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Model for determining spare part safety stock levels considering lateral transshipments between production units

IKEA Industry

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PREFACE

This thesis was conducted during the spring of 2020 as the final part of our Master´s Degree in Mechanical Engineering at The Faculty of Engineering LTH at Lund University. The thesis was written on behalf of IKEA Industry, with the aim of improving stocking decisions within the spare parts flow focusing on production units in Poland. The thesis was hosted by the Institution for Engineering Logistics at LTH.

We would like to extend our most sincere gratitude to everyone from both IKEA and LTH who have contributed to the finalization of this master thesis. We would like to direct special gratitude toward Jaroslaw Godlewski for setting up interviews and giving us a tour of the production site in Lubawa.

Finally, we would like to thank our supervisors Ulrika Garbe and Pavla Lengalova from IKEA, as well as our supervisor Eva Berg from LTH and our examiner Jan Olhager for providing us with support and thoughtful insights without hesitation whenever needed.

ABSTRACT

Title: Model for determining spare part safety stock levels considering lateral transshipments between production units

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Background: IKEA Industry manufactures furniture for all IKEA stores around the world. There are several production units around the world. The production units have a lot of different machines, all in need of spare parts for maintenance. IKEA Industry are interested in investigating how the size of their network can be taken advantage of.

Problem description: Procurement of spare parts represents a significant part of the total indirect cost at IKEA Industry. The stock levels are not optimized and believed to be too high in many cases. Many spare parts are common for several of the production units, but safety stock is defined locally without considering common stock or stock in other units. One of the challenges facing the business today is to optimize the availability of spare parts, while minimizing the cost for handling and storing.

Purpose: The purpose is to develop a model for determining safety stock levels for spare parts at production plants at IKEA industry, taking into account the availability of components in nearby production plants rather than viewing them in isolation.

Research questions:

1. How should the safety stock for spare parts for the manufacturing equipment be determined on the different production units taking transshipments into consideration?
2. How should IKEA Industry measure the performance of the spare parts flow with respect to availability and cost of handling?

Methodology: An abductive approach is used, conducting both interviews, collecting data from internal systems and reviewing literature. For RQ1, suitable models from the literature are considered and adapted. For RQ2, literature is compared with IKEA’s current performance measurement system and improvement areas are highlighted.

Modeling method: A model consisting of three parts is used for finding optimal safety stock levels. The first part determines what the sum of the safety stock in all of the affected production units should be. The second part allocates the safety stock based on the demand rates in the production units. The third part calculates the probability of transshipping items and calculates the total cost considering holding cost, shortage cost and transshipment cost. Finally, the model chooses the allocation of safety stock with the lowest cost.

Results: The model does not suggest any significant decreases in stock levels. For RQ2, a spare parts performance measurement framework is presented which categorizes spare parts based on their demand, material price and availability risk. Using a chosen KPI, in this case the service level, underperforming spare part categories can be identified. This allows management to focus their efforts better.

Conclusion: It is cheaper to keep extra units in stock rather than risk having shortages and transshipments due to imbalance of cost parameters. There is some uncertainty in the input variables that need to be addressed. Performance measurement can be improved as well by implementing the suggested framework. The overall conclusion is that IKEA needs to work a lot more with their data before looking into implementing any models or frameworks.

Keywords: Safety stock, lateral transshipments, inventory pooling, inventory control, spare parts, inventory model, Markov process, performance measurement, availability, service level

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1. INTRODUCTION

This chapter is intended to put the thesis into a context by providing a background of both the study object IKEA Industry and the research area to which IKEA Industry's problem belongs. Furthermore, the chapter specifies the problem formulation, what the study aims to achieve as well as what it will not consider. The chapter is concluded by an outline of the report, specifying the purpose and contents of each chapter.

1.1. Background

Inventory control is a concept that has received increasing attention in literature and in practice over the past decades (Axsäter, 2006, p.1). As supply chain management has taken a more strategic role among practitioners, inventory control is starting to be seen as an opportunity to create competitive advantage rather than just a necessary cost (Axsäter, 2006, p.1; Cachon & Fisher, 2000). Many companies have substantial investments in inventory resulting in large amounts of tied up capital. Furthermore, with high expectations from internal and external customers in terms of availability and flexibility, inventory control plays an important role in ensuring high performance in such areas while keeping costs down.

One key enabler for creating competitive advantage through inventory control is the development of information technology (IT) (Axsäter, 2006, p.1; Cachon & Fisher, 2000). The development of IT has facilitated sharing of information such as demand and inventory data which can be used to reduce stock levels and lead-times. Although there is no clear consensus on whether information sharing across multiple tiers in the supply chain has significant benefits, information sharing with adjacent tiers and within tiers has enabled improvements in the supply chain (Kembro & Näslund, 2014; Kembro *et al*, 2017). With increased visibility of inventory and ease of access to these data, the development of more sophisticated tools and models for managing inventory becomes possible.

An important aspect of inventory control is setting reorder points and safety stock levels. For single-echelon systems, that is inventory systems with only one level, there are established methods for optimizing reorder points and safety stock levels accurately (Axsäter, 2006, pp. 129-145). For multi-echelon systems, that is inventory systems with multiple levels, the optimization problem quickly becomes more complex (Axsäter, 2006, pp. 247-248). Therefore, the models are often approximations providing near-optimal solutions. Despite this, a multi-echelon approach is often both more cost-efficient and effective in terms of service quality than a decentralized approach since it considers the dependencies of the different inventory locations (Axsäter, 2006, pp. 247-248). Multi-echelon systems are generally categorized into distribution inventory systems (divergent system where the number of inventory locations increases when moving downstream in the chain), assembly inventory systems (the opposite of distribution inventory systems) or a combination of the two. In order to improve availability and hedging against uncertainties, some inventories allow for shipment between inventory locations at the same tier in the chain. The concept of having the ability to share inventory across different inventory locations is called *inventory pooling* and the shipments between the inventory locations is called *lateral transshipments*. This can be utilized in spare parts flows where downtime caused by machine breakdowns causes costs that outweigh extra costs that the transshipments bring (Wong *et al*, 2005a). The introduction of inventory pooling affects the stock policies of the involved inventory location as the amount of available stock is expanded from the local stock. Therefore, it is important to evaluate *how* it affects the stock policies (Axsäter, 2006, pp. 192-193).

1.2. Problem formulation

Procurement of spare parts represent a significant part of the total indirect cost at IKEA Industry. The stock levels are not optimized and believed to be too high in many cases. Many spare parts are common for several of the production units, but safety stock is defined locally without considering common stock or stock in other units. One of the challenges facing the business today is to optimize the availability of spare parts, while minimizing the cost for handling and storing. The first spare part harmonization project at IKEA Industry, focusing on harmonizing and improving quality of data for spare parts, was finalized in the beginning of 2020. It delivered around 40,000 records of spare parts with standardized format and information enabling full transparency in the ERP-system for production units to check availability of spare parts in the whole group. IKEA would like to utilize these data when calculating safety stock levels considering lead-time and transport costs in the network of factories, instead of calculating it in isolation per factory as they do today.

1.3. Purpose of study

The purpose is to develop a model for determining safety stock levels for spare parts at production units at IKEA industry, taking into account the availability of components in nearby production units rather than viewing them in isolation.

1.4. Research questions

In order to develop a methodology to base the rest of the thesis on, the purpose is translated into two concrete research questions, RQ1 and RQ2. Ultimately, the study should result in a method for determining the safety stock. Therefore, the first research question is:

RQ1: How should the safety stock for spare parts for the manufacturing equipment be determined on the different production units taking transshipments into consideration?

When taking decisions that affect the inventory management, it is important to be able to make sure that the entire system performs to satisfactory degree. Therefore, the second research question is:

RQ2: How should IKEA Industry measure the performance of the spare parts flow with respect to availability and cost of handling?

At a first glance, it would seem like RQ2 is somewhat unrelated to the background and RQ1. However, since IKEA seeks to understand in what way the introduction of a safety stock model will impact performance, they need to be able to quantify that potential performance increase. For this reason, RQ2 seeks to make sure that IKEA is equipped with the knowledge required to measure performance for the spare parts flow.

1.5. Focus and delimitations

This master thesis will focus on investigating how IKEA can capture the benefits of being a large company. Emphasis will be put on what aspects are taken into account when defining and setting safety stock levels.

IKEA Industry has over 200,000 spare part articles. As part of the harmonization project, the data on these articles has to be cleaned up, removing duplicates etc. The data set being used for this thesis will only cover the already cleaned up data (approximately 40,000 articles). Even with this limitation, the scope is too large both from a time- and complexity perspective. Therefore, a more limited set of articles will be studied, see chapter 4.4.

The model will be designed on a limited number of production units and serve as a proof of concept to be applied to additional production units (see chapter 4.4.). The model will be delivered in a conceptual form and will not be implemented on a large scale during the course of the project. The main decision factors for choosing production units to conduct this study for include the production unit's quality of data regarding, for example, machine breakdowns as well as the number of nearby production units. In other words, production units with poor quality of data or no nearby production units are not of interest in this study.

Another delimitation will be the extent to which the supplier dimension of the problem will be explored. Models like these can include decision-making at the supplier level as well (e.g. supplier stock levels), through contract agreements. However, in this study the focus will lie solely on the allocation of stock levels at the different IKEA Industry production units.

1.6. Target group

This thesis is directed toward three different target groups: (1) IKEA Industry, (2) researches within the field of operations research and (3) students. IKEA Industry is the project sponsor and object of the study. The results and findings of the thesis are intended to be of practical use in IKEA Industry's operations. As for researches, the thesis is intended to further explore how lateral transshipments influence stock levels within a spare part logistics flow as well as performance measurement. For students, the thesis aims to spark interest within operations research and/or inspiration for other master theses.

