by showing the percentage of demand that is not backlogged..

According to the ambition of the company, customer demand orders for the stockable products should be met directly from the shelf without delay with a 98% success rate. This performance measurement is equivalent to the fill rate, which is defined as the percentage of non-backordered demand over the total demand. Hence, the fill rate should be the main driver for the determination of the optimal safety stock levels.

$$P_2 = 1 - \frac{Backorders}{Total\ Demand}$$

3.3.2 Demand uncertainty

Demand levels for the two items in scope is stochastic. Even though they have reached their maturity phase in their life cycle and represent fast-moving items with significant contribution to turnover, demand volatility is always present. Unplanned demand occurs frequently due to constant marketing activity with impact that varies from market to market or customer to customer. Furthermore, customer behavior and the dynamics within the markets can never be fully anticipated, driving retailers to maintain higher stock levels and making the need for accurate forecasting essential. Despite the volatility, demand is considered stationary in this analysis. The assumption is also supported by the fact that the products are going through their normal life cycle phase, with no significant drop or increase expected in the new future periods.

It was agreed with the management that a period of 1 year would suffice to provide the relevant demand data. Consequently, the BI database was utilized to extract the relevant sales histories, resulting in about a hundred thousand order lines per product. These lines are coming from demand orders placed to the stockpoints within scope. The refinement of the demand history was required, since it was comprised of customer orders, internal replenishment orders from agents that have been excluded from the scope of this analysis (Hilti Centers, Repair Centers, Travelling Salesmen, Van fleet, Consignment stock etc), returns and finally, cancelled orders.

In the context of production and distribution planning at Hilti, the demand distribution that is, implicitly or explicitly, used, is the Normal distribution. The Normal distribution has both advantages and disadvantages. On one hand, it is highly tractable and easy to implement and communicate. On the other hand, it is not so versatile and in most cases, it fits poorly to the demand data. On top of that, the demand data analysis showed that in the case of the Power Tool and other items with similar sales pattern, it is very common to encounter products with low average demand and high demand deviation. Since the Normal distribution does not restrain the generated data points from taking negative values, assuming normally distributed demand in such cases could significantly affect the accuracy of the results. Henceforth, the demand is assumed to be comprised of independent and identically distributed (i.i.d) Gamma distributed random variables, to simulate the demand of the two SKUs. Gamma distribution provides a good fit in the case of the Anchor (high demand – high CV) and the Power Tool demand also benefits from the non-negative property. Additionally, it is the default distribution used by ChainScope. Detailed tables and demand data charts are presented in Appendix C.

The Gamma distribution is defined by calculating two parameters: shape (alpha) and scale (beta). Both are derived by the demand mean and standard deviation.

$$a = \frac{\mu_d^2}{\sigma_d^2}$$

$$\beta = \frac{\sigma_d^2}{\mu_d}$$

There are two common practices to characterize the demand parameters that determine the shape and scale of the Gamma distribution. The first, relies entirely on historical demand to calculate an average and standard deviation of historical order lines. The second approach uses the forecast and the actual demand history to calculate how the forecast deviates from the actual. For most the Hilti products, especially for those going through their running life cycle phase, Hilti applies a *push* fashion replenishment system, based on forecasted demand levels. The latter approach is more effective than solely relying on historical data, as marketing events and several promotional efforts render the demand history of an item a poor indicator (Willems & Manary, 2008). On the other hand, common occasions of last minute changes or miscalculation of the effects on the demand levels lead to forecast errors. Forecast errors in Hilti are measured using a Mean Absolute Deviation (MAD). Various methods are used to generate the demand forecast: linear regression, exponential smoothing, Croston's method etc.

$$MAD = \frac{1}{n}\sum_{i=1}^{n} |D_i - FC_i|$$

$D_i\text{: }actual\ demand\ at\ period\ i$

$FC_i\text{: }forecasted\ demand\ at\ period\ i$

While considering the forecasted demand and forecast error data seems to be the appropriate approach to model the inventory and generate accurate targets, there were a few restrictions that denied it. First, the demand forecast was not available for all locations in scope. This is due to some locations, primarily downstream such as DCs, operating partially in a pull fashion and do not release orders based on planned demand and material requirements for all SKUs. On top of that, the forecast error data for some of the locations that forecast the SKU, were missing from the BI library. Additionally, the forecasted figures for all locations did not distinguish between customer (exogenous) demand and internal replenishment demand, a distinction that is necessary for multi-echelon analysis. Thus, the demand input for the inventory models used in the remainder of this report will originate from the historical demand data of the SKUs. This is also in line with one the main assumption of the models, that the demand is stationary and i.i.d.

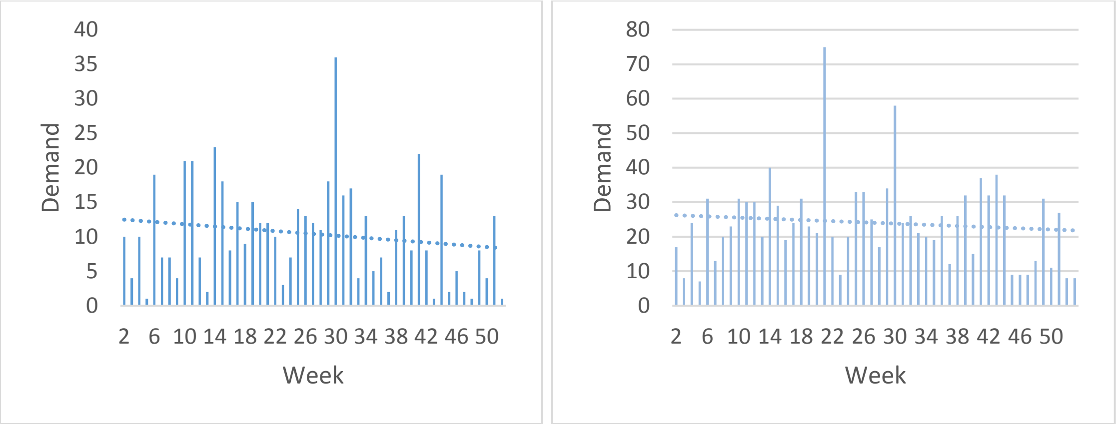


Figure 3.3 Weekly demand data from CWs 6000 & 6004

3.3.3 Supply uncertainty

The main uncertainty factor that the supply chain faces in terms of its supply process, is the stochasticity of the lead times. The Replenishment Lead Time (RLT) data maintained in the business warehouse of Hilti, are used for the calculation of the several KPIs that the company uses to measure its supply reliability on different levels. The stochastic variations observed in the replenishment lead times of the stockpoints are generated due to two main reasons. First, availability issues in upstream locations where stockouts may occur, leading to delays in the deliveries of goods to downstream positions. These stockout periods can last from a few days, if an emergency shipment can be arranged, to months in case of long lead times large backordered quantities in the echelon. Furthermore, the throughput times of each stockpoint, comprised by the warehousing and transport operations, may also show fluctuations. Such fluctuations may occur due to increased traffic in the warehouse, human mistakes, transport disruptions etc. The next chapter will elaborate on which type of lead time deviation should be considered and why, depending on the inventory modelling approach.

Data from the past 12 months were extracted from the BI system and then analyzed, to study the behavior of the lead time stochasticity. The high number of order lines in conjunction with the relatively low levels of deviation, allow the use of the Normal distribution to simulate the lead time. However, during the multi-echelon analysis of the supply chain using ChainScope, the replenishment lead time is considered fixed. Therefore, in Chapter 6, an approach will be presented on how to incorporate a safety time buffer and work around the fixes lead time assumption. Detailed tables with the lead time values of the stockpoints along the two supply chains in scope is presented in Appendix D.

3.4 Single-echelon modeling

Single-echelon, single-item approaches are the most basic techniques of inventory management. Under single-echelon analysis, all inputs are measured on a local level and any information relevant to the other entities of the supply chain are not considered. Such an analysis may appear simplistic, due to the number of parameters affecting the performance of the stockpoint but are ignored. It is, however, widely used in the industry because of the small computational effort and ease of implementation that it offers.

One such example of using a single-echelon heuristic to calculate optimal reorder levels in a multi-stage supply chain is Hilti. Hilti, like a vast number of other organizations in the industry, rely on commercial software packages, like the modules offered by SAP, that make use of such a heuristic. Many researchers have argued that their suggested procedures for a single-echelon environment should work in a multi-echelon environment, and this is common practice. For example, documentation published by SAP AG (2001), the world leader in ERP software, describes how multi-echelon problems should be processed using the term “Consumption-Based Planning” logic. The reference describes the use of reorder level calculations to trigger replenishments using a heuristic based on single-echelon calculations. In particular, the documentation describes both “manual” and “automatic” reorder point planning. With the automated approach, the reorder and safety stock levels are calculated using data from the integrated forecasting module and a service level based on the probability of stocking out specified by the planner. In the system, the forecast is updated at regular intervals with the reorder level and safety stock level continually adapted to the current consumption and delivery situation. The forecasting is done using exponential smoothing and reorder points are calculated using the same logic as described by Jacobs and Chase (2010). Key to the application of single-echelon, single-item approaches is to assume a target service level at each location and assume that the upstream stages can always deliver according to the lead time assumed.

3.4.1 Control policy

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*. Under the assumption of deterministic supply and demand, it would be straightforward that the reorder point should be equal to the demand during the lead time. However, to buffer against the uncertainties seen in real-life operations, the reorder point needs to be increased by an amount of safety stock, that allows for the target service level to be achieved.

$$s = Safety\ Stock + Lead\ Time\ Demand$$

The model that will be used for the single-echelon modeling is the (R,s,Q) and its analysis is taken from the work of Ton de Kok (2002) who extended the original analysis by Silver, Pyke & Peterson (1998) by relaxing the assumptions they made. It is described as the strategy where the stock is reviewed every R^{th} time unit. If at a review moment the inventory position is below b, then an integral multiple of Q is ordered, such that the inventory position is raised to a value between b and $s+Q$. The (R,s,Q)-policy is applied implicitly in many MRP packages, SAP being one of them, where fixed lot sizes are used and a time phased order point determines the order (or explosion) moments.

The model is considered under a discrete time instance, where depletion of stock is registered at equidistant points in time, setting the system to operate in a batch mode. Although this may sound controversial, considering that SAP registers all incoming demand real time, experience and inputs from Hilti employees showed that there is a fixed ordering pattern, where replenishments are triggered once per day. Thus, a time unit equal to a day will be used, at the end of which data are collected about stock depletion during the time unit, as well as arrivals of replenishments during that time unit. Accordingly, the review period *R* is set: how many time-units elapse between decision epochs, at which we may order an amount at the supplier. *R* is an integral number of time units and in this case, equal to 1. Then, decisions about when and how much to order are governed by the *(R,s,Q)*-policy. Additionally, it is assumed that replenishments arrive at the end of the day.

An expression linking the P2 service level with the reorder point s, can be seen below. The first expectation reflects the excess demand during the lead time that cannot be met due to the reorder level being s, ergo, the backorders. Furthermore, assuming the net inventory is always positive when a random replenishment arrives to the stockpoint, the second expectation is reduced to zero and, thus, can be dropped from the equation.

$$P_2 = 1 - \frac{1}{Q}\left(E[(D((\tau_1, \tau_1 + L_1] - s)^+] - E\left[\left(D(0, L_0] - (s+Q)\right)^+\right]\right)$$

τ_i: i^{th} $moment\ of replenishment$

L_i: $lead\ time\ for\ i^{th}\ replenishment$

With the above formula, P2 can be determined numerically under the assumption that $D((\tau_1, \tau_1 + LT_1]$ and $D(0, L_0]$ have a normal or gamma distribution. Calculation of the reorder point *s* for a given $P_2 = \beta$ is also done numerically, by means of bisection or a similar method. Here we use the fact that P2 is strictly ascending in s. So the assumption of non-negative net stock levels after replenishment is only needed in order to use tables for the calculation of the reorder point. More analytical mathematical derivations of the expectation and variance and variance of the lead time demand can be found in the analysis of Silver, Pyke and Peterson (1998) and a numerical calculation for the safety factor using the Gamma distribution can be seen in papers such as the one from Strijbosch & Moors (1999).

3.4.2 Assumptions

The original assumptions used in the single-echelon analysis by SPP are:

1. Lead time demand is normally distributed.
2. At the moment of ordering the stock position is exactly equal to *s.*
3. Subsequent orders cannot overtake each other; so: an order placed later cannot arrive earlier.
4. Delivery times are constant and equal to *L*.
5. The net inventory after arrival of an order is positive.

Implicitly, there are two more assumptions used:

6. The reorder quantity is constant and equal to *Q*.
7. All demand which cannot be met immediately from stock is backordered.

However, as explained in the previous section, the analysis by De Kok provides analytical derivations for more general setups. For the sake of this analysis, the assumptions that will be used are:

- Assumption 2: The effects of undershoot will not be analyzed.
- Assumption 3: Elimination of this assumption is not sensible in the framework of our present model. So, assumption 3 has a general validity.
- Assumption 5: The net inventory after arrival of an order is positive, according to this assumption. This is realistic if $Q \gg D(0, L]$. It only regards the expression for P2. So, assumption 5 is only needed in order to use tables for the calculation of the reorder point.

3.5 Multi-echelon modeling

The multi-echelon modeling will be carried out using the simulation software ChainScope. Below are presented its basic mathematical principles and modes. Excerpts on its functions and underlying concepts where taken from the previous Master Theses of van Cruchten (2016) and van Wanrooij (2012).

3.5.1 Introduction to ChainScope

ChainScope is a program designed to analyze the complete supply chain of an organization, from production to distribution, from a multi-echelon perspective. With the program it is possible to analyze the current performance of a supply chain through an evaluation and it is possible to identify what the stock division should be in an optimized the supply chain. Whereas in the evaluation the average target stock is taken as fixed input data, in the optimization the inserted average target stock is ignored so that the program can calculate the optimal stock levels per tier. The program takes into account the supply chain until the last stock point owned by the organization, i.e. for Hilti this means that the transportation time from the last stock point (e.g. the CW or the DC for the given scope and supply chains) to the customer and the costs of this transportation are not taken into account. Customer-location combinations can be defined and for each of this combination the expected demand and standard deviation have to be inserted. For Hilti this means that a distinction can be made between the customers that buy at HCs and those that by at DCs. Furthermore, we would like to point out that ChainScope is based on mathematical models. This means that, actually, it is a calculation based on the demand characteristics, not a discrete-event simulation.

3.5.2 Model solving 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 in Appendix F. All relevant mathematical concepts 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 (2005).

SBS relies on a finding in De Kok and Visschers (1999). In this paper, the researchers 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. Having established this artificial hierarchy, which is based on the BOM structure and the planned lead times, the divergent decision node network is constructed Appendix G. 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.

3.5.2.1 Key model inputs

3.5.2.1.1 Demand mean and standard deviation

The demand input for ChainScope refers to customer demand only. Therefore, for the upstream locations that meet both customer demand and internal replenishment orders, such as the CWs in the Power Tool supply chain or the HQ warehouse in the Anchor supply chain, the software is fed with demand figures determined from customer order lines and consignment stock requests that are treated equivalently. The remaining part of the demand is generated by the software using the BOM and the item-locations relationships. Due to the nature of a distribution network, the BOM relationships are always 1 to 1. On the other hand, the demand input for the downstream locations on both supply chains is the total demand seen at each specific location. Even though in the actual supply network of Hilti these locations are in their majority intermediate stockpoints that meet both customer and internal replenishment demand, these cannot be treated independently due to scope limitations.