1.7. IKEA Industry as the study object

IKEA Industry is the largest producer of wooden furniture in the world and manufactures wood-based furniture for IKEA customers. Together with external IKEA suppliers, they represent the IKEA production capacity. IKEA Industry consists of 42 production units in eight countries: China, Hungary, Lithuania, Poland, Portugal, Russia, Slovakia and Sweden, see Figure 1-1. They have around 20,000 co-workers and the top five production countries are Poland, Russia, Slovakia, Portugal and Sweden. These production units are divided into four divisions:

1. *Boards*: Designs and produces innovative and sustainable wood-based boards and panels. 1000 co-workers at five production units in five countries. The boards are used for products such as PAX, METOD and BRIMNES.
2. *Flatline*: Produces furniture based on wooden boards. 9500 co-workers at 20 production units (12 sites) in eight countries. Contributes to product lines such as PAX, KALLAX and LACK.
3. *Solid wood*: Produces solid wood furniture. Operates the entire value chain from forest to furniture manufacturing. 7500 co-workers at 16 production units in four countries. Produces products such as HEMNES, IVAR and HURDAL.
4. *Purchase*: Responsible for purchase of wood boards, chemicals, foils, edges and paper. 70 co-workers in ten countries with different home sites.

Figure 1-1: Geographical map of the production units belonging to IKEA Industry (IKEA Industry, 2020).

1.8. Report outline

Structurally, the report for this master thesis is divided into six main parts that follow a traditional way of reporting, see Figure 1-2.

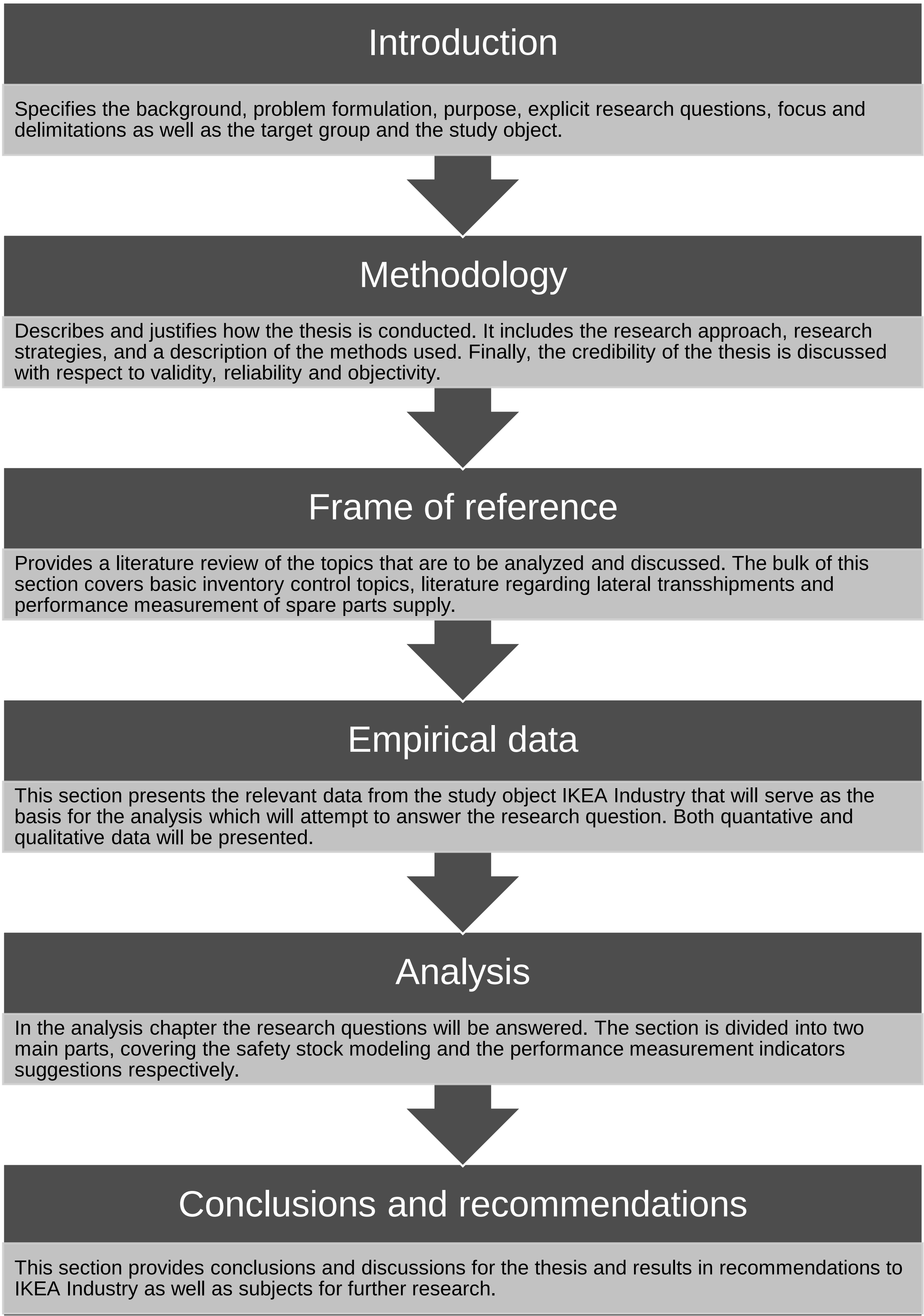

Figure 1-2: Outline of the report including all chapters.

2. METHODOLOGY

The aim of this section of the thesis is to both describe how the thesis is conducted and to justify the choices made. It includes the overall approach to address the problem formulation and research questions, the strategy for acquiring knowledge from the literature and the methods for collection of empirical data from IKEA Industry. This section also discusses the credibility of the study with respect to validity, reliability and objectivity.

2.1. Approach

The first step of developing the methodology is to decide upon a research approach. Within academia, research approaches are often categorized into three main types: (1) the inductive approach, (2) the deductive approach and (3) the abductive approach (Spens & Kovács, 2006). All three of these types will be briefly described before justifying the choice of research approach for this thesis.

2.1.1. The deductive approach

Described by some as the most common research approach within logistics (Mentzer & Kahn, 1995; Näslund 2002; Golicic *et al*, 2005), the deductive research approach is centered around the notion of basing the research on already existing research. The deductive approach is sometimes described as a quantitative approach (Näslund, 2002). The first step of deductive research is to review theory and subsequently testing it empirically. In effect, this means that deductive research uses the existing theory and tests it to see whether it applies to similar but different contexts. After the testing, the findings are generalized which is the product of the study (Spens & Kovács, 2006).

2.1.2. The inductive approach

Inductive research is sometimes referred to as the qualitative approach. Even though quantitative research approaches have dominated the literature within logistics, a need for complementary qualitative research has been recognized (Näslund, 2002). Contrary to the deductive approach, the first step of an inductive research strategy is to collect empirical data, which eliminates the requirement of an existing knowledge base of the subject. Instead of relying on existing theory, the inductive study should create new theory originating from the empirical data. Since there is nothing to test the empirical data against, the generalizations are generated through logical reasoning and argumentation (Spens & Kovács, 2006).

2.1.3. The abductive approach

Researchers see abduction as a form of breaking out of the traditional approaches deduction and induction by using creativity to connect familiar facts in new ways (Kovács & Spens, 2005). The research process for an abductive approach differs from the processes for inductive and deductive research because it determines what can be generalized in a situation and what is specific for that situation (Kovács & Spens, 2005). Golicic *et al* (2005) defines the phenomenon as the balanced approach, see Figure 2-1.

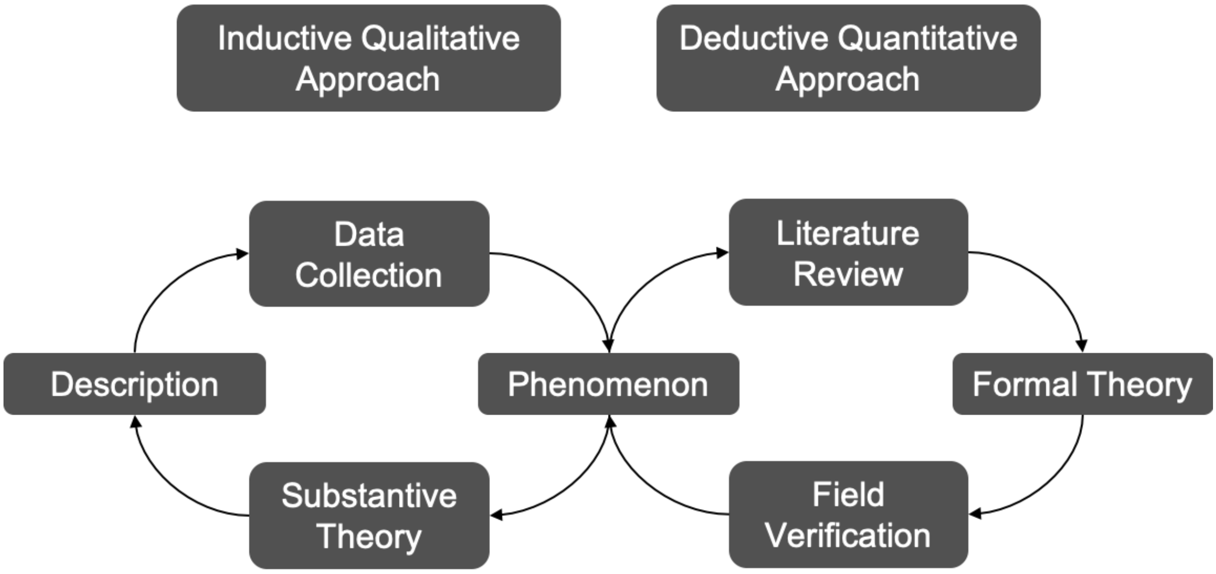

Figure 2-1: The Balanced Approach Model (Woodruff 2003).

2.1.4. Choice of approach

As stated, the purpose was concretized into two research questions. The nature of these two research questions was different and thusly required different approaches. RQ1 is to develop a model for determining safety stock taking stock availability of nearby inventory locations into consideration. Indeed, this subject has been covered extensively by researches in the last decades. It is also of a quantitative character and should be based on and adopted to the empirical data collected from IKEA Industry. Therefore, RQ1 was tackled by a deductive research approach. RQ2 is to suggest indicators for ensuring the performance of the spare parts flow. There is literature that cover the topic fairly extensively, implicating that a deductive approach is suitable. However, the issue is more open-ended than that of safety stock modeling. When generating the generalization for RQ2, interpretation, reasoning and discussion determined the result. The choice was of a more qualitative character than for RQ1. Because of this, the approach for RQ2 leans more towards an inductive research approach.

It can be concluded that no single research approach could cover the entire scope of this thesis and fulfil its purpose. This called for a more flexible research. As the research questions called for both deductive and inductive approaches, it seemed reasonable that an *abductive research approach would be chosen*. In practice, this was evident as the methodology for answering RQ1 was similar to a typical deductive methodology whereas the methodology for answering RQ2 had elements from both inductive and deductive methodologies.

2.2. Research strategies

There are many types of strategies for conducting research. Which one depends on the overall approach and ultimately the nature of the purpose and research questions. In this sub-chapter, some of the most common strategies will be briefly described followed by a justification of the chosen strategies. Not all of the strategies described below are going to be deployed in the study. The purpose of these short descriptions is to let the reader get a grasp of some of the most common research questions so that the choice of strategies makes sense. It is not meant to give an in-depth view of the strategies.

2.2.1. Case study

A case is defined as a phenomenon that includes data from interviews and direct observations. Different cases from the same company could be used to study the same issue in different contexts. Case studies can be used in different contexts for different purposes; some of them are presented below (Voss *et al,* 2002):

- *Exploration*: conducted in the early stages of research to find research ideas and questions.
- *Theory building*: a theory consists of definitions of terms and variables, a setting for the theory, a set of relationships and specific predictions. It can be viewed as "a system of constructs and variables in which constructs are related to each other by propositions and the variables are related to each other by hypotheses" (Voss *et al,* 2002, p. 198). The data obtained from case studies can be used to build theories.
- *Theory testing*: case studies can be used to test theories. In operations management, it is often used to test strategy implementation. The testing is often combined with survey-based research to achieve triangulation.

According to Yin (2009, p. 2) there are six steps to conducting a case study research: (1) plan, (2) design, (3) prepare, (4) collect, (5) analyze and (6) share.

Since the study will include empirical data, there will be a need of a research design. The purpose of the research design is to describe the activities and linkages that are needed to answer a research question (Yin, 2009, p. 26). Typically, this includes the description of data collection, data analysis and how it all connects to the research question. Specifically, the purpose is to explain *how* to begin with a research question and get to a conclusion. Yin (2009, p. 27) describes the case study design as consisting of five components:

1. The study's question
2. its propositions
3. its unit(s) of analysis
4. the logic of linking the data to the propositions
5. the criteria for interpreting the findings

2.2.2. Quantitative modeling

The initial research in operations was based on quantitative modeling, in the beginning it was more focused on solving specific problems instead of developing scientific knowledge. However, during recent years, there has been a change and general theoretical frameworks have been created. Model-based quantitative research describes models that entail causal relationships between variables. The variables are analyzed and tested to prove their relation. Examples of variables are inventory position, utilization rate or economic variables such as profits or costs (Bertrand & Fransoo, 2002).

Simulation

The difference between mathematical modeling and simulation is that simulation is capable of handling relationships that are more complex. The relationships do not need to be described exactly and there is no need for proofs, this makes simulation a good alternative for exploration and uncertainty modeling (Bertrand & Fransoo, 2002).

Operations research

During the last 60 years, the field of operation management has expanded significantly (Bertrand and Fransoo, 2002). A classical research method for operational research is presented in a four-step model, see Figure 2-2.

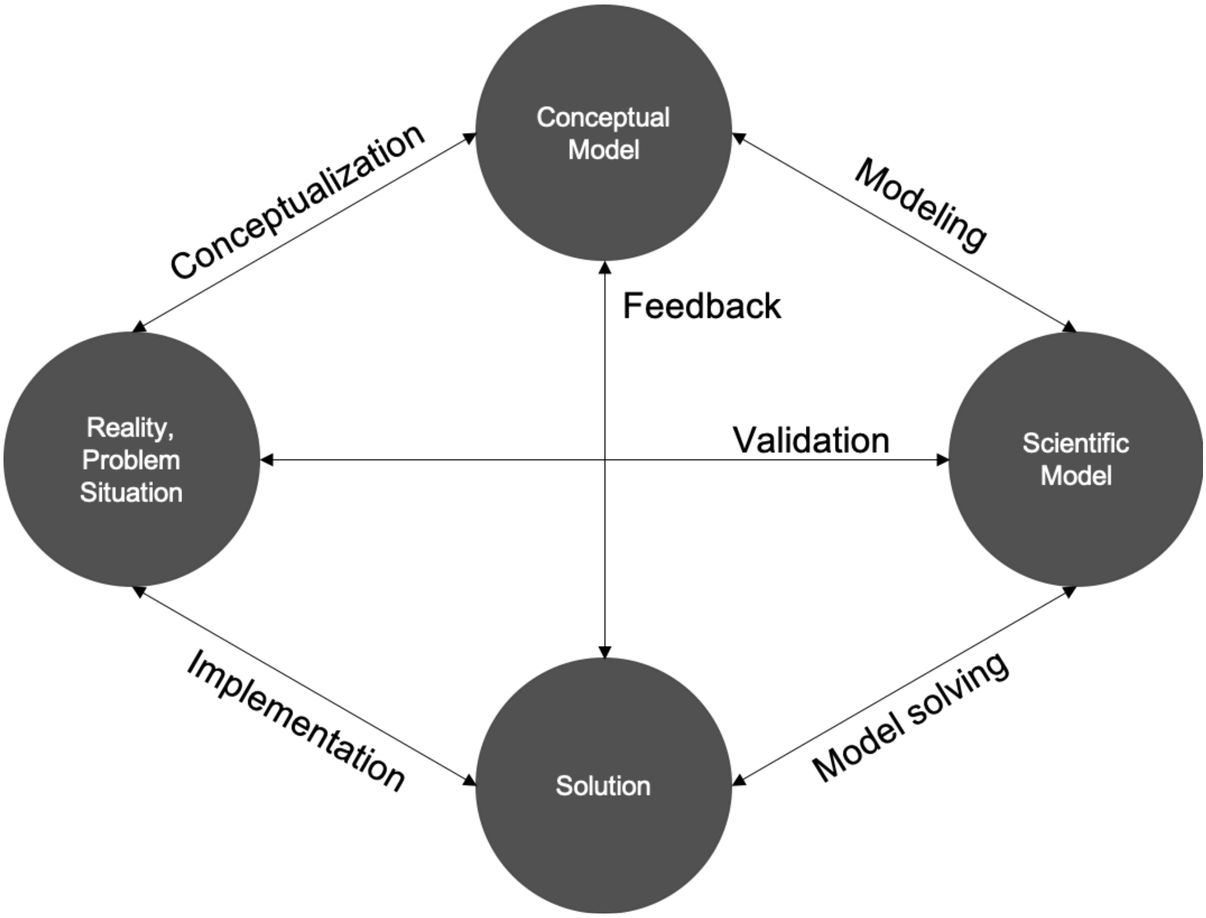

Figure 2-2: The four steps of modeling within operations research (Mitroff et al, 1974).

The four steps, as seen in the model, are the following:

- *Conceptualization*: A conceptual model is constructed in the conceptualization phase, relevant variables are determined, and the scope of the problem is set.
- *Modeling*: The quantitative model is built which ultimately defines causal relationships between the variables. The model is expressed in mathematical terms.
- *Model solving*: Combining intuitive and analytical skills in order to solve the problem with the model.
- *Implementation*: Putting the model to practical use.

In addition to the four steps, there is a link between the scientific model and the problem situation in the form of validation. The other link is between the formal theory and the conceptual model and highlights the issue that some researches take shortcuts in the methodology i.e. by mistaking the conceptualization for modeling. The framework in Mitroff *et al* (1974) illustrated in Figure 2-2 is a good way to ensure that critical parts of the modeling methodology are not overlooked, and that the methodology is easy to follow (Bertrand and Fransoo, 2002).

2.2.3. Survey research

A survey is a method that collects information from individuals. The means of collecting such information are for example questionnaires (either mailed or e-mailed), telephone conversations or interviews. The information supplied by the survey taker is usually of a personal or contextual character. The collective set of information gathered by the survey is meant to represent a larger population with sufficient accuracy so that it can be used of either developing, testing or describing concepts. There are different sampling methods (such as probability sampling and nonprobability sampling) that consider different factors to ensure that the sample is representative and accurate (Rae & Parker, 2014, pp. 177-200). Survey research is typically divided into three categories: exploratory, confirmatory i.e. theory testing as well as descriptive survey research (Forza, 2002).

2.2.4. Action research

Action research puts emphasis on "research *in* action rather than *about* action" (Coughlan & Coghlan, 2002, p. 222). Research that is conducted should not only result in theory and knowledge, but also in taking action. Usually it includes a sequence of events together with an approach to solve the problem. Action research also differs from traditional research because the knowledge acquired is of a particular character. It is situational and contextually embedded in a specific situation. In order to succeed, both researchers and client personnel need to adjust to new information and new events. The researcher needs to have a broad knowledge of organizational systems and an understanding for the organization in question.