In a similar fashion to the demand input of the single-echelon models, the daily mean and the standard deviation of the customer demand are the two demand inputs of the model.

3.5.2.1.2 Expected lead time

In a multi-echelon environment, the component of the total RLT that needs to be considered is the throughput time of each stockpoint. The throughput time includes solely transport and warehouse operations. As was already mentioned, the lead time between stock points show stochastic variations. These variations are caused primarily by limited upstream availability and in second degree by delays in warehouse and transport operations, such as supply route disruptions, fixed shipping schedules, human errors and so on. Any delays due to upstream availability are, in this case, calculated and dealt with by the software engine.

In contrast to the lead time input of the single-echelon model, the nominal transport duration from SAP is used, which is conveniently comprised by the expected transport and warehouse processing times. The variability measurement is provided by the *delay FXr* KPI, which measures any positive delay in shipments on top of the agreed delivery time. Finally, for the data to be reliable, the shipments considered were only the ones carried out within the same time frame that demand is measured. Additionally, outliers were ignored to avoid misleading influences from old/temporary routes or emergency shipments.

To implement the lead time variability into ChainScope, which only uses a lead time expectation input, a simple method was used to calculate time buffers added on top of the expected values. Using the assumption of normally distributed lead times, this time buffer is calculated using the delay component as the lead time deviation and considering a coverage over the 95% percentile of the distribution of lead times. The rest of the observations seen in the end of the lead time curve tail, is assumed to be taken care of by operational flexibility measures.

$$Planned\ lead\ time = \mu_L + \Phi^{-1}(0.95)\sigma_L$$

$\mu_L: Lead\ time\ expectation, expected\ delivery\ time$

$\sigma_L: lead\ time\ variability, average\ delay$

3.5.2.1.3 Target stock

The average inventory level of the stockpoint, calculated from the daily stock level values. It is directly influenced by the cycle stock and the safety stock. In the evaluation mode of the software, the target stock is used as an input, with the performance measurement being the achieved service level. On the other hand, it is the output of the optimization mode which calculates the optimal target stock according to the required service level.

3.5.2.1.4 Added value

The various costs generated by the supply chain operations to transform and move an item downstream towards the customer reflect the value added to it. In the most upstream point of the scope, the finished goods stock of the production plant, an item’s value is equal to the COGS. As it moves from one stockpoint to another, though, it’s value is increased by the transport and warehouse handling costs. The inventory holding costs at each stockpoint are calculated as a percentage of the unit’s current value. Finally, to create an accurate approximation of the transport costs, the rates are calculated assuming that the truck or sea freight shipment is always a full container. The transport costs are single-dimension variables as the source location of each stockpoint is unique.

$$V_{ij} = COGS + \sum_{j \in P} \left(\frac{t_j}{100} w_i + q_j \right)$$

$V_{ij}: Value\ of\ product\ i\ in\ stockpoint\ j$
$t_j: Transport\ cost\ per\ 100kg$
$w_i: product\ weight$
$q_j: Fixed\ order\ processing\ cost\ per\ order\ line\ in\ warehouse\ j$

3.5.2.1.5 BOM Structure

The BOM structure is the list of the raw materials, sub-assemblies, intermediate assemblies, sub-components, parts and the quantities of each needed to manufacture an end-product. The networks in scope are pure distribution systems, hence, the relation between items of predecessor and successor stockpoints is always 1 to 1.

3.5.2.1.6 Other inputs

Other input parameters of ChainScope are:

- *Yield*: always equal to 1 in a distribution system
- *Review period*: 1 day
- *Average order size*: according to the packaging quantities and EOQ
- *Customer order lead time*: 0 days, stockpoints delivery instantly
- *Margin*: not considered
- *Max stock*: no warehouse capacity restrictions considered

Other data fed to the ChainScope engine are the item codes, descriptions and classes, customer information, service level targets on item-customer level, and the inventory holding cost percentage.

3.5.3 ChainScope evaluation mode

ChainScope's evaluation mode is based on analytical expressions and not on a discrete event simulation. It is used to validate the base model. The validity check takes place by assessing whether the simulation model behaves as expected and the results are in line with reality. The model inputs are based on data gathered from activities during the past 12 months and the model outputs are compared with the real-life measurements at Hilti for September, which is considered as the running month. For most of the stock locations August is a low activity month with significantly less demand (fraction of the rest of the year's average). However, demand planning and safety stock levels are adjusted accordingly to avoid stock outs from the increase in demand. Thus, for both items we would still expect ChainScope to deliver a performance above the general ambition target of 98% and much closer to 100%, relevant to that of the previous months and a common property of all high-contribution to turnover, fast-runner products of the portfolio of Hilti.

3.6 Validation of the models

In real-life operations, flexibility measures exist which cannot be considered when simulating inventory using models. The effect that these measures have, is that the modeled performance of a stockpoint is oftentimes lower than the actual reported performance. On the other hand, the effect of human influence can also have negative effects on the outcome of the operations. Together, these influences can generate deviations between modeled and actual supply chain performance due to the following facts:

1. *__Stricter definition of service level:__* The definition of fill rate in the models does not allow any flexibility when an item is not available directly. However, delivery dates can be postponed in real-life operations or an emergency shipment can be used, without affecting the performance of the stockpoint. This is the reason for the existence of the various KPIs (ATS, PA, CPOi, OTA etc.) relevant with product availability and on-time delivery.
2. *__Human interference:__* Human interference affects performance both positively, aiming to correct undesired situations such as a stock-out, and negatively, by manually setting safety stock levels or selecting sub-par calculation methods, late booking of goods receipt, missing the cut off time/date for orders, errors, mistakes etc. On the positive aspect, the flexibility is offered in different forms of lead time reducing activities that happen in practice, but cannot be included in the models. Lead times for orders can be reduced by rescheduling to allow for priority orders instead of FIFO processing, creating combined shipments for multiple products, such that items arrive earlier, air freight emergency shipments or inter-company sales, and, lastly, the postponement of promotional orders.
3. *__Data reliability:__* Deviations are also caused by estimations, variability in historical data, and deviations between SAP data and actual data.

The analysis of the supply chain using single-echelon modelling yields results which are very close to the reported performance. The deviation of the average actual and modelled performance is 0.33% for the Power Tool and 1.3% for the Anchor SC. As expected, the models underestimate the performance of the stockpoints in their majority, verifying the anticipated effect of the non-modellable flexibility measures. Furthermore, the bulk of the results fall into the diagonal of the performance comparison matrix presented in the next chapter, indicating that the models are valid.

Regarding modelling with ChainScope, this modelling approach is not appropriate to evaluate the current performance of the SCs. The inventory control paradigm is not comparable to the MRP II logic currently used, where the planning is performed for each individual location, considering only local parameters. Insights can still be drawn, though, by evaluating and optimizing the SCs with the software, on how the two paradigms compare with each other and how the system behaves under a multi-echelon control redesign.

4 Results

Chapter 4 reports and explains the results generated by solving the models. The supply chains are evaluated and optimized for the target service level of 98%, then analyzed under various optimization scenarios that will provide insight on the impact of the uncertainty factors. Section 4.1 presents the results of the supply chains' evaluation. The optimal stock levels under given set up are given in section 4.2. Section 4.3 shows the impact of the influence factors on the stock levels. Section 4.4 compares discusses the accuracy and effectiveness of the Hilti method reduction targets.

4.1 Evaluation of the supply chains

The performance of the two supply chains is evaluated by using two different paradigms of inventory modeling, single-echelon and multi-echelon modeling. Under the given operational set up and uncertainties' influence, the models use the average inventory levels as input and calculate what is the achieved fill rate. As a reference point for the comparison of the modeled with the actual supply chains, the AS-IS performance metrics are shown in the table below in Table 5.

Table 5 Actual supply chains reported performance

Power Tool SC			***Anchor SC***		
Location	**Fill Rate**	**Profile**	**Location**	**Fill Rate**	**Profile**
6000	96.24%	(Q,V,G1)	0506	-	(Q,V,G1)
6004	96.75%	(Q,V,G1)	0550	99%	(Q,W,G2)
6120	99.47%	(R,W,G2)	0900	98.11%	(Q,V,G1)
6134	99.17%	(Q,V,G1)	0980	94.02%	(Q,W,G2)
6135	98.12%	(Q,W,G1)	2100	98.41%	(Q,W,G2)
6140	97.59%	(R,W,G2)	2600	100%	(Q,W,G2)
6145	99.88%	(Q,V,G1)	3300	100%	(Q,W,G2)
6150	98.92%	(Q,V,G1)	4400	98.53%	(Q,W,G2)
6160	98.63%	(Q,V,G1)	7500	98.78%	(Q,V,G1)
6805	97.46%	(Q,V,G1)	8110	95.04%	(Q,V,G1)
6815	96.53%	(Q,V,G1)	8120	95.83%	(Q,W,G2)
6820	98.98%	(Q,W,G2)	8130	91.72%	(Q,W,G2)
			8140	99.33%	(Q,W,G2)
			8150	98.23%	(Q,V,G1)
			8180	99.75%	(Q,V,G1)
			9150	99.66%	(Q,W,G2)
Overall	**97.97%**		**Overall**	**94.91%**	

As seen above, there are cases where the average service level was significantly higher or lower than the target service level of 98%. If a service level is higher than needed, then probably the stock in the distribution network of these SKUs was higher than needed. In other words, if the stock of these SKUs is lowered, still the desired service levels can be met but against lower costs. On the other hand, locations with low performance indicate that the allocated stocks were insufficient to buffer against the uncertainties and a higher investment is necessary to reach the service level targets.

Comparing the actual with the modeled performance, one can extract different insights, depending on the modeling paradigm that is used. Applying single-echelon models, which is similar to the MRP planning logic currently employed by Hilti, the comparison of the performances will highlight what is the extent of the human interference on the planning and execution processes. If the modeled inventory performs better than the actual, the influence of human interference on the various operations has an overall unfavorable impact. On the contrary, if the actual supply chains perform better than modeled ones, the operational flexibility offered by the human factor is beneficiary. Putting all cases of actual and modeled performance into an array, one can form a matrix indicating the positive, negative or no influence of human interference. Results on the diagonal indicate the validity of the models, while results above and below the diagonal indicate significant positive and negative influence respectively. Intuition suggests that no results will be placed above the diagonal of the matrix.

Table 6 Possible outcomes of single-echelon evaluation

Modeled Actual	< 95%	95-98.5%	>98.5%
< 95%	Insufficient stock	negative influence	negative influence
95-98.5%	positive influence	on par performance	negative influence
>98.5%	positive influence	positive influence	overstock

4.1.1 Single-echelon models

Using single-echelon inventory models with an (R,s,Q) control policy and a forecasted demand input, lead to a very similar set up with the inventory management framework at Hilti. As thoroughly explained in the previous chapters, replenishment orders in the actual supply chain are released whenever there is a *Net Requirement* generated, based on a planned inventory netting procedure. Direct results of the single-echelon modeling evaluation, is the maximum theoretical service level that can be achieved under the given inventory investment. The achieved service level is calculated by feeding the model the respective reorder point of each individual location. A comparison between each location's actual and evaluated performance can be seen in the two charts below.

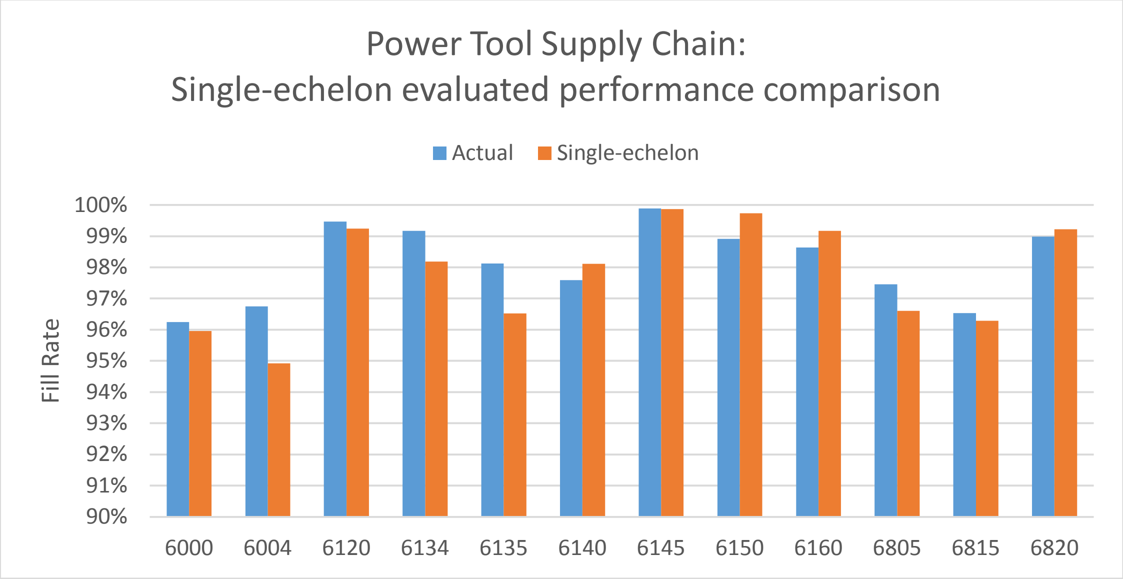


Figure 4.4.1 Performance of actual and modeled Power Tool supply chain

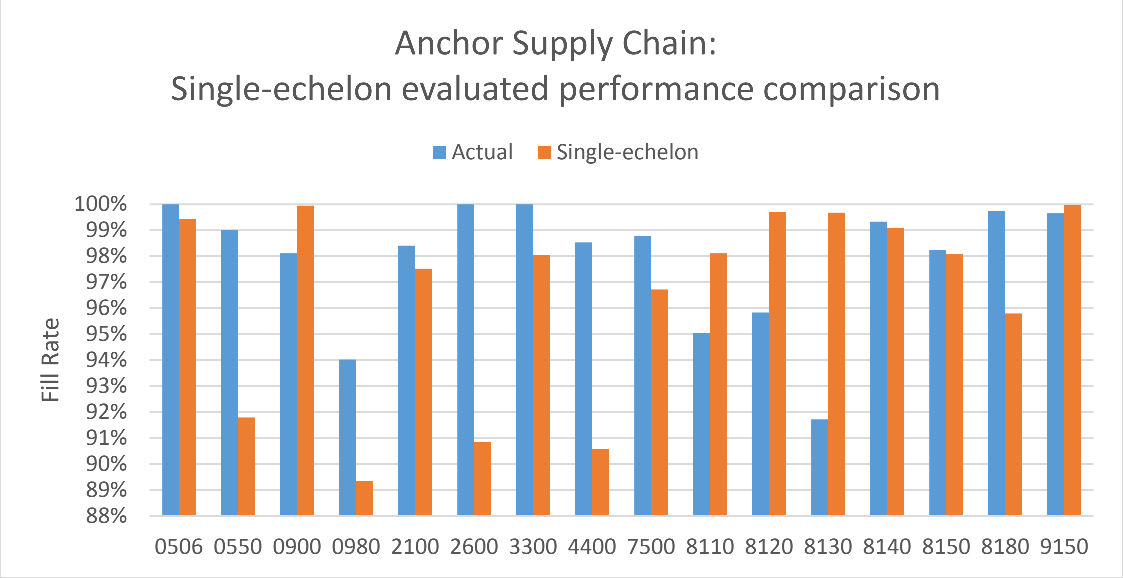


Figure 4.4.2 Performance of actual and modeled Anchor supply chain

One can observe that in many stockpoints, the evaluated fill rate is close to 100%. Considering that the evaluated inventory performance of these locations is higher than the target service level, it is a strong indicator that some of the stocks Hilti currently maintains are superfluous. This means that current stocks at those locations are higher than necessary to achieve the 98% target, indicating potential for reducing inventory sizes, tied up capital and, also, reducing the risk of obsolescence. On the other hand, the results also show that there are also locations which do not reach the target performance due to insufficient inventory levels. By taking into account that the safety stock levels are frequently not tied to performance or the uncertainties seen in each location, one can assume that overstocking and understocking, is a general phenomenon, also seen in further locations and items. Therefore, it is deducted that real issue that the Hilti SCs face is not simply superfluous inventories, but rather inaccurate inventory target setting.