Before action research can be initiated, a real issue of both research and managerial significance needs to be identified. The issue most likely has an uncertain outcome and the organization has a willingness to subject it to analysis (Coughlan & Coghlan, 2002).

2.2.5. Choice of research strategies

Similar to the way no single approach could be applied to the entire project, no single strategy could be deployed either. For RQ1, developing a model to determine stock levels required processing of much data from the internal systems. It also meant to utilize some scientific method resulting in near optimal solutions. For these reasons, including some form of *quantitative modeling* was inevitable. This aspect is rather intuitive, but there was also a qualitative element to it. For the model to be applicable to IKEA Industry, mapping of both the supply chain and stock definitions was conducted which required data collection, not only from internal systems but also interviews as well as visits to production plants. As for RQ2, which is a topic more open for interpretation and discussion, the focus was put more towards interviews and literature, but some information from internal systems was used to understand the current situation. Surveys was *not* used for any research questions in order not to take away focus from the other strategies being used. The value the surveys would bring was not deemed to outweigh the cons of distraction. Action research was not used either since the action was outside the scope of the thesis. Overall the research strategy was a *case study* which encompassed the phenomena of spare part stock level decisions and performance measurement in the context of lateral transshipments considering both quantitative and qualitative factors. In accordance with Yin (2009, p.2), the following study proposition and unit of analysis were formulated for the case study.

The study's question and its propositions

The phenomenon explored in the case study portion of the thesis is related to stock modeling and performance measurement. More specifically, how should IKEA determine optimal stock levels and how should the performance of the flow of spare parts for their manufacturing equipment be measured? The propositions for areas to explore within the scope are stock modeling considering lateral transshipment and determining indicators for availability and cost of handling.

Unit of analysis

For RQ1, the unit of analysis for this thesis is the stock levels for a set of spare parts articles at selected production units in IKEA Industry's supply chain. Current definitions of and routines for determination of safety stock was mapped in order to base the model on the appropriate literature. Given the limitations of time and other resources, only a selection of articles could be analyzed and only some production units could be used. The results of the analysis serve as a proof of concept that can be replicated using other articles and/or production units. When selecting articles to use for the model, the aim was to establish a set of articles that was representative of the collection of articles. For this part, assistance was supplied by the planning teams that determine stock levels at the selected production units. When selecting the production unit to use for the analysis, factors like proximity to other production units and quality of documentation as well as the possibility to visit the site were of interest. Because of this, production units like the one in Portugal were not relevant since they were not compatible with the study propositions. The production units that were the basis for the analysis are based in Zbaszynek (Poland West), Goleniow, Stepnica, Resko and Pine Sawmills, all of which in the western parts of Poland. The choice of production units is justified in chapter 4.4.1.

For RQ2, the unit of analysis is the performance of the production flow at the production units since this implicated by the spare parts flow. Data regarding time between maintenance and downtime due to lack of spare parts were of special importance. Similar to RQ1, current usage of indicators and their ability to capture the performance of the spare parts flow was mapped.

The logic of linking the data to the propositions

The collected data should be used for answering the research questions. In order to answer RQ1, an appropriate modeling technique should be chosen given the acquired data. In this thesis, the aim was to develop a model that has a sound foundation in literature. Given that analytical methods are dominant in the literature and that they produce results more efficiently than simulation methods and more effectively than simpler methods, an analytical solution method was chosen. The analytical solution method was used to describe the causal relationship between real data from IKEA Industry and the outputs of interest through mathematical and inventory control concepts. For RQ2, a model which considers spare parts directly should be chosen since the goal is to investigate performance for the spare parts inventory. The model should translate data into insightful KPIs which help IKEA understand their level of performance within spare parts management. The most effective way to do this is to use a framework which visually presents the performance, and that is also what the research strategy for this thesis is supposed to deliver.

The criteria for interpreting the findings

In order to interpret the data, an understanding of how the causal relationships in the analysis work and how they affect one another is key for accurately interpreting and drawing conclusions from the results. The mix of qualitative and quantitative data calls for a combination of different methods of interpreting the results. For example, for RQ1, the results to interpret are comprised of safety stock levels and their corresponding costs. These results depend on a number of different input parameters that subsequently depend on various qualitative factors. Therefore, the qualitative factors that affect the input parameters were noted and the influence the input parameters have on the results were evaluated. By utilizing this information, conclusions and discussions about the model and its results could be made. In the case of RQ2, it is more difficult to interpret the results as the analysis mainly consists of identifying similarities and differences between performance measurement in academia and at IKEA Industry. The difficulty lies in the fact that it is challenging to interpret in what ways the implementation will affect other parts of the company. To correctly interpret the results, an understanding is needed for how different business functions are connected to each other and how increase in performance for one business function affects performance in other functions. The results should be interpreted with having this in mind, together with an awareness of that KPIs, even though being defined mathematically in a specific way, still can be interpreted differently at different production units.

2.3. Data collection

Data collection is integral to several parts of the thesis including chapter 2, 3 and 4. Obviously, the quality of the input data of the thesis will determine the quality of the output data. In this thesis, there will be a number of different ways data will be collected including literature, interviews, internal systems and internal documents. These are described below following a distinction between primary and secondary data.

2.3.1. Primary and secondary data

There are several ways to collect data; some examples include experiments, surveys, interviews, participant observation, focus groups and IT-systems. Primary data is data that is collected specifically for the issue that is being analyzed. The collected data is added to the existing bank of knowledge and hence made available for use to other researchers as secondary data. Correspondingly, secondary data is data that has been collected by someone else for another purpose (Hox & Boeije, 2005). In this thesis, examples of primary data are demand data of spare parts and interviews. Examples of secondary data in this thesis are internal documents and literature.

2.3.2. Literature review

For both RQ1 and RQ2, a literature review is the first step (even though RQ2 leans more towards an inductive approach by nature). The initial steps of a literature review can be daunting given the vastness of the literature. It is therefore beneficial to use a search strategy. By using a structured way of reviewing the literature, one can ensure that as much as possible of the current literature is captured. There are several ways of doing this; four common search strategies are listed below (Rowley & Slack, 2004):

- *Citation pearl growing*: find a few documents from which search words are chosen to find related or similar documents.
- *Briefsearch*: quickly gives a few documents that can be used for further work.
- *Building blocks*: a thorough and lengthy research is conducted by extending the concepts from the search statement with synonyms and related terms.
- *Successive fractions*: this method is used when a large set of documents is reduced by searching within it to eliminate less relevant documents.

In this thesis, the same search strategy was used for finding material intended for both RQ1 and RQ2. The chosen strategy deployed citation pearl growing in the initial stages of the literature review and successive fraction once an extensive bibliography had been established.

Starting small

First, initial keywords for the topics of interest were identified through brainstorming sessions. For RQ1, these keywords include “safety-stock”, “modeling”, “spare parts” and “lateral transshipments” etc., see Figure 2-3. For RQ2, these keywords include “spare parts”, “performance measurement”, “service level” and “availability” etc., see Figure 2-4. In both cases, the list of keywords was expanded through studying the keywords of the initial literature.

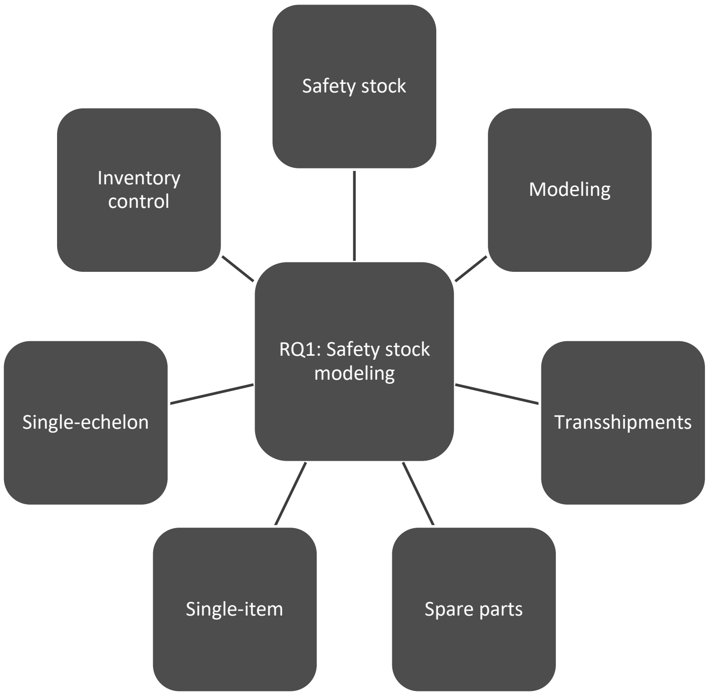

Figure 2-3: Keywords related to RQ1 used for finding literature.

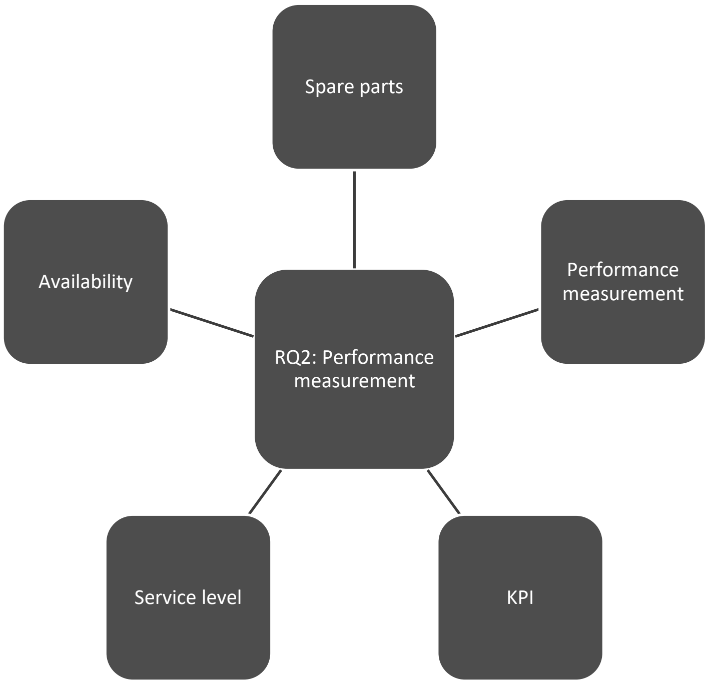

Figure 2-4: Keywords related to RQ2 used for finding literature.

The initial keywords were used for finding the first few articles in the database WebOfScience. By using two-word combinations of the initial keywords (in order to not limit the initial searches too much) and sorting the results by citations, an initial screening could begin. An example of an input in the database search function is using the search terms “transshipments” and “safety stock” and using an AND-statement to ensure that both of these key terms are in the topic. Since the number of citations is dependent on how old the article is, citations per year was noted rather than total number of citations.

Expanding the bibliography

When having identified a few initial articles, studying the reference list expanded the reading list. For both RQ1 and RQ2, highly cited literature studies for the topics could be found quickly. These literature studies compile literature within the topic and categorizes it. This can be a powerful tool to both expand the bibliography as well as shifting the focus to a certain part of the topic. For RQ1 for example, when studying a literature review by Paterson *et al* (2011), a categorization of single- and multi-item system was identified. When it had been concluded that single-item systems were of interest to the thesis, focus could be shifted towards these types of articles.

Narrowing down the selection

In the initial selection, articles were first screened through reading the title, keywords and abstracts. The second selection included skimming through the contents of the articles to ascertain whether the articles were relevant to the thesis. In the final selection, the articles were read more thoroughly so that a good understanding of the topics could be developed. It was at this stage that the literature review was written.

2.3.3. Interviews

Different methods exist for performing these kinds of interviews, some of which are listed and explained below.

Unstructured interviews

A form of interview where no preparation is made, similar to a regular guided conversation. Usually “key informants” are chosen due to their extensive knowledge or specific role. They serve as a source of information and study, sometimes on several occasions. The investigator takes notes while observing and questioning the key informant who can serve as a translator, teacher or mentor. Usually the interviews are not scheduled at a specific time or place. Instead, they happen randomly during several informal occasions (Dicicco-Bloom & Crabtree, 2006).

Semi-structured interviews

The semi-structured interview is scheduled beforehand to a specific date and time. Usually they revolve around a number of predetermined open questions from which other questions can emerge. Semi-structured interviews can be performed both individually and in a group for around 30 minutes. It is the most common method for performing in-depth interviews. An individual interview allows the interviewer to understand social and personal matters, while the group interview gives a wider range of experience (Dicicco-Bloom & Crabtree, 2006).

Structured interviews

In structured interviews, the questions being asked are standardized and the interview does not deviate from the pre-determined agenda. In general, the product of such interviews are of a quantitative character. This sort of interview is well suited for contexts where a hypothesis is to be tested and is therefore commonly used in health services research (Dicicco-Bloom & Crabtree, 2006).

Usage of interviews in this thesis

Interviews were used in this thesis primarily to collect information that was needed for the model but not available in the internal systems or secondary data like text documents and presentations. The interviews were also used to verify findings from other sources of information internally. Information gathered through interviews include current practices regarding both the planning of and follow-up on the spare parts flow as well as financial data. If the majority of the interviews would be structured, there is a risk that only information about the specific questions being asked would be given by the interviewee. Since the knowledge of how IKEA's current practices were limited, it seemed more suitable to opt for a semi-structured approach in order not to miss anything important. Another reason structured interviews were not used in this thesis is that the information that it is best suited for is quantitative. Collection of quantitative information was done in the internal systems and documents instead. The semi-structured approach enabled exploration while keeping the interviews productive. Therefore, the semi-structured approach was chosen for this thesis. A complete list of interviews is summarized in Appendix A and the interview questions for the different people being interviewed are summarized in Appendix B.

2.3.4. Internal systems

For the purpose of quantitative data collection, two main sources were used: the ERP-system M3 and an internal spare parts management catalogue called "Navigation portal". Data from M3 was supplied in the form of QlikView reports and in some cases directly from M3 through staff with access to the system. Data extracted from M3 included e.g. demand data and lead-time data. Navigation portal was also an important source of data since it contains the 40,000 harmonized articles; these articles have been analyzed and the data has been revised by the company. Data extracted from navigation portal included e.g. properties such as commonality of articles across the production units.

2.4. Analyzing the data

After collecting the data, there were a number of activities to execute in order to solve the problem and draw conclusions. These activities include mapping of the current practices, the preparation of data, developing the model and comparing performance measurement literature with IKEA Industry's performance measurement.

2.4.1. Mapping the current practices

The reason for mapping the current practices was two-fold. Firstly, in order to develop solutions that are applicable to IKEA Industry, an understanding on how it works currently was needed. Secondly, it allows for the demonstration of improvement; if a new solution is meant to improve on the current situation, one has to know the character and performance of it. Three main areas to map in this thesis were identified: (1) how safety stock is defined at IKEA Industry, (2) the process for determining stock levels for spare parts and (3) how performance of the spare parts flow is measured. The process of mapping these areas was partly just data collection whereas the analytical part of it was using the collected data to produce an easy-to-understand overview of the areas. The product was generalizing texts and figures.

2.4.2. Preparation of demand data

Understanding how the spare parts are used plays an important role when setting the stock levels. Since demand was only reported in the form of demand occurrences, describing the mathematical patterns required manual processing. If there would have been enough data points are available, statistical analyses could have been be used to describe the demand patterns. Using information about demand event sizes (number of parts demanded at a single event) and time in-between demand events, histograms would be plotted. By studying the histogram, an initial hypothesis of the demand distribution would be formulated. The hypothesis would subsequently be tested by a hypothesis test such as a χ^2-test. If there would not be enough data points for such a test to have statistical significance, the distribution would have to be approximated using qualitative factors. In this thesis, that was the case (see chapter 4.4.2). By studying usage of demand distributions in similar contexts, an approximation of the demand distribution was made.

2.4.3. Developing the model

Development of the model followed the main steps described in chapter 2.2.2. with the omission of the implementation step since this was outside the scope of the thesis. Weighing in both the literature and the requests of IKEA Industry, the overall functionality of the model was specified in the conceptualization phase. In the modeling and model solving phases, the model parameters were defined and the relationships between them were specified. This phase was based on existing models in literature to a great extent. The model itself was built in Microsoft Excel using the built in programming language VBA (Visual Basic for Applications). Excel was used because: (1) it is available at all IKEA Industry business laptops, (2) VBA is powerful enough to carry out the modeling technique and (3) it is easy to design a user interface with cells to contain input and output data and buttons to execute the code. Using the collected and prepared data, results were acquired.

There were several uncertainties tied to the input data which needed to be highlighted. In order to evaluate the impact of these uncertainties, sensitivity analyses were conducted. Despite the stochastic elements of the model, the outputs (safety stock levels and the total cost incurred by the stocking decision) will be the same every time the model is run if the input parameters remain constant. In other words, the outputs can be seen as deterministic (Borgonovo, 2017, p. 10). A common way of evaluating the sensitivity of such models is to use “One-way sensitivity functions”. The idea is to investigate the model outputs when varying the input parameters one-at-a-time within a predetermined range of values (Borgonova, 2017, pp. 27-28). The findigs are plotted in diagrams to give a visual representation of how the input parameters affect the result. The approach of the sensitivity analyses was to take one of the selected spare part articles that had been used in the analysis. Then each of the input parameters was altered while keeping all other parameters constant. The output parameters that the input sensitivity was tested against were both the safety stock levels and the total cost. Increment sizes and lower/upper boundaries for testing the input parameters were determined through trial-and-error in order to make sure that interesting model behavior was not missed.

2.4.4. Performance measurement comparison

In the case of performance measurement, the literature studied was critically reviewed. The usage of spare part performance measurement at IKEA Industry was studied; as was ways of collecting the data and the data infrastructure. With this acquired knowledge, it was discussed what IKEA Industry can learn from the literature. Since spare part measurement is not the sole focus of the thesis, pilot projects of testing any new suggestions would not take place during the thesis.

2.5. Credibility of study

In order for research to be taken seriously, credibility has to be proven. It is not a matter of course that research is of good quality. Readers of research are expected to critically scrutinize the means by which the research has taken. Therefore, authors have to demonstrate that their work is based on sound methodologies. Typically, there are three dimensions of research quality: validity, reliability and objectivity (Denscombe, 2010, pp. 297-298). These concepts are described briefly below.

2.5.1. Validity

Validity refers to whether the data is the right kind for the study and if it has been measured correctly, the accuracy and precision of the data should be correct in order to answer the posed research question. There are several methods for evaluating the validity of data; one is *Respondent validation*, which means that the researcher goes back to the participants to check the validity of the findings. In general, it is easier for a researcher to validate quantitative data, as qualitative data can be much harder to validate (Denscombe, 2010, p. 298).

Higher levels of validity can be achieved by using multiple perspectives to explain a single phenomenon (Björklund & Paulsson, 2012, p. 62). This can be done e.g. by the use of triangulation. In triangulation, two or more methods are used for the same purpose, see Figure 2-5.