Furthermore, the results show that for most of the locations the actual performance is higher than the modelled one. As expected, in these situations the human influence and flexibility measures previously discussed have a positive effect on the operations, and the stockpoint is achieving higher performance than the one expected according to theory. There are a few exceptions, though, where the outcome of the models evaluation is higher than the reported performance. In these three cases, the most probable explanation is either bad quality of data or some sort of disruption in the supply chain operations. The claim is also backed by the fact that it involves only the Anchor and the locations are situated in the same region. Regarding the Power Tool, three stockpoints were found higher modeled performance than the actual one, but the deviation was not significant. As these three locations are small DCs and the demand was scarce, the probability of inaccurate statistical data is higher and, thus, the unexpected results. Finally, for CWs 2600 and 4400 in the Anchor SC, one may notice a significant gap between the two measurements.

Placing the results of the single-echelon evaluation on the matrix presented in section 7.1, the following array is obtained. In general, the results are placed in the lower diagonal part, according to expectation. Apart from the observation that most of the locations fall into the middle and lower-right part of the array, the sample size and the distribution of the results do not allow for extracting further insights on the behavior of the items per their profile classification. The equivalent of Table 7 with the item profiles can be seen in the Appendix H.

Table 7 Single-echelon evaluation outcome

Modeled **Actual**	< 95%	95-98.5%	>98.5%
< 95%	0980		
95-98.5%	6004, 4400	6000, 6135, 6140, 6805, 6815, 2100, 7500, 8110, 8150	0900, 8120, 8130
>98.5%	0550, 2600	6134, 3300, 8180	6120, 6145, 6150, 6160, 6820, 0506, 8140, 9150

4.1.2 ChainScope modelling

ChainScope provides additional insight to the model analysis, by reporting each location's performance from two different perspectives: measuring the achieved performance on item level, considering the overall demand arriving at the stockpoint, including both end-customer and internal replenishment demand, and, also, measuring the performance on end-customer demand only. The motivation for two different service level outputs is clear, as apart from monitoring over the total order lines, key objective of a supply chain is to deliver to the customer on-time and with the minimum required capital investment. Thus, the latter acts as a more accurate KPI. The two measurements show significant variations between them, evidence of the operational flexibility that the control concept of SBS provides: while for the upstream stages stockpoints, the fill rate on item level can be as low as 46%, the end-customer performance is flawless. Hence, more efficient use of the stock. On the other hand, the measurement is identical for the downstream locations, where all incoming demand is coming from the customer. The evaluation results of the two supply chains are presented below in Table 8.

Table 8 ChainScope evaluation results

	Power Tool SC			***Anchor SC***	
Location	**Item Fill Rate**	**Customer Fill Rate**	**Location**	**Item Fill Rate**	**Customer Fill Rate**
0504	0%	-	0506	81%	-
6000	56%	100%	0550	46%	100%
6004	58%	100%	0900	100%	100%
6120	98%	98%	0980	88%	88%
6134	90%	90%	2100	98%	98%
6135	90%	90%	2600	51%	51%
6140	93%	93%	3300	99%	99%
6145	80%	80%	4400	90%	90%
6150	80%	80%	7500	100%	100%
6160	84%	84%	8110	100%	100%
6805	70%	70%	8120	99%	99%
6815	67%	100%	8130	99%	99%
6820	98%	98%	8140	100%	100%
			8150	100%	100%
			8180	100%	100%
			9150	100%	100%
Overall	**80.38%**	**90.3%**	**Overall**	**90.10%**	**94.91%**

The multi-echelon model evaluation results exhibit contrasting results for the two SCs. First thing to notice is the large gap between the performance of the upstream and downstream stockpoints of the Power Tool SC. Even though the three CWS (6000, 6004 and 6815) manage to deliver to customer with 100% fill rate, the actual item fill rate at these locations is rather low. Hence, the low performance for many DCs. On the other hand, the stockpoints of the Anchor SC deliver high performance, greater than the target and close to 100%. There are, however, three easily spotted outliers. The first two, CWs 0980 and 4400, show lower performance comparing to the rest of the downstream warehouses, yet, their performance is on par with results of the single-echelon evaluation. The third is CW 2600, where paradoxically, the performance measurement is only 51%. A possible explanation of the result is the high coefficient of the demand variation calculated for the location in conjunction with the 46% overall delivery performance of the upstream HQ warehouse (0550). Van Wanrooij (2012) in her master thesis project also argues that any stockpoint with a demand coefficient of variance over 1.33 is uncontrollable, hence, the counter-intuitive result. The same applies for locations 4400and 0980. The evaluation result for the production plant in the Power Tool supply chain (location 0504) is 0%, because as explained in the previous chapter, the plant operates under a PTO policy with no finished goods stock. Hence, incoming demand is never met directly.

4.2 Optimization of stock levels

The stock levels of the two supply chains are optimized by using two different paradigms of inventory modeling, single-echelon and multi-echelon modeling. Under the given operational set up and uncertainties' influence, the models use the target fill rate of 98% as input and calculate what is the optimal inventories. An inventory level is the optimal one, when the target performance is achieved under minimum capital investment. As a reference point for the comparison of the modeled with the actual supply chains, the AS-IS safety stocks and average stocks, as reported by the BI database, are shown in the table below in Table 5.

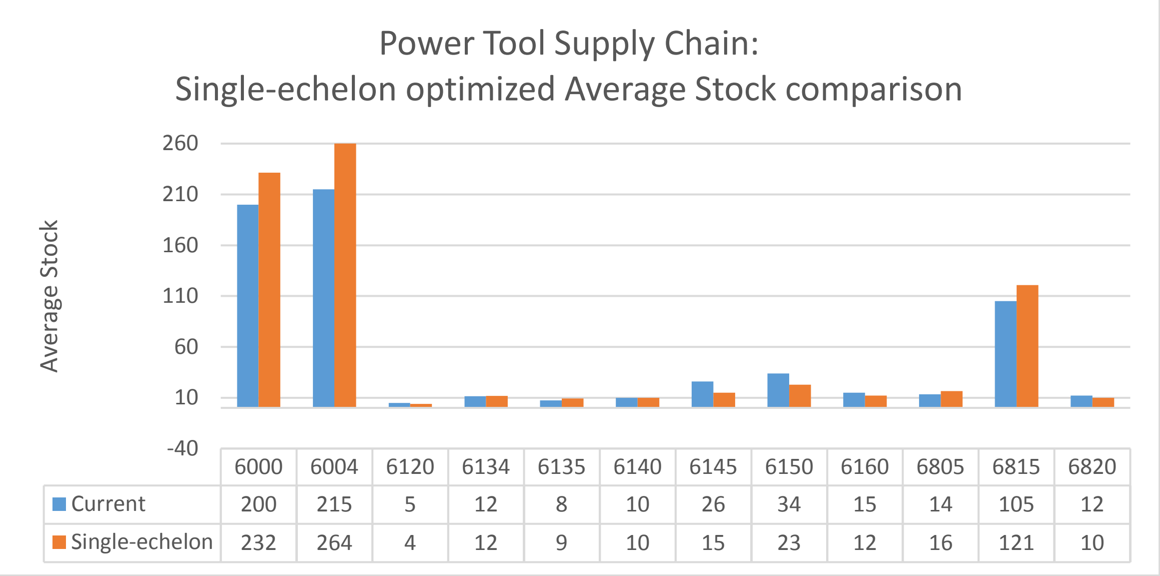
Table 9 Actual supply chains AS-IS safety and average stocks

	Power Tool SC			***Anchor SC***	
Location	**Safety Stock**	**Average Stock**	**Location**	**Safety Stock**	**Average Stock**
6000	35	200	0506	7543	10043
6004	28	215	0550	400	880
6120	4	5	0900	5069	6269
6134	10	12	0980	663	1143
6135	6	8	2100	700	940
6140	8	10	2600	47	127
6145	23	26	3300	182	262
6150	28	34	4400	127	207
6160	13	15	7500	2040	3000
6805	10	14	8110	1500	2220
6815	28	105	8120	990	1230
6820	10	12	8130	191	271
			8140	559	719
			8150	1500	2080
			8180	791	1031
			9150	1884	3004
Total	**203**	**243**	**Total**	**24186**	**29376**

Calculating optimal inventories with single-echelon analysis, provides direct insight to the question whether the stock levels maintained by Hilti excessive. It also verifies the results from the evaluation runs referring. Intuition calls for the locations which had their performance evaluated as higher than the actual target, will also have superfluous stock levels and, therefore, the optimized ones will be lower. Accordingly, stockpoints found operating with performance lower than the target, are expected to have their stock levels increased to reach the optimal level. It will be also interesting to look for counter-intuitive results and assess the reasons behind their emergence. Such a result would be, for instance, stockpoints being evaluated with sub-par performance, yet, seeing their optimal stock levels being lower than the current ones.

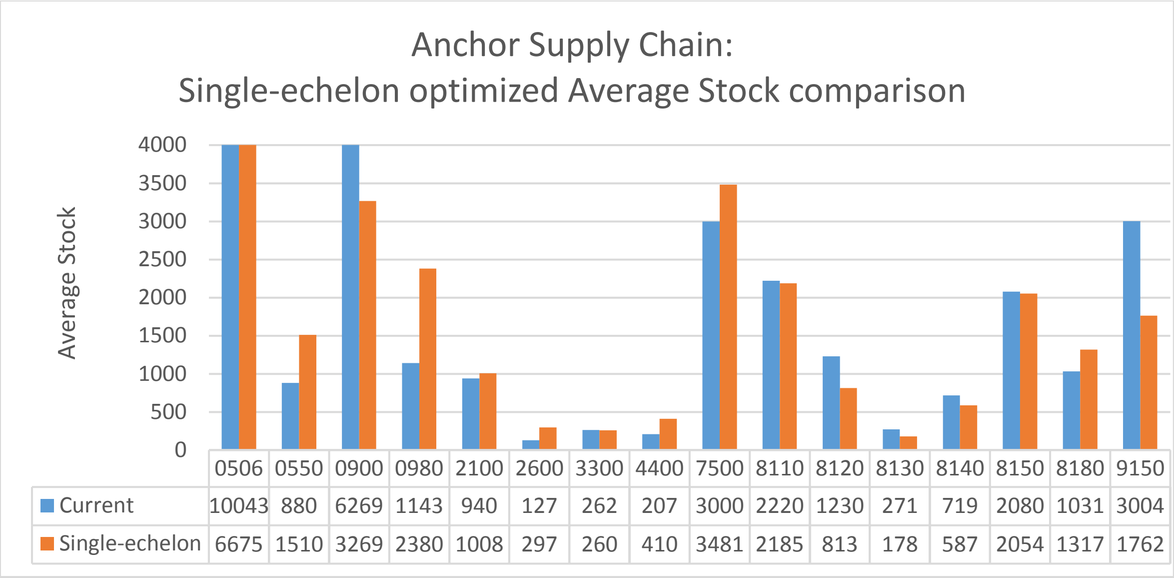
4.2.1 Single-echelon models

Using single-echelon inventory models with an (*R,s,Q*) control policy leads to a very similar set up with the inventory management framework at Hilti. As already discussed in the previous chapters, replenishment orders in the actual supply chain are released whenever there is a *Net Requirement* generated, based on a planned inventory netting procedure. Direct results of the single-echelon modeling optimization, is the minimum theoretical stock level that can be maintained under the given constraint of target fill rate. The primary outputs of the model are the optimal reorder point *s* and the average inventory, which are calculated by setting the target service level of each individual location. Subsequently, by subtracting the lead time demand from the reorder point, the optimal safety stock level is derived. A comparison between each location's current and optimized average stock levels is presented in the two charts below.



	6000	6004	6120	6134	6135	6140	6145	6150	6160	6805	6815	6820
■ Current	200	215	5	12	8	10	26	34	15	14	105	12
■ Single-echelon	232	264	4	12	9	10	15	23	12	16	121	10

Figure 4.4.3 Current and single-echelon optimized Power Tool supply chain



	0506	0550	0900	0980	2100	2600	3300	4400	7500	8110	8120	8130	8140	8150	8180	9150
Current	10043	880	6269	1143	940	127	262	207	3000	2220	1230	271	719	2080	1031	3004
Single-echelon	6675	1510	3269	2380	1008	297	260	410	3481	2185	813	178	587	2054	1317	1762

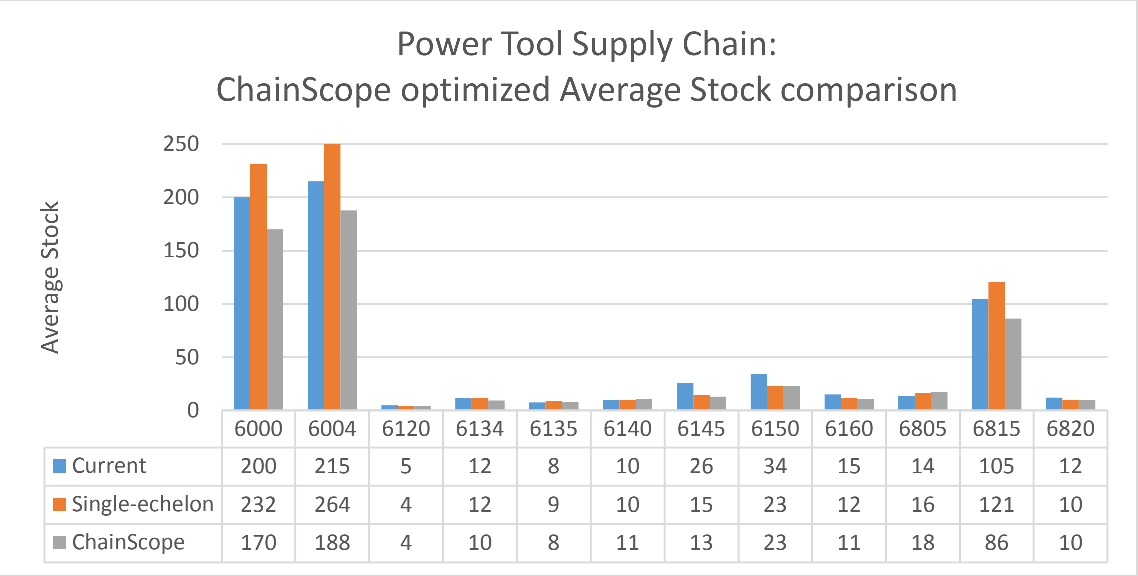
Figure 4.4.4 Current and single-echelon optimized Anchor supply chain

The analysis shows opposite results for the two supply chains. The total optimized stock level of the Power Tool SC is higher than the current one by 16%, while, for the Anchor SC the total optimal stock level is lower by 11%. The optimization results are in line with the findings of the previously discussed evaluation. In the previous section, it was shown that the average evaluated performance was found lower than the target for both SCs, with that of the Power Tool only by a fraction. What makes the difference, is that the three major CWs distributing the Power Tool were found underperforming. Given the large volumes of sales from these locations, the optimized safety stock levels are high enough to affect the result of the entire supply chain. On the opposite, the majority of the stockpoints in the Anchor SC were evaluated higher than the target. Yet, although four of them scored low (approximately 90% fill rate), the increase in the safety stock was insignificant comparing to the reduction seen in the rest of the SC.