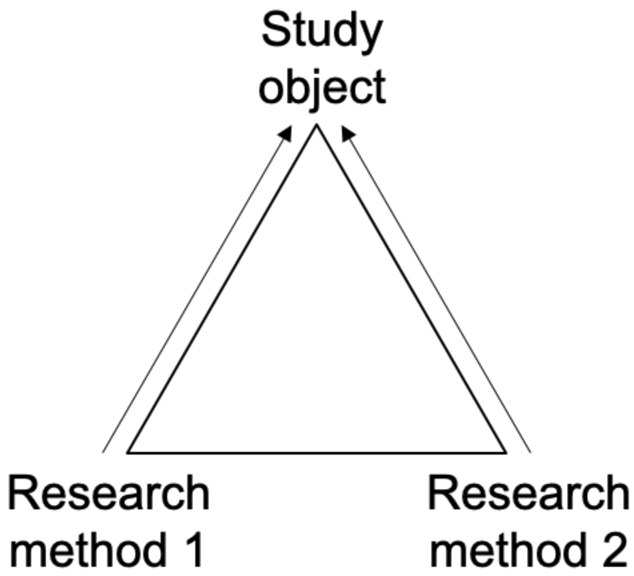

Figure 2-5: Using triangulation means using two or more research methods for the same purpose (Björklund & Paulsson (2012, p. 80).

2.5.2. Reliability

The research instrument used should generate the same result on several occasions to guarantee that it is not affected by other factors. For example, another researcher could use the same instrument to rule out biased results generated by the main researcher. The research process used should be open for audit and another researcher should be able to come to the same result by following the documented process (Denscombe, 2010, p. 298). Higher levels of reliability can be achieved for example by using control questions when conducting interviews/surveys or through the use of triangulation (Björklund, 2012, p. 62). Reliability/validity is seldom studied in isolation and both are needed in order to construe good research quality. Principles of combinations high/low validity and reliability are illustrated in Figure 2-6.

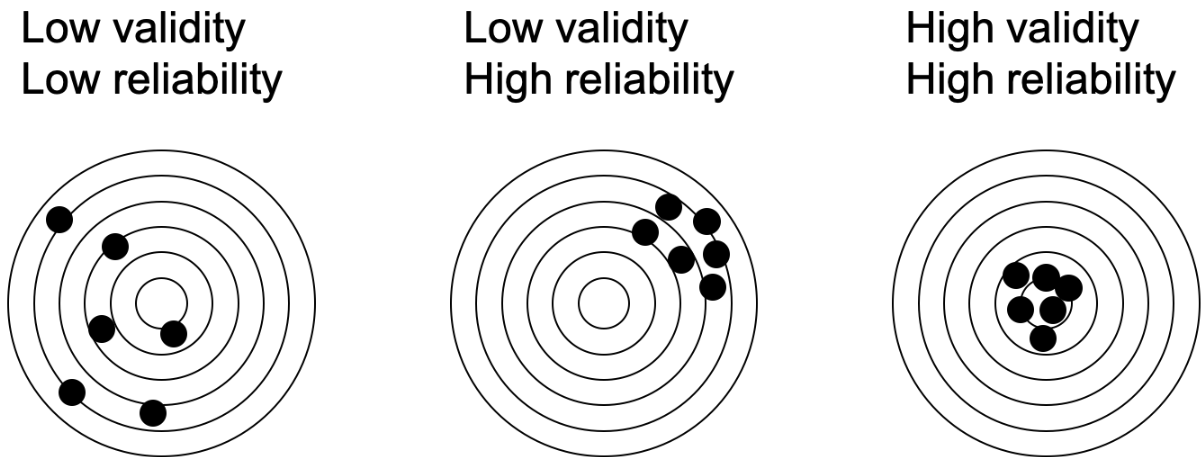

Figure 2-6: Concept illustrations of validity/reliability combinations (Björklund (2012, p. 62)).

2.5.3. Objectivity

Biased research is something that the researcher needs to avoid as much as possible, the research should be impartial and neutral. Unfortunately, no research is completely free from bias since the data, especially qualitative data, needs to be interpreted. The researcher should try to be conscious of the fact that he or she is biased by personal values and beliefs, and consider those when interpreting the results. It will never give a fully clean, unbiased result but it will be enough for the research community to accept it (Denscombe, 2010, p. 302). Higher levels of objectivity are reached when choices and assumptions are clearly explained and motivated since it gives the reader the opportunity to take a stand to what is being presented (Björklund & Paulsson, 2012, p. 63). The author should also be conscious of presenting “true facts”, not only presenting facts that support the hypothesis and not use emotionally charged wording (Björklund & Paulsson, 2012, pp. 63-64).

2.5.4. Ensuring good quality of the thesis

As stated in 1.6., there are multiple target groups of the thesis and what comprises good quality differs among them. The two target groups that were considered when discussing the quality of the thesis were the study object IKEA Industry and the university. To ensure a well conducted thesis from IKEA Industry’s point of view, continuously discussing thoughts and results with all stakeholders in the project, both from the company and from the university were key activities. The data used in the model came directly from the IT-systems in the company; more specifically from the data set that came from the data harmonization project. This helped ensuring the reliability of the model. The development of the model was based on contemporary research within the field that was critically reviewed by the authors. Support was supplied both from the university by experts within the field as well as representatives from IKEA Industry which helped achieving a model that is robust and applicable to IKEA Industry.

From an academic point of view, the validity, reliability and objectivity of the thesis is of special importance. Validity/reliability was ensured through a triangulation principle. For both the development of the model and the suggestions for the indicators, multiple methods were used including interviews and the collection, processing and analysis of data from IKEA Industry’s internal systems. Objectivity was ensured through the transparency of methodologies and assumptions. The development of the model was largely based on the data from the internal systems, which has an objective character. Any shortcomings or uncertainties in the data collected is clearly highlighted so that calculations can be redone if data of better quality should become available in the future. The choice of modeling procedure and the suggestion of indicators, however, is more of a subject for interpretation. Therefore, justifications and explanations of the reasoning behind choices made allows the reader to take a stand to the thesis.

2.6. Summary of methodology

For the thesis, an overall approach is chosen for the research containing a research strategy which can be further divided into research processes. The overall research approach is abductive, including both deductive and inductive elements. The research strategy is a case study strategy utilizing both quantitative (especially for RQ1) and qualitative (especially for RQ2) data. Furthermore, the research processes are divided into data collection, analysis and reporting. Data was collected through literature, interviews internal systems, documents as well as visit to the Lubawa site. Before the analysis was conducted, the data was prepared which included mapping current practices and estimating the demand (number of breakdowns of spare parts). A mathematical modeling technique was implemented in Microsoft Excel for solving the safety stock problem and its sensitivity was analyzed. IKEA Industry's usage of spare part performance measurement was compared with literature about the subject. Reporting was conducted in the form of continuous progress update meetings with both supervisors from IKEA Industry and Lund University. As for the credibility of the thesis, reliability and validity was addressed by triangulation and consultations with stakeholders. Objectivity was addressed by being transparent with methodology and assumptions as well as the usage of objective input data to the model. The overall methodology of this thesis is illustrated in Figure 2-7.

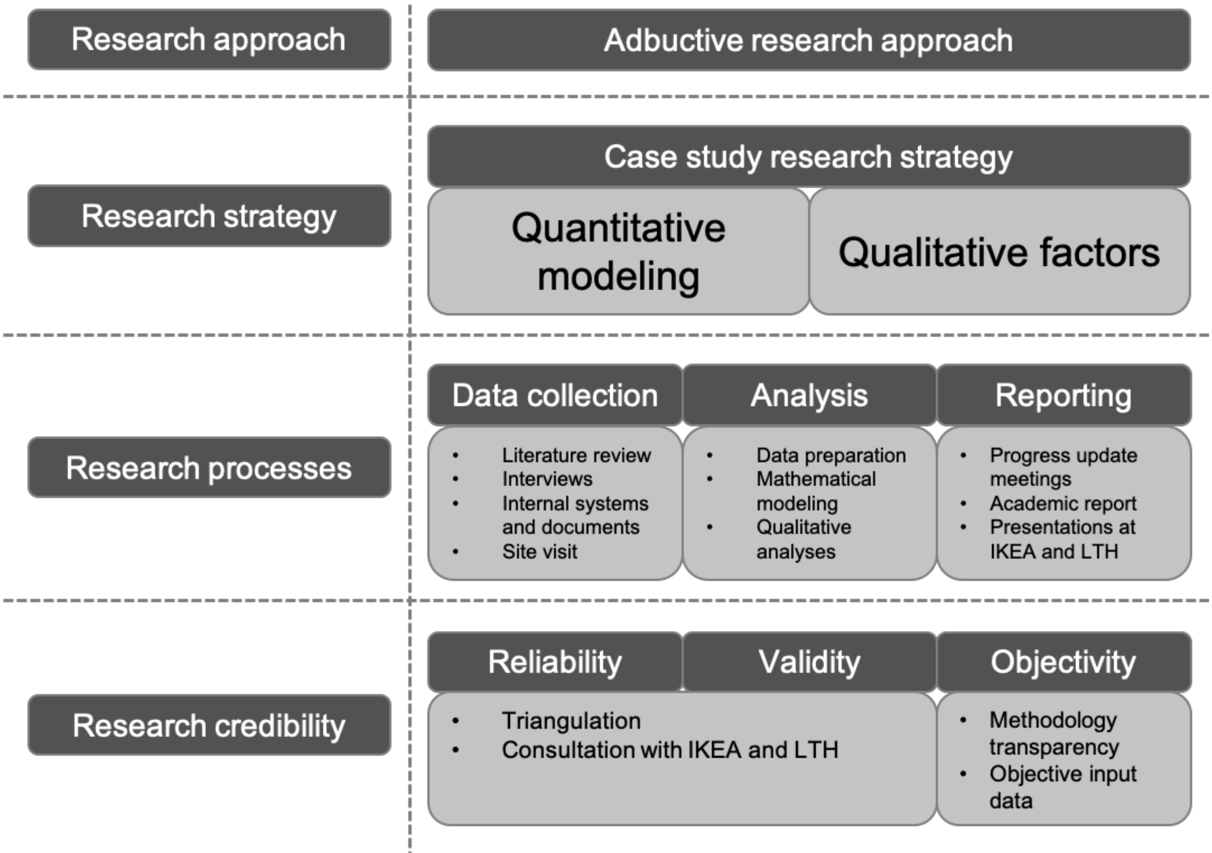

Figure 2-7: Illustration of the overall research methodology of this thesis.