The total percentage increase by optimizing the stock levels of each individual location under single-echelon analysis, is 36% and 11% for the Power Tool supply chain safety stock and average stock levels, while the respective reduction seen in the Anchor supply chain location being 22% and 16%. Significant reduction is seen in the finished goods stock of the PP of the Anchor (0506), where the SS is almost eliminated, where, although the production batch size is large enough to cover a large fraction of the demand variability, there was a substantial amount of safety stock maintained. Further large reductions are spotted in CWs 0900 and 9150, where the performance is evaluated close to 100%. Finally, as a last note, the percentage reduction or increase of the average stock is always lower than that of the safety stock. This is expected since the average stock is a function of both the safety stock and the cycle stock with the latter remaining fixed.

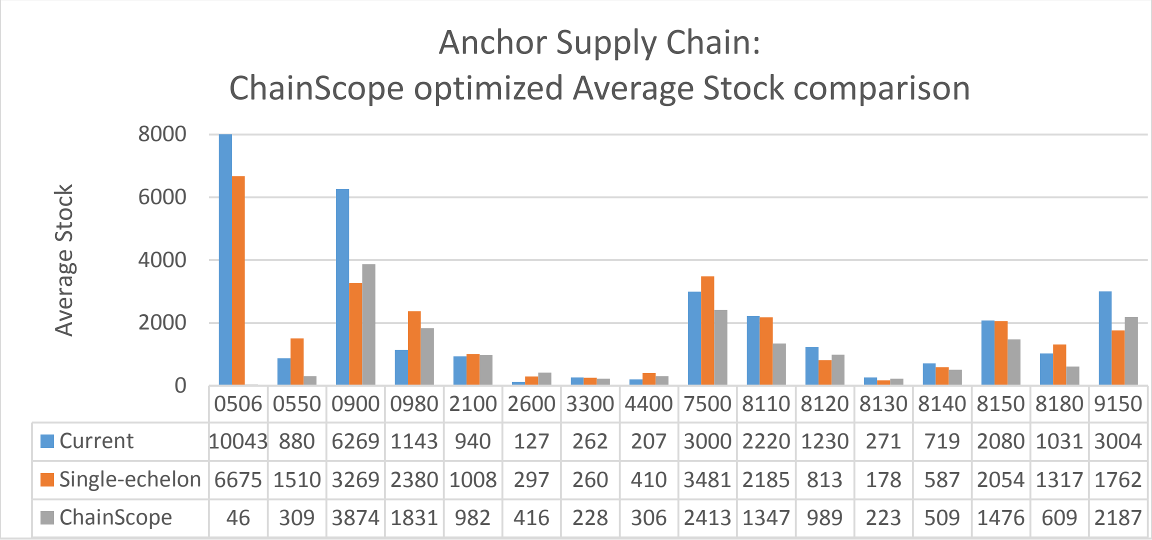
4.2.2 ChainScope modelling

ChainScope's inventory control concept maximizes the efficiency of the stock capital investment. This is achieved by optimizing all the stockpoints of the supply chain simultaneously and, furthermore, by utilizing all bits of relevant information in the supply chain and releasing material feasible orders only. This allows for calculating the optimal allocation of inventory across the various tiers of the SC and, additionally, optimally allocating the existing stocks by ensuring material feasibility and minimization of customer backorders. Primary output of the optimization mode is the average stock level per location. In a multi-echelon setting, it is reasonable to focus the analysis mainly on the average stocks, because safety stocks lose their relevance under many optimal policies. In fact, as these become push systems with low or no stock at upstream stages, these are translated into negative safety stocks from a single-echelon perspective. Hence, the optimal safety stocks are presented but are of secondary importance. The results of the multi-echelon optimization are shown in the charts below.


Power Tool Supply Chain:
ChainScope optimized Average Stock comparison

	6000	6004	6120	6134	6135	6140	6145	6150	6160	6805	6815	6820
🟦 Current	200	215	5	12	8	10	26	34	15	14	105	12
🟧 Single-echelon	232	264	4	12	9	10	15	23	12	16	121	10
⬜ ChainScope	170	188	4	10	8	11	13	23	11	18	86	10

Figure 4.4.5 Optimization of Power Tool supply chain


Anchor Supply Chain:
ChainScope optimized Average Stock comparison

	0506	0550	0900	0980	2100	2600	3300	4400	7500	8110	8120	8130	8140	8150	8180	9150
🟦 Current	10043	880	6269	1143	940	127	262	207	3000	2220	1230	271	719	2080	1031	3004
🟧 Single-echelon	6675	1510	3269	2380	1008	297	260	410	3481	2185	813	178	587	2054	1317	1762
⬜ ChainScope	46	309	3874	1831	982	416	228	306	2413	1347	989	223	509	1476	609	2187

Figure 4.4.6 Optimizations of Anchor supply chain

As seen in the charts with the results of both supply chains, ChainScope provides by far the most efficient inventory management approach, by achieving the 98% service level target with the lowest average stock levels. It becomes apparent from the comparison of the two paradigms, that in a multi-echelon environment that faces various uncertainties, the versatility of being able to simultaneously optimize the inventory levels of various stockpoints by setting the right target average stocks and, moreover, allocate on-hand stocks according to global information, generates a significant strategic advantage. The total average stock maintained in the system is 727 and 14352 pieces for the Power Tool and Anchor SCs respectively, using single-echelon modelling. On the contrary, the average stocks achieved by the optimization performed by ChainScope under the same set up are 551 and 11686. Percentage-wise, the total average inventory of the two supply chains is reduced by 24% and 19% by switching to multi-echelon control. Detailed tables with the results of the ChainScope optimization run can be seen in Appendix J. Further tables providing the comparison between the optimization results can be seen in Appendix K.

4.3 Calculation of the influence factors impact

Aiming to calculate the impact that uncertainties have on the inventory levels, a number of scenarios was created, in which one of the factors is parameterized each time and the stock optimization process is repeated. Chapter 3 discusses thoroughly the uncertainties faced by the distribution networks of Hilti. These two come in the form of supply uncertainty, expressed as replenishment lead time variance, and demand uncertainty due to the demand stochasticity, causing deviations between forecasted and actual demand. Moreover, the effect of the target service level will be calculated. Since an optimal service level cannot be accurately calculated, because of the presence of intangible understock costs, the company’s management has set its ambition target to 98% fill rate. Whether this setting is cost-efficient is debatable and is not part of this project. Nevertheless, it is commonly seen that the safety stock levels for fast running items, especially in important markets that contribute highly to the total company turnover, are manually set to cover 99% or even 99,99%. Literature clearly indicates that the service level curve become increasingly steep after the 95th percentile of demand coverage, meaning that the required increase in safety stock becomes too high for ever-decreasing service level gains.

The impact of the influence factors is calculated both with single-echelon and the multi-echelon modelling. The parametric analysis under the single-echelon paradigm provides quantitative insight on the stock behavior as a function of the extent of the uncertainties. On the other hand, studying the effect that these uncertainties have on the same locations under a different theoretical control concept, will show their sensitivity level under various levels of them. Finally, showing the variance between the impact on each different location and item, it will be revealed how accurate a target setting process can be, by treating all stockpoints within turnover clusters the same and creating inventory targets on warehouse level, ignoring the underlying differences on item level.

Apart from the service level sensitivity analysis which tests different service level targets, the scenarios for the other two factors are created by adjusting the current level of uncertainty of each location. Considering the demand variability, the optimization is first performed for a case where all locations meet incoming demand subject to 50% less variability, comparing with the current measurements. Subsequently, the optimal stocks are calculated again for an instance where there is almost perfect information from the market and the demand variability is reduced to 10% of the original one. In the same fashion, the current lead time variability levels are first reduced to 50%, then eliminated. The overview of the scenarios design is presented below in Table 11.

Table 10 Scenario design

Factors **Scenario**	Service Level	Demand Variability	Lead Time Variability
Target Service Level	parameter	current	current
Demand Uncertainty	98%	parameter	current
Supply Uncertainty	98%	current	parameter

The sensitivity analysis of the service level verifies the expected results, given the existing service level curves. For both optimization approaches, approximately the same inventory investment that raises the service level from 95% to 98%, is required to increase it by 1% to 99%. It is, therefore, confirmed that the efficiency of maintaining high stock levels aiming to achieve a performance close to 100%, is decreasing rapidly.

As for the impact of the demand volatility, the inventory reduction achieved is significant under both single- and multi-echelon analysis. The total impact is close between the two paradigms, 57% for the single-echelon model and 64% for the multi-echelon one. It is interesting to observe, however, that the reduction rate per step is different for the two models. The total average inventory of the single-echelon model initially drops by 23% and, then, by 43%. On the other hand, the total average inventory of the multi-echelon model decreases at a steady rate with each reduction step in the demand variability, 42% and 39%.

A different model behavior is observed when the lead time variability is parameterized. Before presenting the results, one should be reminded of the contrasting lead time input of the two models. On one side, the single-echelon model considers the total replenishment lead time of each stockpoint, considering the period from the moment an order is released, till the moment it is available on stock. In a different manner, the multi-echelon model is fed with a measurement that considers only the transport and the warehousing operations lead times (throughput time). The main difference between the two, is that in single-echelon modelling the delays due to upstream availability are required to accurately calculate safety lead times and, in this case, safety stocks. The topic is discussed thoroughly in the previous sections of this chapter and detailed tables can be seen in Appendix D. Regarding the results, the single-echelon model shows much higher sensitivity comparing to the multi-echelon one. This outcome was expected, since the deviation of the lead time due to availability issues is significantly larger than the deviations in the throughput time of each stockpoint. The total impact of the supply reliability on the single-echelon model is 29%, whereas on the multi-echelon model it is only 8%. A notable observation is that the reduction rate seen in the multi-echelon models is, similarly to the demand variability analysis, rather linear. On the opposite, the reduction rate of the total inventory in the single-echelon model is lowered by half from the first step to the second, 22% after lowering LT variability by 50%, then 9% after eliminating the remaining 50%.

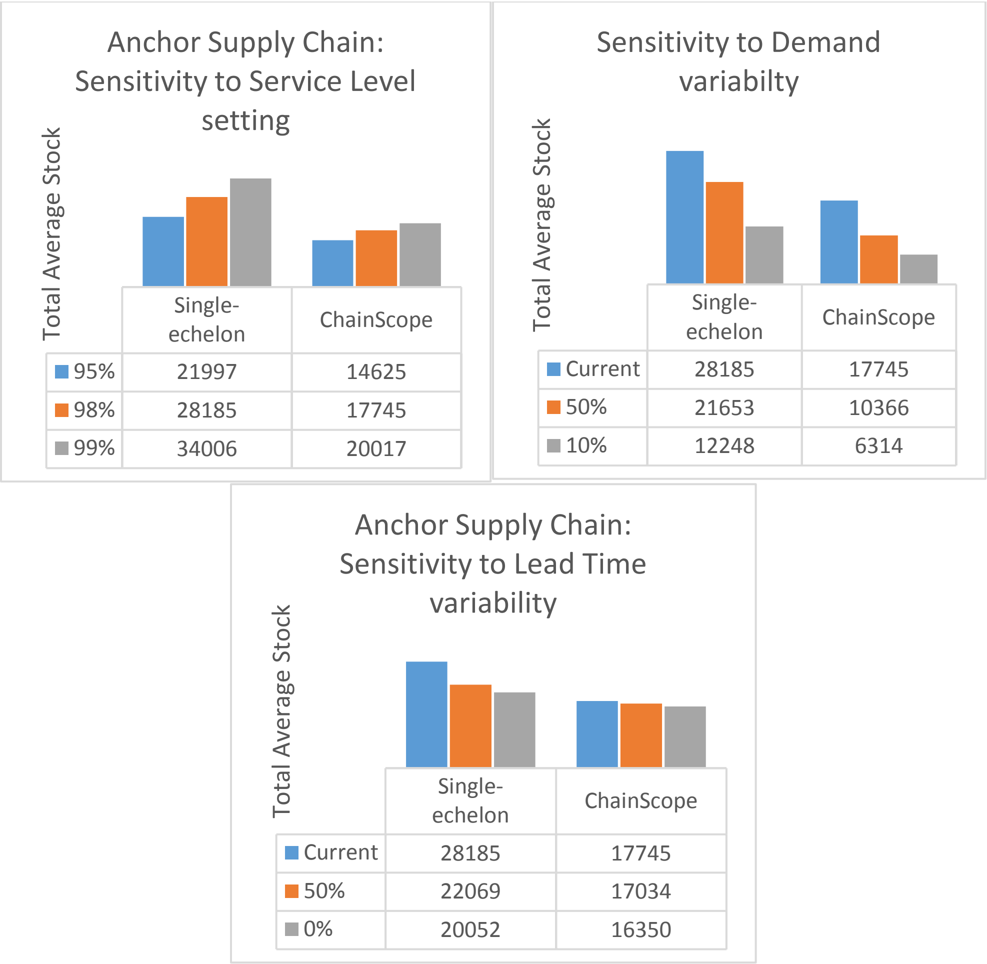


Figure 4.4.7 Scenario analysis for the Power Tool SC

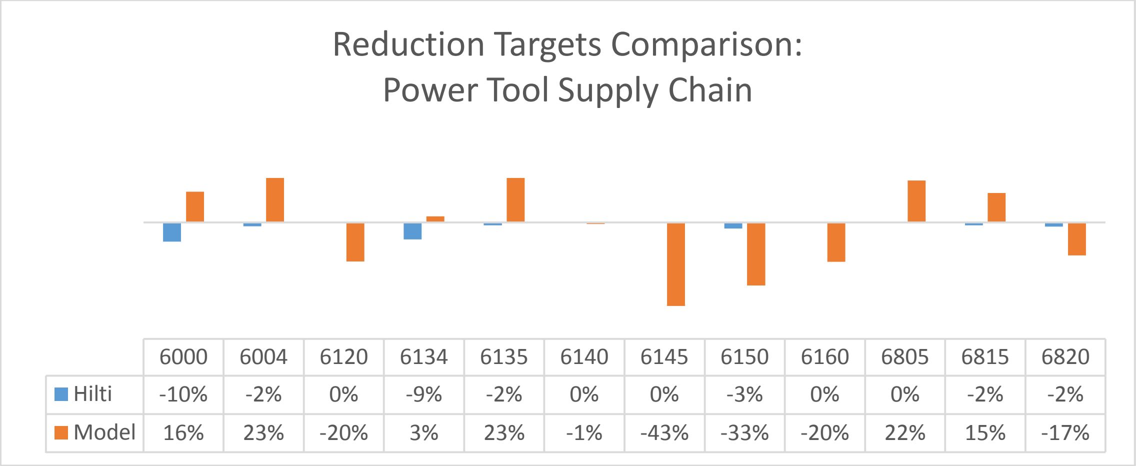
The results of the Anchor SC sensitivity analysis exhibit the same pattern with that of the power tool. The sensitivity to the target service level and the lead time variability shows the same behavior. Slightly different is the reduction rate seen in the demand variability analysis. In that case, both supply chains had their total inventory reduced at a higher rate (13% and 17%), then in the next step the reduction rate dropped to single digits (5% and 9%). The total impact of the demand variation is 17% and 24% respectively. Detailed tables with the results per location for both supply chains, along with the charts for the Anchor, can be seen in Appendix L.

4.4 Assessing the accuracy of the existing inventory reduction rule

Through the models presented in the previous chapters, the optimal inventory levels have been calculated for both supply chains under the AS-IS system condition and given target service level. The optimization approaches used are formal, consider all inputs necessary and, inevitably, are bottom-up methods that optimize the stocks on item level. It is now only left to compare the results obtained from the models with the inventory reduction targets that the established method is calculating for the stockpoints in scope. Section 3.3.1 discusses how the Hilti inventory reduction targets are calculated and why this method is expected to generate inaccurate inventory targets.

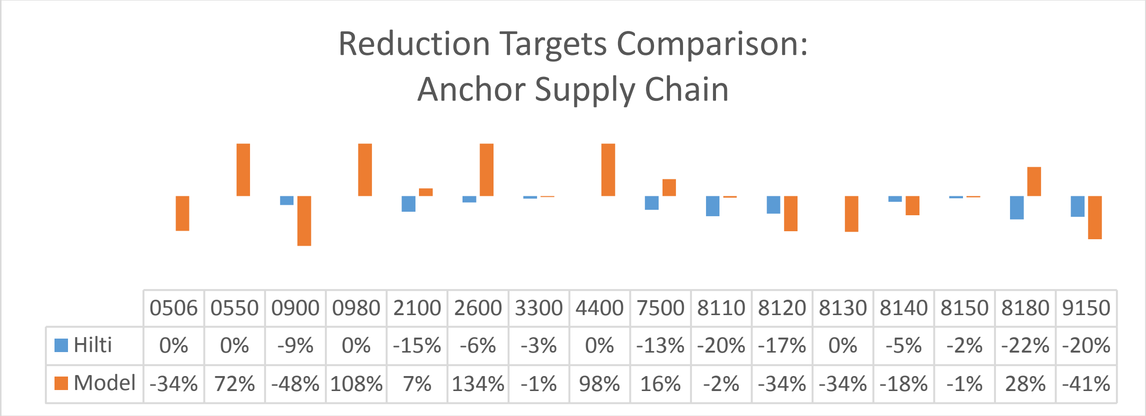
Having said that, one can easily notice the misalignment between the two targets: the Hilti methodology generates reduction targets on location level, while the formal methodology requires for optimals to be calculated on item level, then compared with the existing stocks. To generate comparable targets, the requirement would be to optimize the entire SKU portfolio of each stockpoint or at least an adequate sample size, then, calculate the aggregated difference. Unfortunately, that was infeasible to do in the time span of the project, due to cumbersome effort to collect and analyze the necessary demand and lead time data for each item. However, the underlying assumption that the total inventory adjustment will have a negative sign, is strongly challenged. The outcome of the optimization showed that the stocks of the two items analyzed had to be significantly increased is some locations to theoretically reach the target performance. Even considering the flexibility measures available in real-life operations, some of stock levels were found insufficient, whereas, others were found superfluous.

To compensate for this lack of actual comparison between the two target setting methodologies, it is assumed that the Hilti target is applied equally to all the SKUs of each stockpoint. As discussed in the beginning of this chapter, the Hilti methodology is compared only with the results from the single-echelon analysis which is the one directly comparable with the MRP planning logic that drives the actual supply chain operations. Figure 4.4.8 and Figure 4.4.9 below summarize the comparison between the reduction targets that the stockpoints need to achieve for the running period under the current Hilti target setting method and inventory reduction obtained from single-echelon optimization.



	6000	6004	6120	6134	6135	6140	6145	6150	6160	6805	6815	6820
■ Hilti	-10%	-2%	0%	-9%	-2%	0%	0%	-3%	0%	0%	-2%	-2%
■ Model	16%	23%	-20%	3%	23%	-1%	-43%	-33%	-20%	22%	15%	-17%

Figure 4.4.8 Inventory reduction targets comparison for the Power Tool supply chain



	0506	0550	0900	0980	2100	2600	3300	4400	7500	8110	8120	8130	8140	8150	8180	9150
🟦 Hilti	0%	0%	-9%	0%	-15%	-6%	-3%	0%	-13%	-20%	-17%	0%	-5%	-2%	-22%	-20%
🟧 Model	-34%	72%	-48%	108%	7%	134%	-1%	98%	16%	-2%	-34%	-34%	-18%	-1%	28%	-41%

Figure 4.4.9 Inventory reduction targets comparison for the Anchor supply chain

The misalignment between the two methodologies is obvious. For most of the stockpoints, the established reduction targets miss a large part of the potential to get closer to optimal levels. As a general rule, the Hilti reduction method tries to reduce the inventories of similar storage locations by bringing them to the levels of the top performers in their cluster. Consequently, the different levels of uncertainties faced by each location or the fact that the top performers might be under-performing, is neglected. Additionally, it can be seen that the theoretical models have found that specific locations need to increase their safety stock levels in order to achieve the 98% performance target. However, the Hilti methodology, due to its empiric approach, miss this. Such inaccuracies are expected to cause not only issues on the operational spectrum of these stockpoints, but also frictions between local and central management, as they are called to increase their performance while, at the same time, reduce their average inventories. The targets for every stockpoint and how they compare with the findings from the models is presented in Appendix M.

5 Conclusion

The final chapter of the report summarizes the results presented in Chapter 4 and combines them with all information gathered along the process of conducting this master thesis project to turn them into useful insights. Section 5.1 answers the research questions originally set to drive the course of the project. Section 5.2 discusses the contributions of this project to literature. Finally, section 5.3 provides a framework of recommendations to Hilti AG, fueled by the AS-IS analysis and generated results.

5.1 Answering the research questions

R.Q. 1: *Which models yield empirically valid results?*

The setting of the project is multi-echelon supply chain networks fully controlled by the company. Following literature, the first choice for a model that accurately depicts the real-life operations would be a type of multi-echelon inventory control concept. However, Hilti carries out its operations using MRP II logic, which generates a demand planning for each individual location. Hence, a single-echelon approximation is expected to be more fitting. Indeed, the results of the models evaluation, presented in section 4.1, prove that the single-model yield more empirically valid results, whereas the multi-echelon models show significant deviations. Therefore, the appropriate approach to generate inventory targets for the current setup at Hilti, is to optimize the inventories for the items and locations in scope using single-echelon modelling. The results from the multi-echelon models can be used to provide insight on an alternative and, as was proved in section 4.2.2, more effective inventory control paradigm.

R.Q. 2: *What is the relative evaluated performance of the models comparing to that of the actual the supply chains?*

In section 4.1.1 the current inventory levels maintained by Hilti were evaluated under single-echelon inventory modelling. Simulating the inventory in such a way, provided an on-par theoretical model which could directly be compared to the MRP planning logic used to drive the actual supply chain operations. The results of the evaluation, shown in Figure 4.4.1 and Figure 4.4.2 show that, apart from a few exceptions, the stockpoints analyzed achieve a lower theoretical performance than what the company reports for the same locations. The results however show slight deviations which in conjunction with the expected lower theoretical performance, verifies the validity of the models. Some of the stockpoints were diagnosed with an overstock, while others were found with insufficient inventory. Thus, the first conclusion drawn from the models evaluation, is that the Hilti stock levels are not strictly superfluous. Considering also that the safety stock levels in their majority are not tied to performance or ignore the uncertainties in total, the verdict is that, the target inventory levels are not accurately set to achieve the ambition performance under minimum inventory investment, under the existing levels of uncertainty. Furthermore, comparing the evaluated theoretical performance levels with the actual reported ones, enabled the identification of human influence and the impact of the various flexibility measures on the supply chains along with determining its positive or negative sign (Table 8).

R.Q. 3: *What are the optimal stock levels to achieve the target service level under minimum inventory investment using single-echelon models?*

In section 4.2.1 the theoretical optimal stock levels for the two supply chains were presented. The optimization provided the minimum inventories required so that each stockpoint performs in agreement with the company ambition fill rate level of 98%. Following the results of the SCs evaluation, the optimization results showed that optimal stock levels lie both higher and lower than the current levels maintained by Hilti. This optimization approach is not determining a cost-optimal policy, but rather calculates the minimum stock requirement under given control policy, control parameters and uncertainty levels. Among the given parameters were also considered the lot sizes, which were asked to remain fixed. The figures are summarized in Table 21 and Table 22.

R.Q. 4: *What are the optimal stock levels to achieve the target service level under minimum inventory investment using multi-echelon models?*

Section 4.2.2 presents the results for the optimized stock levels under multi-echelon analysis. The software tool used to calculate the optimal stock levels is ChainScope. ChainScope uses a technique called Synchronized Base Stock, which performs end-to-end optimization and releases material-feasible orders, opting to minimize customer backorders along the supply chain. The combination of advanced inventory monitoring, in the form of echelon-stock, and further operational flexibility, such as smart allocation of inventory on-hand, generates a total optimal average stock level that is significantly lower than individually optimizing the stockpoints. The results show that the multi-echelon models outperform single-echelon modelling by 24% and 19% in total inventory for the Power Tool and the Anchor supply chain respectively. Detailed results of the ChainScope optimization run can be seen at Table 23 and Table 24.

R.Q. 5: *What is the impact of the uncertainty factors on the stock levels using single-echelon models?*

Several optimization scenarios have been designed by parameterizing each time one of the inventory influence factors and leaving the rest fixed, in order to calculate the effect on the stock levels. The uncertainties are initially reduced to a median value and then afterwards eliminated. The outcome shows what is the impact of each factor and provides a basic sensitivity analysis of the inventory on each one of them. Under single-echelon modelling, the uncertainty factor that has the larger impact on the stock levels is the demand volatility. The total average inventory is reduced to almost identical levels when each factor is reduced by 50%. The total impact, though, seen when eliminating them, is far greater for the demand uncertainty. From another perspective, one could also argue that based on the AS-IS state of the stocks, the most influential factor currently is the service level. The reason is, that safety stock methodologies which are not tied to the service level target are widely used, even for items going through their free life-cycle phase with plenty of statistical data. This causes inaccurate and superfluous safety stock levels. The topic is addressed in section 4.3 and summary tables are presented in Appendix L.

R.Q. 6: *What is the impact of the uncertainty factors on the stock levels under multi-echelon analysis?*

Using ChainScope for the optimization runs with multi-echelon modelling, the calculated impact of the influence factors on the inventory exhibits certain variations in comparison with the single-echelon analysis. The most notable one is that the stock levels remain rather unaffected by reducing the lead time variability. Opposed to the lead time input of the single-echelon models, ChainScope is fed with lead time data that concern only the throughput times of each location. Any delays due to limited stock availability in upstream locations are dealt by the software's engine. On the other hand, the stock reduction achieved by reducing the demand uncertainty is significant, with the reduction rate dropping as the uncertainty level is further limited. Finally, when parameterizing the service level, the behavior of the stock levels of both items is similar and according to the service level curves encountered all across the field of literature. Ignoring slight deviations, the two items exhibit similar behavior. The topic is addressed in section 4.3 and summary tables are presented in Appendix L.

R.Q. 7: *How accurate is the current inventory reduction target setting rule?*

The inventory reduction target setting methodology currently used by Hilti is explained in section 3.2.1. Summarizing it, all inventory reduction targets are generated combining three components. First component is determined through an internal benchmarking process, where stockpoints are divided into clusters based on their turnover and then their performance is compared to that of the top performers' of the same cluster. The second component is calculated from the productivity level of the location, considering the changes in the sales volume and the amount of inventory. Third and last component of the Hilti reduction targets calculation is the expected impact on the stock levels from the upcoming integrated planning project. Most importantly, the reduction targets are generated on a stockpoint level. Apparently, no part of this process is formally derived according to existing literature and the reduction targets are a product of business intuition and empirical approaches. In general, the inventory targets are pushing the total inventories downwards to lower levels. In other words, the current methodology assumes that the existing inventories maintained by the company are either superfluous or correctly set. This belief, however, is challenged by the fact that the analysis showed many SKUs with insufficient stock levels. In truth, the lack of formality and proper inclusion of all relevant influence factors in the target setting process -supply and demand uncertainty, target service level, lead to targets which fail to tap into the full potential to further improve the efficiency of the supply chain operations. An exact target on stockpoint level could not be generated, but, under the assumption that the Hilti targets are universally applied equally to all SKUs, the differences found between the two methodologies are significant. Detailed tables presenting the compare son of the two reduction targets determination methodologies are shown in Appendix M.

5.2 Contribution to literature and further research

This project contributed to literature by providing a case study where the differences between two inventory control paradigms could be quantified. The first of the two paradigms is single-echelon approximations, selected as the most valid approach to simulate the actual supply chains of Hilti, and is used as the base case. Then, multi-echelon analysis is used in order to showcase the benefits of applying more advanced techniques, given the technological developments in information processing and sharing. The tool used to carry out such an analysis, which is highly cumbersome to be analytically approached from scratch for supply chains of that complexity, is ChainScope. ChainScope makes use of the SBS technique developed by De Kok & Fransoo (2003) which provides high levels of operational flexibility due to its end-to-end information utilization and scope of control. Comparing the optimal stock levels as calculated be the two approaches, brings solid evidence of the benefits of applying multi-echelon techniques in a complex multi-stage networks. Additional insight is generated by comparing the inventory behavior as a function of the influence factors under each inventory management framework.

As recommendation for further research, it would be interesting to investigate the efficiency of the target service levels set as ambition targets by the company management. As the current project was focused on the actual target setting process itself, the service level target was considered as a constraint. However, no evidence justifies that the given target is cost-optimal. Further analysis on the true overstock and understock costs of each product family could hone even further the profitability of the supply chains of Hilti.

5.3 Recommendations

As a bottom line of this project, the company is advised to consider the implementation of the following recommendations:

Switch to a formal inventory target setting process

The realization that the stock levels are not generally superfluous, but not accurately set is the pre-requisite to any further towards increasing the effectiveness of the supply chains. Rather than setting inaccurate stock levels, then later spending extra resources to generate reduction targets of debatable effectiveness, it is more efficient to invest in a formal design that optimizes the stock levels. First, a tool will be needed to extract the relevant data from the business warehouse, which in turn will be used to calculate accurate safety stocks. Paired with already existing method that defines the cost-optimal lot sizes, the result will be more accurate inventory positioning, enabling the company to reach its ambition targets under minimum inventory investment and less friction between central and local management.