The different activities of which the thesis is comprised are visualized in Figure 2-8.

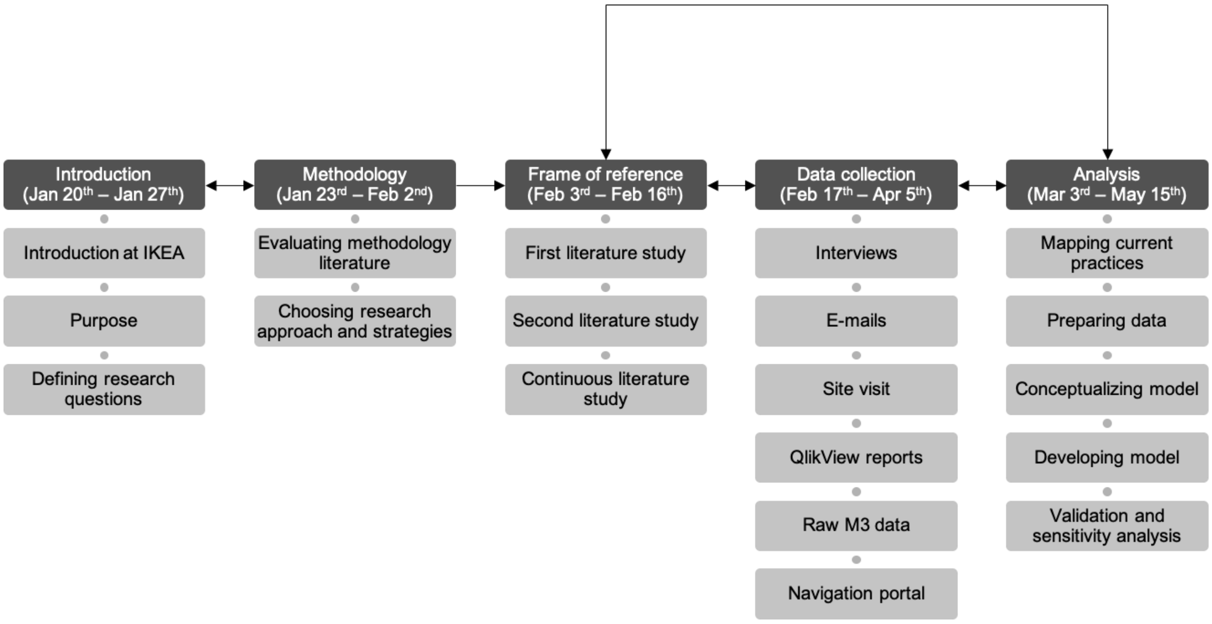

Figure 2-8: Outline of activities conducted during this thesis. The dates represent the time frame in which most of the work was done.

3. FRAME OF REFERENCE

The aim of this section is to provide a reference for the following data collection and analysis. Both the case study and the mathematical modeling requires a review of the existing literature. The information gathered from the literature will not only serve as a basis for the analysis but will also support in deciding what information that has to be collected from IKEA Industry. The purpose is not to provide in-depth explanation of each area, but rather provide enough information such that a basic understanding of modeling, performance measurement and its related elements can be established.

3.1. Chapter breakdown

Since the purpose of the thesis has been concretized into two research questions, the literature studied should address both of these research questions. With this in mind, the topics studied in the literature review are categorized with respect to which research question they address, see Figure 3-1. The following sub-chapters will cover each of these areas.

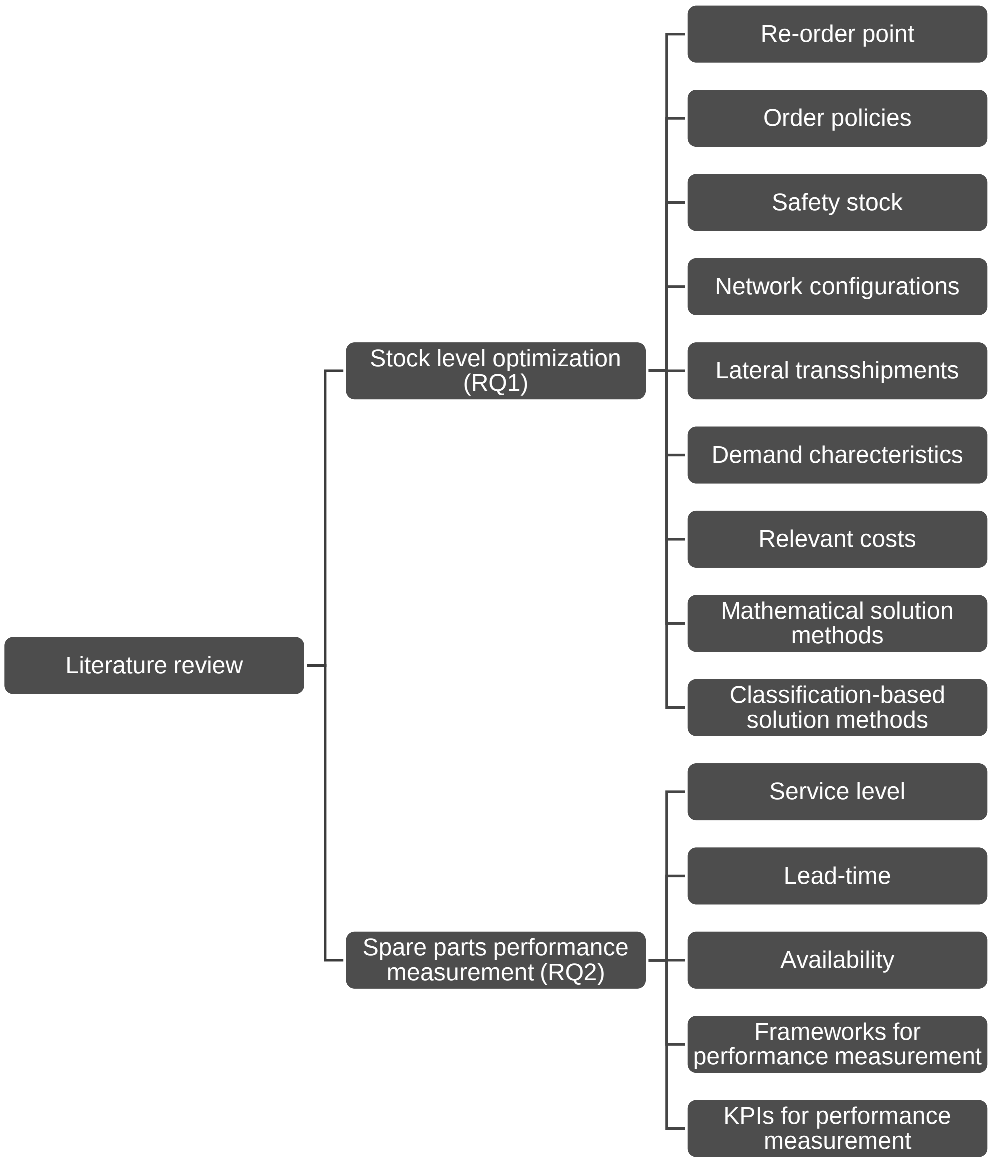

Figure 3-1: Overview of the topics to be covered by the literature review.

3.2. Definitions

Throughout this chapter and the rest of the thesis, a selection of inventory control terminology will be used. Some of these sub-topics will be explained further in the frame of reference while some will be used without further explanation. The purpose of this list is to serve as a quick reference or a reminder if the reader is unfamiliar with a term. The list is presented in Table 3-1.

Table 3-1: Table containing a selection of inventory control terminology used in the thesis.

Term	Definition
Outstanding order	Goods that have been ordered but not yet delivered
Backorder	When an item is demanded but not available and the customer waits until it is available
Lost sales	When an item is demanded but not available and the customer leaves
Stock on hand	Physical inventory
Inventory level	Stock on hand - backorders
Inventory position	Stock on hand + outstanding orders - backorders
Safety stock	Additional stock that is used to hedge against uncertainties
Holding cost	The cost of holding goods (percentage of goods value)
Shortage cost	Costs associated with the situation when an item is requested but cannot be delivered
Lead-time	The time between the placement and delivery of an order
Transportation time	The amount of time an order is in transit
Lateral transshipment	The shipment of goods between inventory locations at the same level in the distribution network
$SERV_1$	The probability of experiencing no stockout during the order cycle
$SERV_2$	The fraction of the demand that can be satisfied directly from the stock on hand (fill-rate)
$SERV_3$	The fraction of the time with positive stock on hand (ready-rate)

3.3. Stock level optimization

Setting the correct stock levels in an inventory is in many cases a difficult task, which requires the consideration of many different elements. The literature on the subject is rich. When developing a model for optimizing the stock levels, both in academia and in practice, the work is based on existing models. However, it is important to understand what parts of the existing models that are applicable to the context in which the new model is to be developed. Depending on different factors such as order policies and network configurations, different approaches to the modeling have to be taken. With this in mind, the following sub-chapters will describe the main factors so that an informed selection of existing models to base the analysis on can be made.

3.3.1. Re-order point

In an inventory system, a main parameter to determine is the point where an order is placed to replenish the stock. This is called the re-order point. To fully understand what it means, a grasp of concepts like stock on hand, outstanding order, backorder, inventory position and inventory level is needed. Stock on hand denotes actual physical stock at the inventory location. An outstanding order is goods that have been ordered but have not been delivered yet. A backorder is when an item is demanded but not available and the customer waits until it is available (Axsäter, 2006, pp. 45-46). The inventory level is

$$IL = \text{stock on hand} - \text{backorders}.$$

The inventory position is

$$IP = \text{stock on hand} + \text{outstanding orders} - \text{backorders}.$$

The re-order point is the inventory position at which an order is placed (Axsäter, 2006, pp. 48-49). There are different principles regarding what this re-order point should be (see chapter 3.3.2. Order policies).