More robust safety stock calculation framework

The current safety stock calculation framework does not provide the necessary guidelines needed to set safety stocks accurately. All 5 of the calculation methods are free to be used for any product during any of its life cycle phase. Additionally, most of the components of each calculation method are free to be manually manipulated by the responsible Materials Manager. The result is a vast number of SKUs going through their maturity phase, with plenty of statistical data regarding its demand pattern and its lead time variability, having their safety stocks arbitrarily set to x months of forecasted demand coverage, completely neglecting all relevant uncertainty factors. Another common occurrence is the use of an appropriate method but with a service level target close to 100%. Moreover, whereas the safety stocks are set considering single-echelon approximations, the stochastic variations of the total replenishment lead time are not properly captured. Instead of calculating lead time means and variations considering the significant delays due to upstream availability issues, the actual lead time input pertains a fixed delivery time expectation and delay measurement calculated only from deviations on the planned delivery date. In other words, upstream availability is assumed to be 100%, inevitable lowering the accuracy of the inventory planning. A more structured safety stock setting methodology would eliminate such issues and increase its accuracy.

Adoption of multi-echelon inventory management

Plenty of literature studies suggests that the most efficient inventory management frameworks in a multi-stage supply chain setting, are multi-echelon approaches paired with centralized control concepts. The results of the multi-echelon analysis presented in this project are significantly lower than the ones generated using single-echelon models. The single-heuristic has been proved to be a very handy heuristic due to its simplicity to understand and employ, however, its efficiency rapidly decreases the more stages and locations are added to a supply chain.

Bibliography

Axsäter, S. (2015). *Inventory Control.* International Series in Operations Research & Management Science.

Bertrand, J. W., & Fransoo, J. C. (2002). Operations management research methodologies using quantitative modeling. *International Journal of Operations & Production Management*, 241.

Boulaksil , Y., & Fransoo, J. C. (2009). Setting safety stocks in multi-stage inventory systems under rolling horizon mathematical programming models. *OR Spectrum*.

Brealey, R. A., Myers, S. C., & Allen, F. (2011). *Principles of Corporate Finance - 10th edition.* McGraw-Hill/Irwin.

Cattani, K. D., Jacobs, F. R., & Schoenfelder, J. (2011). Common inventory modeling assumptions that fall short: Arborescent networks, Poisson demand, and single-echelon approximations. *Journal of Operations Management*.

De Kok, A. (1990). Hierarchical production planning for consumer goods. *European Journal of Operational Research*, 55-69.

De Kok, A. (2002). Analysis of stock control models for one location with one product. *Unpublished course notes at Technical University Eindhoven*.

De Kok, A. (2005). Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect. *Interfaces*, 37-48.

De Kok, A., & Eruguz, S. (2015). INFORMS: Strategic Safety Stocks under Guaranteed Service and Constrained Service Models. *Eindhoven University of Technology*.

De Kok, A., & Fransoo, J. (2003). *Planning Supply Chain Operations: Definition and Comparison of Planning Concepts. In Handbooks of Operations Research: Supply Chain Management: Design, Coordination and Operation.* Technical University of Eindhoven.

De Kok, A., & Visschers, J. (1999). Analysis of assembly systems with service level constraints. *Internation Journal of Production Economics*.

De Kok, A., Lagodimos, A., & Seidel, H. (1994). Stock allocation in a two-echelon distribution network under service constraints. *Eindhoven University of Technology*.

Diks, E., & De Kok, A. (1999). Optimal control of a divergent multi-echelon inventory system. *European Journal of Operational Research*.

Diks, E., De Kok, A., & Lagodimos , A. (1995). Multi-echelon systems: a service measure perpsective. *European Journal of Operations Research*.

Enns, S. T. (2002). MRP performance effects due to forecast bias and demand uncertainty. *European Journal of Operational Research*.

Eppen, G., & Martin, R. (1988). Determining Safety Stock in the Presence of Stochastic Lead Time and Demand. *Journal of Management Science*.

Graves, S. C., & Willems, S. P. (2003). Supply Chain Design: Safety Stock Placement and Supply Chain Configuration. In A. G. De Kok, & S. C. Graves, *Handbooks in Operations Research and Management Science.* Elsevier B.V.

Guide, V., & Srivastava, R. (2000). A Review of Techniques for Buffering against Uncertainty with MRP systems. In *Production Planning & Control* (pp. 223-233).

Hausman, W., & Erkip, N. (1994). Multi-echelon vs single-echelon inventory control policies for low demand-items. *Management Science*.

Humair, S., & Willems, S. (2006). Optimizing Strategic Safety Stock Placement in Supply Chains with Clusters of Commonality. *Operations Research, 54(4)*, 725-742.

L. W. G. Strijbosch, J. J. (1999). Simple Expressions for Safety Factors in Inventory Control. *Center for Economic Research*.

Lee, H., & Whang, S. (1992). Decentralized Multi-Echelon Supply Chains: Incentives and Information. *Management Science*.

Silver, E. P. (1998). *Inventory management and production planning and scheduling (3rd ed.).* Chichester: Wiley.

Stenius, O., Karaarslan, A., Marklund, J., & de Kok, A. (2015). Exact Analysis of Divergent Inventory Systems with Time-Based Shipment Consolidation and Compound Poisson Demand. *INFORMS*, 906-921.

van Aken, J., Berends, H., & van der Bij, H. (2012). *Problem-solving in organizations : a methodological handbook for business students.* Cambridge: Cambridge University Press.

van Cruchten, A. (2016). *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.* Technical University Eindhoven.

van Donselaar, K. &. (1987). Commonality and safety stocks. *Engineering Costs and Production Economies*.

van Wanrooij, M. (2012). *Strategic supply chain planning in a multi-echelon environment: Identification of the CODP location constrained by controllability and service requirements.* Technical University Eindhoven.

Willems, S., & Manary, M. (2008). Setting safety stock targets at Intel at the presence of forecast bias. *Interfaces*.

6 Appendix

A. Cause and effect diagram

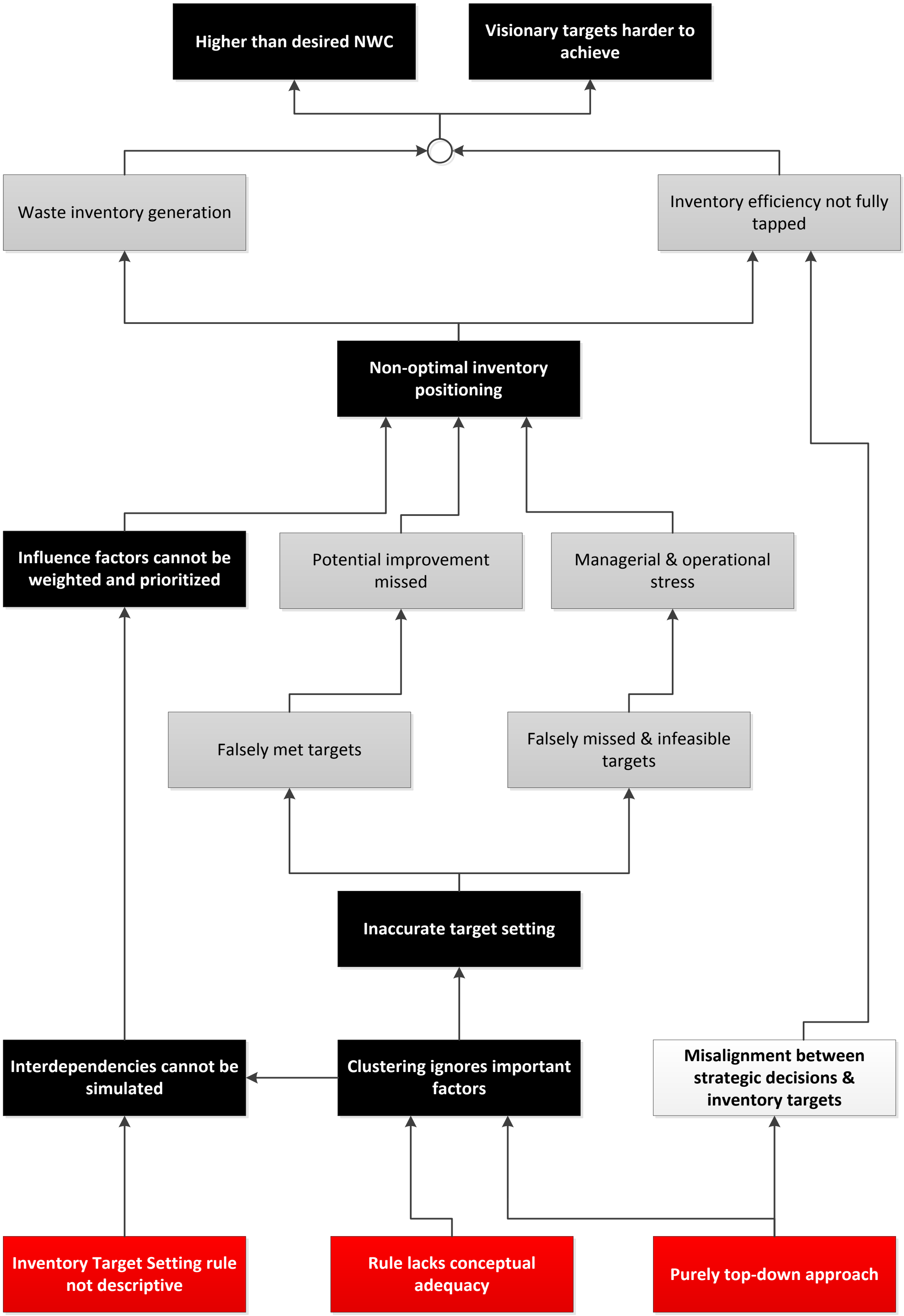
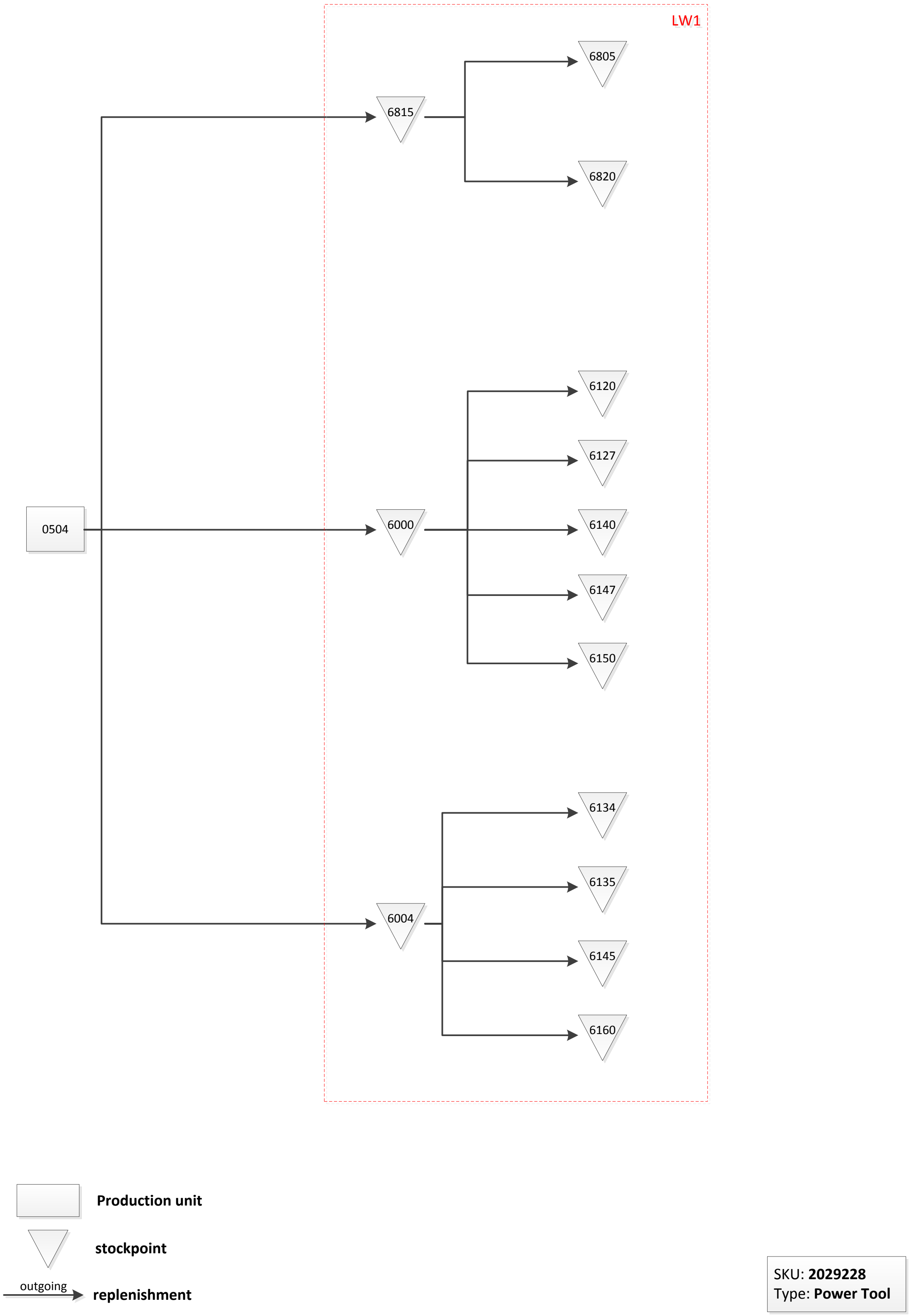
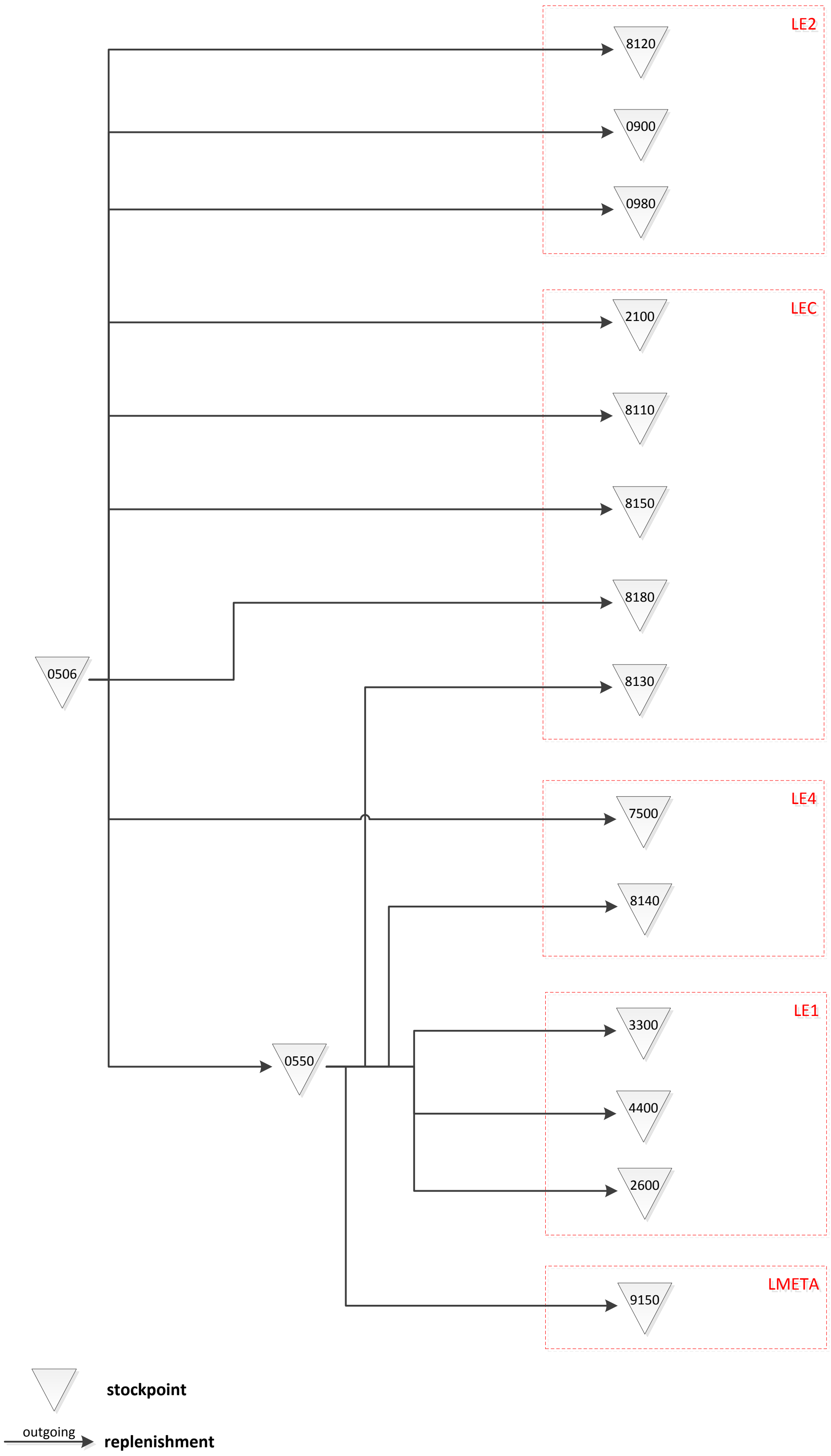


Figure 6.1 Cause & Effect Red: root causes, black: key effects

B. Supply chains





SKU: **2101918**
Type: **Anchor**

C. Demand data

Table 11 Single-echelon total demand data: Power Tool

Location	Daily mean	Daily St.Dev.	CV
6000	6.30	6.63	1.05
6004	8.93	7.64	0.86
6120	0.21	0.52	2.45
6134	0.83	1.23	1.48
6135	0.59	0.95	1.60
6140	0.57	1.15	2.02
6145	1.89	1.94	1.03
6150	2.41	2.84	1.18
6160	1.22	1.51	1.24
6805	1.00	1.98	1.97
6815	4.05	4.19	1.04
6820	0.35	0.88	2.51

Table 12 ChainScope customer demand data: Power Tool

Location	Daily mean	Daily St.Dev.	CV
6000	2.34	3.19	1.36
6004	3.34	4.19	1.25
6120	0.21	0.52	2.45
6134	0.83	1.23	1.48
6135	0.59	0.95	1.60
6140	0.57	1.15	2.02
6145	1.89	1.94	1.03
6150	2.41	2.84	1.18
6160	1.22	1.51	1.24
6805	1.00	1.98	1.97
6815	2.02	2.38	1.17
6820	0.35	0.88	2.51

Table 13 Single-echelon total demand data: Anchor

Location	Daily mean	Daily St.Dev.	CV
0506	1239.76	1400.17	1.13
0550	140.34	222.65	1.59
0900	287.86	399.30	1.39
0980	59.94	155.15	2.59
2100	43.60	89.58	2.05
2600	3.39	21.34	6.29
3300	12.61	19.76	1.57
4400	9.02	25.52	2.83
7500	293.98	262.91	0.89
8110	160.19	129.33	0.81
8120	55.57	94.96	1.71
8130	11.91	21.57	1.81
8140	28.84	44.25	1.53
8150	149.40	171.64	1.15
8180	62.58	68.95	1.10
9150	41.50	64.43	1.55

Table 14 ChainScope customer demand data: Anchor

Location	Daily mean	Daily St. Dev.	CV
0506	0.00	0.00	0.00
0550	6.66	304.81	0.00
0900	287.86	399.30	1.39
0980	59.94	155.15	2.59
2100	43.60	89.58	2.05
2600	3.39	21.34	6.29
3300	12.61	19.76	1.57
4400	9.02	25.52	2.83
7500	293.98	262.91	0.89
8110	160.19	129.33	0.81
8120	55.57	94.96	1.71
8130	11.91	21.57	1.81
8140	28.84	44.25	1.53
8150	149.40	171.64	1.15
8180	62.58	68.95	1.10
9150	41.50	64.43	1.55

D. Lead times

Table 15 Power Tool supply chain lead times

Location	Mean	St.Dev.	Transport	Delay FXr	Percentile	factor	Buffer	Planned LT
6000	49.31	7.44	43	1.14	0.95	1.64	1.88	44.88
6004	39.87	6.59	38	0.39	0.95	1.64	0.64	38.64
6120	4.80	1.40	4	0.6	0.95	1.64	0.95	4.95
6134	3.20	3.47	4	2.7	0.95	1.64	4.43	8.43
6135	3.90	3.13	5	2.9	0.95	1.64	4.73	9.73
6140	5.40	3.09	6	2.4	0.95	1.64	3.90	9.90
6145	2.80	2.27	4	1.7	0.95	1.64	2.81	6.81
6150	4.60	2.41	5	1.8	0.95	1.64	3.01	8.01
6160	2.50	2.64	4	2.0	0.95	1.64	3.23	7.23
6805	6.10	2.13	7	1.5	0.95	1.64	2.41	9.41
6815	35.62	6.98	27	2.21	0.95	1.64	3.63	30.63
6820	8.60	4.12	7	3.6	0.95	1.64	5.92	12.92

Table 16 Anchor supply chain lead times

Location	Mean	St.Dev.	Transport	Delay FXr	Percentile	factor	Buffer	Planned LT
0506	1	1	1	1	0.95	1.64	1.64	2.64
0550	4.31	1.23	3	0.51	0.95	1.64	0.84	3.84
0900	6.92	1.54	4	1.45	0.95	1.64	2.39	6.39
0980	10.70	8.12	3	1.57	0.95	1.64	2.58	5.58
2100	6.67	4.59	3	2.54	0.95	1.64	4.18	7.18
2600	11.83	6.74	6	0.67	0.95	1.64	1.10	7.10
3300	10.35	4.89	6	1.04	0.95	1.64	1.71	7.71
4400	10.58	9.08	4	0.83	0.95	1.64	1.37	5.37
7500	5.69	3.40	3	1.58	0.95	1.64	2.60	5.60
8110	7.74	4.18	3	1.72	0.95	1.64	2.84	5.84
8120	7.21	1.94	5	2.04	0.95	1.64	3.36	8.36
8130	5.30	2.04	3	0.84	0.95	1.64	1.38	4.38
8140	8.08	5.00	5	1.72	0.95	1.64	2.83	7.83
8150	6.41	3.60	3	0.90	0.95	1.64	1.48	4.48
8180	7.21	5.81	3	1.28	0.95	1.64	2.10	5.10
9150	52.32	7.35	48	3.65	0.95	1.64	6.00	54.00

E. Cost structure

Table 17 Power Tool cost structure per location

Location	Transport cost / Added Value	Release costs / Fixed Order costs
0504	Confidential	5
6000	1.04	7
6004	1.04	7
6815	1.04	5
6120	0.54	5
6140	0.54	5
6150	0.54	5
6134	0.54	5
6135	0.54	5
6145	0.54	5
6160	0.54	5
6805	0.27	7
6820	0.27	5

Table 18 Anchor supply chain per location

Location	Transport cost / Added Value	Release costs / Fixed Order costs
0506	Confidential	5
0550	0.03	7
0900	0.10	5
0980	0.10	5
2100	0.05	5
2600	0.14	5
3300	0.14	5
4400	0.14	5
7500	0.10	7
8110	0.10	7
8120	0.10	5
8130	0.07	5
8140	0.21	5
8150	0.09	7
8180	0.09	7
9150	0.16	7

F. Echelon-stock concept

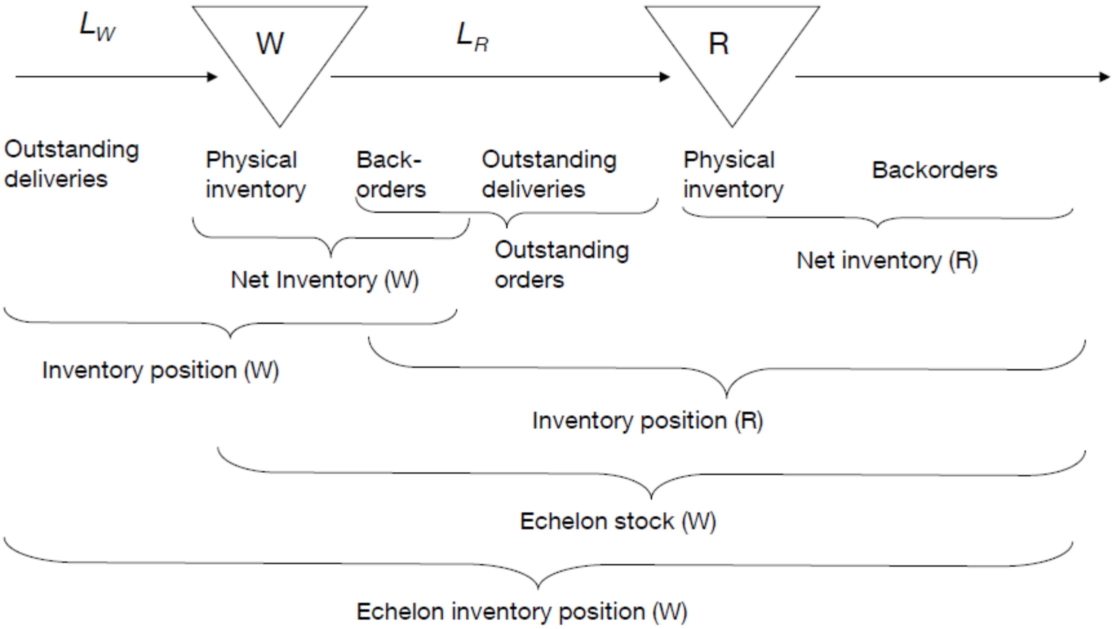


Figure 6.2 Echelon Concept for Retailer and Warehouse - (Minner, 2015)

G. ChainScope artificial hierarchy

Assume that: $(L_f, L_s, L_{sc}, L_c) = (1,1,2,4)$:

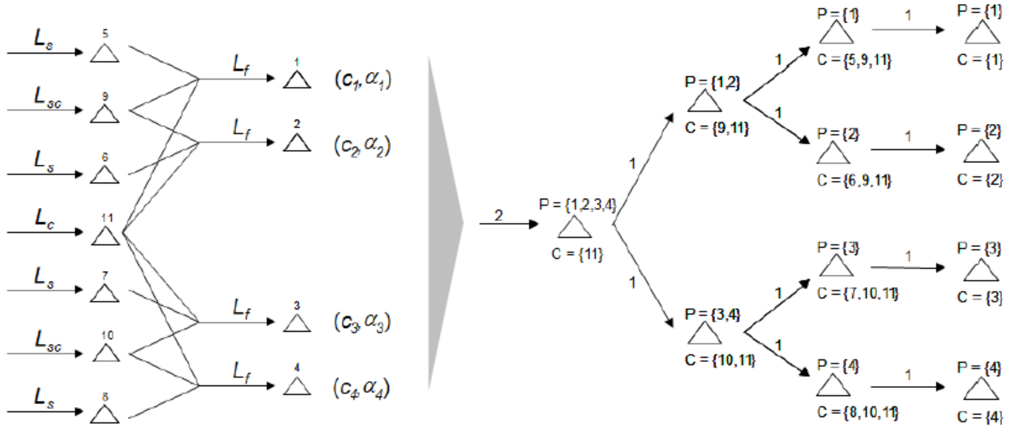


Figure 6.3 Artificial hierarchy based on Lead Times and BOM (De Kok, 2011)

H. Single-echelon evaluation

Table 19 Actual & Modelled performance per item profile

Modeled / Actual	< 95%	95-98.5%	>98.5%
< 95%	(Q,W,G2)		
95-98.5%	(Q,V,G1), (Q,W,G2)	(Q,V,G1), (Q,W,G1), (R,W,G2), (Q,V,G1), (Q,V,G1), (Q,W,G2), (Q,V,G1), (Q,V,G1), (Q,V,G1)	(Q,V,G1), (Q,W,G2), (Q,W,G2)
>98.5%	(Q,W,G2), (Q,W,G2)	(Q,V,G1), (Q,W,G2), (Q,V,G1)	(R,W,G2), (Q,V,G1), (Q,V,G1), (Q,V,G1), (Q,W,G2), (Q,V,G1), (Q,W,G2), (Q,W,G2)

I. Single-echelon optimization results

Table 20 Single-echelon stock optimization of Power Tool supply chain

	Current		***Optimized***			
Location	**Safety Stock**	**Average Stock**	**Safety Stock**	**Average Stock**	**% Delta SS**	**% Delta Avg Stock**
6000	35	200	67	232	90%	16%
6004	28	215	77	264	175%	23%
6120	4	5	3	4	-25%	-20%
6134	10	12	10	12	3%	3%
6135	6	8	8	9	29%	23%
6140	8	10	8	10	-1%	-1%
6145	23	26	12	15	-49%	-43%
6150	28	34	17	23	-40%	-33%
6160	13	15	10	12	-23%	-20%
6805	10	14	13	16	29%	22%
6815	28	105	44	121	57%	15%
6820	10	12	8	10	-20%	-17%
Total	**203**	**655**	**276**	**727**	**36%**	**11%**

Table 21 Single-echelon stock optimization of Anchor supply chain

Location	*Current* Safety Stock	Average Stock	*Optimized* Safety Stock	Average Stock	% Delta SS	% Delta Avg Stock
0506	7543	10043	4175	6675	-45%	-34%
0550	400	880	1030	1510	158%	72%
0900	5069	6269	2069	3269	-59%	-48%
0980	663	1143	1900	2380	187%	108%
2100	700	940	768	1008	10%	7%
2600	47	127	217	297	361%	134%
3300	182	262	180	260	-1%	-1%
4400	127	207	330	410	159%	98%
7500	2040	3000	2521	3481	24%	16%
8110	1500	2220	1465	2185	-2%	-2%
8120	990	1230	573	813	-42%	-34%
8130	191	271	98	178	-49%	-34%
8140	559	719	427	587	-24%	-18%
8150	1500	2080	1474	2054	-2%	-1%
8180	791	1031	1077	1317	36%	28%
9150	1884	3004	642	1762	-66%	-41%
Total	**19452**	**26592**	**15325**	**22465**	**-21%**	**-16%**

J. ChainScope optimization results

Table 22 Stock optimization with ChainScope for the Power Tool supply chain

Location	*Current* Safety Stock	Average Stock	*Optimized* Safety Stock	Average Stock	% Delta SS	% Delta Avg Stock
6000	35	200	5	170	-86%	-15%
6004	28	215	1	188	-97%	-13%
6120	4	5	3	4	-20%	-16%
6134	10	12	8	10	-19%	-17%
6135	6	8	7	8	12%	9%
6140	8	10	9	11	13%	10%
6145	23	26	10	13	-57%	-50%
6150	28	34	17	23	-39%	-32%
6160	13	15	9	11	-34%	-29%
6805	10	14	14	18	41%	31%
6815	28	105	9	86	-67%	-18%
6820	10	12	8	10	-23%	-19%
Total	**203**	**655**	**100**	**551**	**-51%**	**-16%**

Table 23 Stock optimization with ChainScope for the Anchor supply chain

Location	***Current***		***Optimized***		% Delta SS	% Delta Avg Stock
	Safety Stock	**Average Stock**	**Safety Stock**	**Average Stock**		
0506	7543	10043	0	46	-100%	-100%
0550	400	880	0	309	-100%	-65%
0900	5069	6269	2674	3874	-47%	-38%
0980	663	1143	1351	1831	104%	60%
2100	700	940	742	982	6%	4%
2600	47	127	336	416	615%	228%
3300	182	262	148	228	-18%	-13%
4400	127	207	226	306	78%	48%
7500	2040	3000	1453	2413	-29%	-20%
8110	1500	2220	627	1347	-58%	-39%
8120	990	1230	749	989	-24%	-20%
8130	191	271	143	223	-25%	-18%
8140	559	719	349	509	-38%	-29%
8150	1500	2080	896	1476	-40%	-29%
8180	791	1031	369	609	-53%	-41%
9150	1884	3004	1067	2187	-43%	-27%
Total	**19452**	**26592**	**8450**	**12965**	**-57%**	**-51%**

K. Comparison of the two inventory management paradigms

Table 24 Optimizations for the Power Tool supply chain

Location	***Single-echelon***		***ChainScope***		% Delta SS	% Delta Avg Stock
	Safety Stock	**Average Stock**	**Safety Stock**	**Average Stock**		
6000	67	232	5	170	-92%	-27%
6004	77	264	1	188	-99%	-29%
6120	3	4	3	4	7%	5%
6134	10	12	8	10	-22%	-19%
6135	8	9	7	8	-13%	-11%
6140	8	10	9	11	14%	11%
6145	12	15	10	13	-16%	-12%
6150	17	23	17	23	0%	0%
6160	10	12	9	11	-14%	-12%
6805	13	16	14	18	9%	7%
6815	44	121	9	86	-79%	-29%
6820	8	10	8	10	-3%	-2%
Total	**276**	**727**	**100**	**551**	**-64%**	**-24%**

Table 25 Optimizations for the Anchor supply chain

	Single-echelon		***ChainScope***			
Location	**Safety Stock**	**Average Stock**	**Safety Stock**	**Average Stock**	**% Delta SS**	**% Delta Avg Stock**
0506	4175	6675	0	46	-100%	-99%
0550	1030	1510	0	309	-100%	-80%
0900	2069	3269	2674	3874	29%	19%
0980	1900	2380	1351	1831	-29%	-23%
2100	768	1008	742	982	-3%	-3%
2600	217	297	336	416	55%	40%
3300	180	260	148	228	-17%	-12%
4400	330	410	226	306	-31%	-25%
7500	2521	3481	1453	2413	-42%	-31%
8110	1465	2185	627	1347	-57%	-38%
8120	573	813	749	989	31%	22%
8130	98	178	143	223	46%	25%
8140	427	587	349	509	-18%	-13%
8150	1474	2054	896	1476	-39%	-28%
8180	1077	1317	369	609	-66%	-54%
9150	642	1762	1067	2187	66%	24%
Total	**15325**	**22465**	**8450**	**12965**	**-45%**	**-42%**

L. Optimization scenarios

Table 26 Power Tool safety stock under single-echelon analysis

	Target Service Level			***Demand variability***		***Lead Time variability***	
Location	**95%**	**98%**	**99%**	**50%**	**10%**	**50%**	**0%**
6000	25	67	94	44	37	44	36
6004	29	77	109	56	49	45	34
6120	2	3	4	1	1	3	3
6134	7	10	13	7	6	7	5
6135	6	8	10	5	4	6	5
6140	6	8	10	4	3	7	7
6145	8	12	15	8	7	8	7
6150	11	17	21	10	7	13	12
6160	7	10	13	7	6	7	6
6805	9	13	16	5	2	12	12
6815	20	44	60	31	27	28	22
6820	5	8	10	4	2	7	7
Total	**134**	**276**	**374**	**181**	**150**	**186**	**155**

Table 27 Power Tool average stock under single-echelon analysis

	Target Service Level			***Demand variability***		***Lead Time variability***	
Location	**95%**	**98%**	**99%**	**50%**	**10%**	**50%**	**0%**
6000	190	232	259	209	202	209	201
6004	216	264	296	243	236	232	221
6120	3	4	5	2	2	4	4
6134	9	12	15	9	8	9	7
6135	7	9	11	6	5	7	6
6140	8	10	12	6	5	9	9
6145	11	15	18	11	10	11	10
6150	17	23	27	16	13	19	18
6160	9	12	15	9	8	9	8
6805	12	16	19	8	5	15	15
6815	97	121	137	108	104	105	99
6820	7	10	12	6	4	9	9
Total	**585**	**727**	**825**	**632**	**601**	**637**	**606**

Table 28 Anchor safety stock under single-echelon analysis

	Target Service Level			***Demand variability***		***Lead Time variability***	
Location	**95%**	**98%**	**99%**	**50%**	**10%**	**50%**	**0%**
0506	3560	4175	5865	2760	560	2860	2560
0550	624	1030	1335	406	53	946	918
0900	1261	2069	2655	891	131	1870	1804
0980	1220	1900	2419	1220	312	1276	1062
2100	479	768	986	465	113	542	466
2600	112	217	301	71	6	203	199
3300	114	180	230	120	32	123	104
4400	210	330	423	214	55	217	179
7500	1619	2521	3194	2059	610	1319	878
8110	915	1465	1866	1255	377	710	422
8120	363	573	729	245	40	517	499
8130	51	98	134	42	6	85	81
8140	269	427	544	304	83	264	207
8150	939	1474	1870	1093	309	882	673
8180	724	1077	1340	930	279	497	285
9150	298	642	876	339	43	519	476
Total	3560	4175	5865	2760	560	2860	2560

Table 29 Anchor average stock under single-echelon analysis

	Target Service Level			***Demand variability***		***Lead Time variability***	
Location	**95%**	**98%**	**99%**	**50%**	**10%**	**50%**	**0%**
0506	6060	6675	8365	5260	3060	5360	5060
0550	1104	1510	1815	886	533	1426	1398
0900	2461	3269	3855	2091	1331	3070	3004
0980	1700	2380	2899	1700	792	1756	1542
2100	719	1008	1226	705	353	782	706
2600	192	297	381	151	86	283	279
3300	194	260	310	200	112	203	184
4400	290	410	503	294	135	297	259
7500	2579	3481	4154	3019	1570	2279	1838
8110	1635	2185	2586	1975	1097	1430	1142
8120	603	813	969	485	280	757	739
8130	131	178	214	122	86	165	161
8140	429	587	704	464	243	424	367
8150	1519	2054	2450	1673	889	1462	1253
8180	964	1317	1580	1170	519	737	525
9150	1418	1762	1996	1459	1163	1639	1596
Total	**21997**	**28185**	**34006**	**21653**	**12248**	**22069**	**20052**

Table 30 Power Tool safety stock with ChainScope

	Target Service Level			***Demand variability***		***Lead Time variability***	
Location	**95%**	**98%**	**99%**	**50%**	**10%**	**50%**	**0%**
6000	5	27	41	13	8	27	29
6004	1	31	51	21	20	34	36
6120	3	4	5	2	0	4	4
6134	8	10	12	3	0	9	8
6135	7	9	10	3	0	8	7
6140	9	12	14	4	0	11	10
6145	10	12	15	4	0	11	10
6150	17	22	25	6	0	20	18
6160	9	11	12	4	0	10	9
6805	14	18	22	6	0	18	17
6815	9	22	31	10	6	22	23
6820	8	11	13	4	0	10	9
Total	**100**	**189**	**251**	**11**	**34**	**185**	**182**

Table 31 Power Tool average stock with ChainScope

	Target Service Level			***Demand variability***		***Lead Time variability***	
Location	**95%**	**98%**	**99%**	**50%**	**10%**	**50%**	**0%**
6000	170	192	206	178	173	192	194
6004	188	218	238	208	207	221	223
6120	4	5	6	3	1	5	5
6134	10	12	14	5	1	11	10
6135	8	10	12	4	1	9	9
6140	11	14	16	6	2	13	12
6145	13	15	18	7	3	14	13
6150	23	28	31	12	5	26	24
6160	11	13	14	6	2	12	11
6805	18	22	26	10	4	22	21
6815	86	99	108	87	83	99	100
6820	10	13	15	6	2	12	11
Total	**552**	**640**	**703**	**532**	**484**	**636**	**633**

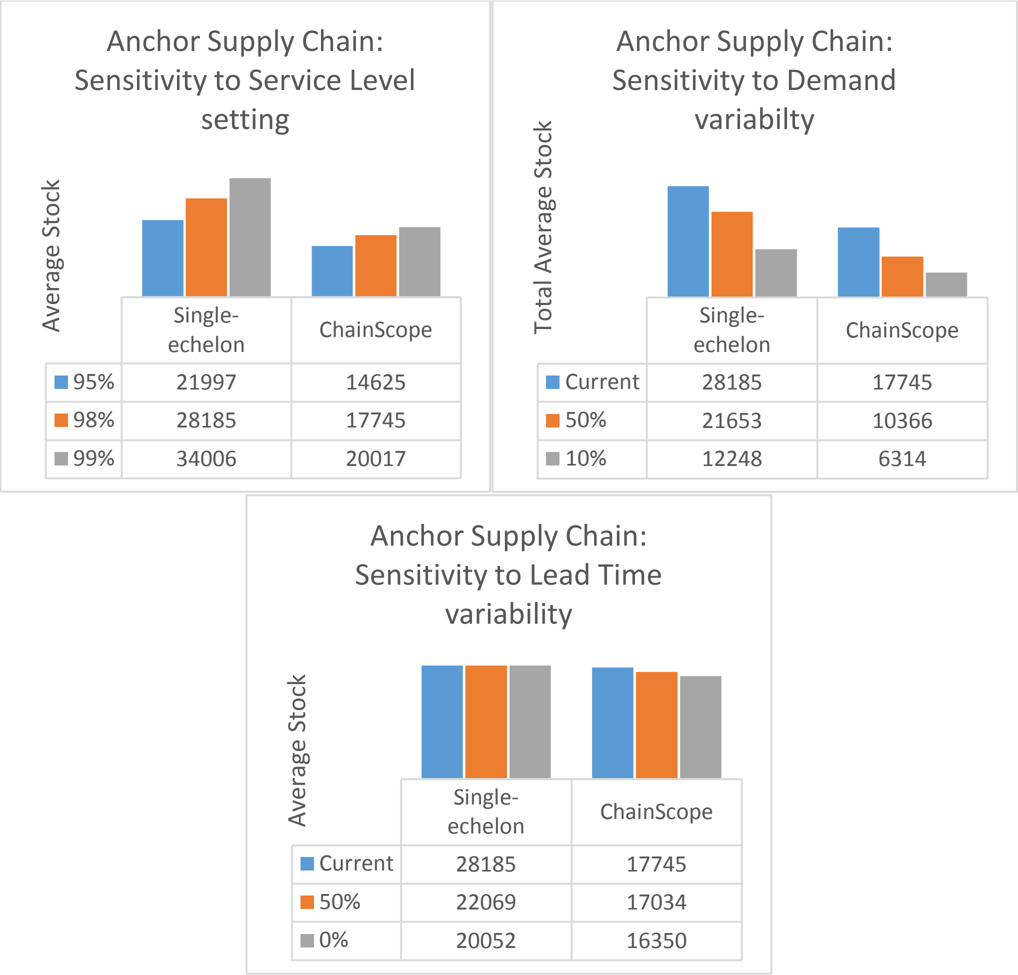
Table 32 Anchor safety stock with ChainScope

	Target Service Level			***Demand variability***		***Lead Time variability***	
Location	**95%**	**98%**	**99%**	**50%**	**10%**	**50%**	**0%**
0506	0	0	0	0	0	0	0
0550	0	0	0	0	0	0	0
0900	1943	2674	3199	919	0	2506	2327
0980	1021	1351	1630	472	17	1287	1221
2100	549	742	875	261	4	682	629
2600	258	336	408	103	9	350	349
3300	110	148	178	52	0	146	138
4400	168	226	268	77	3	230	219
7500	963	1453	1777	437	0	1228	1095
8110	410	627	782	184	0	534	484
8120	551	749	925	267	0	717	662
8130	104	143	168	48	0	144	136
8140	253	349	402	123	0	314	311
8150	609	896	1056	275	0	901	836
8180	257	369	454	114	0	345	321
9150	829	1067	1269	450	37	1035	1007
Total	**8024**	**11130**	**13391**	**3782**	**70**	**10420**	**9735**

Table 33 Anchor average stock with ChainScope

	Target Service Level			**Demand variability**		**Lead Time variability**	
Location	**95%**	**98%**	**99%**	**50%**	**10%**	**50%**	**0%**
0506	46	46	46	46	46	46	46
0550	294	309	320	278	263	309	309
0900	3143	3874	4399	2119	1143	3706	3527
0980	1501	1831	2110	952	497	1767	1701
2100	789	982	1116	501	244	922	869
2600	338	416	488	183	89	430	429
3300	190	228	258	132	79	226	218
4400	248	306	348	157	83	310	299
7500	1923	2413	2737	1397	845	2188	2055
8110	1130	1347	1502	904	650	1254	1204
8120	791	989	1165	507	238	957	902
8130	184	223	248	128	79	225	216
8140	413	509	562	283	157	474	471
8150	1189	1476	1636	855	528	1481	1416
8180	497	609	694	354	218	585	561
9150	1949	2187	2389	1570	1157	2155	2127
Total	**14625**	**17745**	**20017**	**10366**	**6314**	**17034**	**16350**

M. Sensitivity analysis of Anchor supply chain influence factors



Anchor Supply Chain: Sensitivity to Service Level setting

	Single-echelon	ChainScope
🟦 95%	21997	14625
🟧 98%	28185	17745
⬜ 99%	34006	20017

Anchor Supply Chain: Sensitivity to Demand variabilty

	Single-echelon	ChainScope
🟦 Current	28185	17745
🟧 50%	21653	10366
⬜ 10%	12248	6314

Anchor Supply Chain: Sensitivity to Lead Time variability

	Single-echelon	ChainScope
🟦 Current	28185	17745
🟧 50%	22069	17034
⬜ 0%	20052	16350

Figure 6.4 Influence factors impact calculation for the Anchor supply chain

N. Comparison of Hilti and formal reduction targets

Table 34 Comparison between Hilti and formal reduction targets

	Power Tool SC			***Anchor SC***	
Location	**Hilti**	**Model**	**Location**	**Hilti**	**Model**
6000	-10%	16%	0506	-	-34%
6004	-2%	23%	0550	-	72%
6120	0%	-20%	0900	-9%	-48%
6134	-9%	3%	0980	0%	108%
6135	-2%	23%	2100	-15%	7%
6140	0%	-1%	2600	-6%	134%
6145	0%	-43%	3300	-3%	-1%
6150	-3%	-33%	4400	0%	98%
6160	0%	-20%	7500	-13%	16%
6805	0%	22%	8110	-20%	-2%
6815	-2%	15%	8120	-17%	-34%
6820	-2%	-17%	8130	0%	-34%
			8140	-5%	-18%
			8150	-2%	-1%
			8180	-22%	28%
			9150	-20%	-41%