3.3.2. Order policies

There are different policies for re-ordering which is interesting in the context of stock levels. The two most common order policies are the (R,Q)-policy and the (s,S)-policy.

(R,Q)-policy

The (R,Q)-policy has two main parameters, the re-order point R and the batch size Q. When the inventory position is equal to or below the re-order point R, new goods are ordered with the batch size Q. Depending on the review system, the ordering will take place at different inventory positions. If the inventory is monitored continuously (*continuous review*) and the demand is continuous, the order will always be triggered at the inventory position R. If the inventory is monitored on scheduled points in time (*periodic review*), the inventory position at the time is often lower than R. The maximum stock level in an inventory system with an (R,Q)-policy is $R + Q$ which assumes that the inventory position at the point of ordering is R and that there is no lead-time for replenishing the stock (Axsäter, 2006, pp. 48-49).

(s,S)-policy

In an (s,S)-policy, also known as the base stock policy, s is equivalent to R in the (R,Q)-policy i.e. the re-order point. S, however, denotes the so-called "order-up-to point". Depending on the inventory position at the point in time when ordering, the batch size will vary. In the case of continuous review and continuous demand, as stated above, the replenishing order will always be triggered exactly at the re-order point. In such cases, the (s,S)-policy is equivalent to an (R,Q)-policy where $R = s$ and $Q = S - R$. Note that the equivalence is not present in a periodic review system since the orders are not always triggered at the re-order point. A common variation of the (s,S)-policy is the (S-1,S)-policy where s = S -1. According to this policy, an order will always be triggered if one or more units have been demanded (Axsäter, 2006, pp. 49-50).

3.3.3. Safety stock

Due to uncertainty in demand, it is almost impossible to always have optimal stock levels and because of this, almost all inventory models use *safety stocks* (Axsäter, 2006, p. 2; Lumsden, 2007, p. 227). Safety stock is separate from the normal inventory and acts like a security towards uncertainty in demand (Axsäter, 2006, p. 94). In other words, in ideal conditions, the safety stock should not need to be utilized. The problem is to set the safety stock at a proper level to avoid to high holding costs but at the same time be prepared for uncertainties in demand, which could result in backorder costs, loss of sales or even penalties (Axsäter, 2006, p. 59).

3.3.4. Network configurations

When modeling an inventory system, the configuration of the system has to be considered. There are many different ways to categorize inventory systems. In Paterson *et al* (2011), which provides an overview of models for determining stock levels taking lateral transshipments into consideration, the network configuration is defined according to five different factors:

1. Single-echelon vs. multi-echelon
2. Single-item vs. multi-item approach
3. Number of bases
4. Identical bases vs. non-identical bases
5. Backorders vs. lost sales

Single-echelon systems

Single-echelon systems or single-stage systems are of the most basic kind, only consisting of one level of inventory locations, see Figure 3-2. In this configuration, all inventory is stocked at a single position, which can be the case for many wholesalers (Axsäter, 2006, p. 43). It is important to keep in mind that in most of its applications, the assumption of a single-echelon system is a simplification of reality. Despite of this, the solutions, which are obtained relatively simply, can be of satisfactory quality in many cases (Axsäter, 2006, p. 43). One advantage of single-echelon systems is that it is possible to determine optimal solutions for stock levels, safety-stock levels and re-order points (Axsäter, 2006, p. 129-145). Such optimization methods are compiled in Axsäter (2006) but since they do not consider transshipments, these methods will not be presented in this thesis.

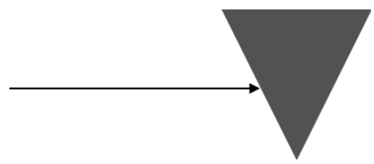

Figure 3-2: Illustration of a single-echelon system where all inventory is stocked at one location.

Some configurations also allow for shipments between inventory locations at the same level (parallel inventory locations), see Figure 3-3. Such shipments are called lateral transshipments. Since this is a central part of the problem formulation of the thesis, this phenomenon has a dedicated chapter, see chapter 3.3.5.

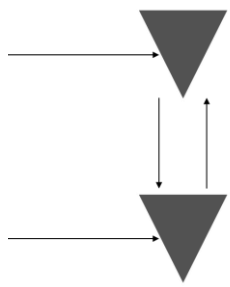

Figure 3-3: Illustration of an inventory system allowing lateral transshipments between parallel inventory locations (adapted from Axsäter, 2006, p. 193).

In some networks, a return flow is also considered, sometimes in the form of repairable items. This means that when an item at one inventory location breaks, it can be sent to another inventory location to be repaired and stocked until it is sent back to the location at which it broke. For stock models for spare parts flows, repairable items is sometimes an assumption (Lee, 1987; Axsäter, 1990; Wong *et al*, 2005a; Hochmuth & Köchel, 2012). Most of such literature also assumes that the capacity for repairs is unconstrained (Díaz & Fu, 1997). The model proposed by Axsäter (1990) can, however, be modified to assume consumable items instead of repairable items.

Multi-echelon system

In many different supply chain contexts, a single-echelon system is not realistic. Such contexts include where the supply chain is covering large geographical areas or when different raw materials, components and products are combined into finished goods (Axsäter, 2006, p. 199). In these situations, the systems are multi-echelon (or multi-stage) systems meaning that stock is kept at multiple levels in the network. Multi-echelon system is an umbrella term and comprises many different ways to configure a network of inventory locations. The simplest multi-echelon system is the two-echelon serial system, which consists of two installations, see Figure 3-4. In this system, installation 1 is supplied by installation 2, which is supplied by an outside supplier. An example of this could be a company where installation 1 is the stock of finished goods while installation 2 is the stock of components used to assemble the final goods.

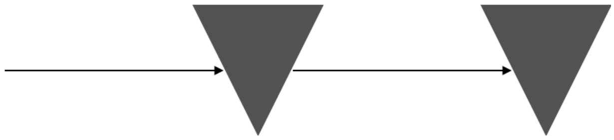

Figure 3-4: A simple two-echelon serial system (adapted from Axsäter, 2006, p. 188).

Another type of system is a diverging inventory system, sometimes called a distribution system, see Figure 3-5. In these systems, the number of inventory locations increases for each level. An intuitive example of this is a central warehouse supplying a number of retailers (Axsäter, 2006, pp.188-189).

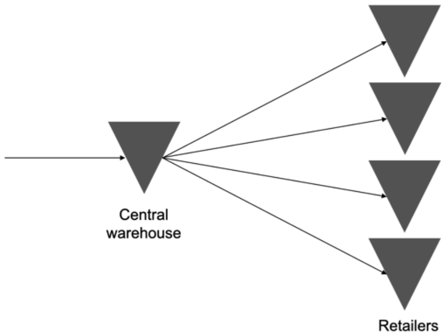

Figure 3-5: Illustration of a two-level diverging system containing a central warehouse and some retailers (adapted from Axsäter, 2006, p. 189).

On the other hand, there are converging inventory systems as well (sometimes called assembly systems), see Figure 3-6. In these systems, the number of inventory locations decreases for each level. This is prevalent in production systems where there are several parallel inventory locations upstream for materials and components eventually being combined into finished goods downstream (Axsäter, 2006, pp.189-190).

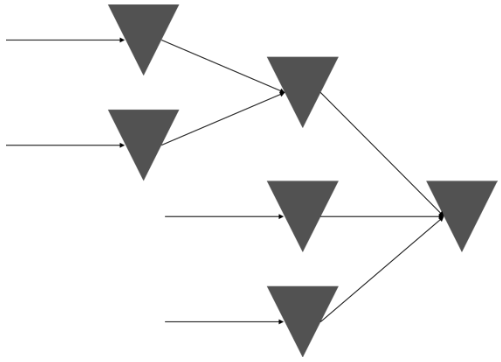

Figure 3-6: Illustration of a converging inventory system (adapted from Axsäter, 2006, p. 190).

Some networks are neither strictly divergent nor strictly convergent, see Figure 3-7. These systems are called general multi-echelon systems, which typically are more difficult to optimize, compared to serial, strictly divergent or convergent systems.

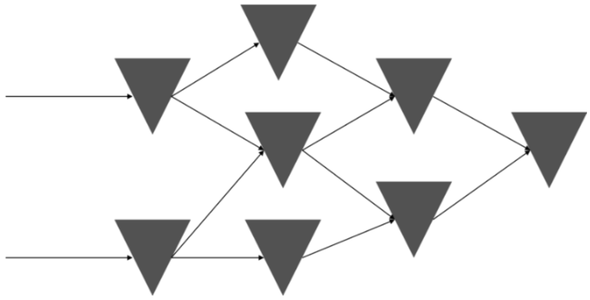

Figure 3-7: Illustration of a general multi-echelon inventory system with both converging and diverging sub-structures (adapted from Axsäter, 2006, p. 191).

Single-item approach vs. multi-item approach

Single-item systems are systems that view each item in isolation when setting inventory levels while multi-item systems consider all items in the system when making inventory decisions (Wong *et al*, 2005a). In the context of optimizing inventory levels, literature covering single-item systems has always been dominating (Wong *et al*, 2005a; Paterson *et al*, 2011). The literature covering the multi-item approach is limited in comparison. Examples of multi-item approach models are Archibald (1997), Wong *et al* (2005a) and Wong *et al* (2006). There is however, literature that shows that the multi-item approach results in more significant cost savings than the single-item approach (Thoneman *et al*, 2002).

Number of bases and whether they are identical or not

The number of bases denotes how many different locations there are at the same level among which the lateral transshipments will be sent. The minimum number of bases is two. There are a handful of models with two or three bases e.g. Archibald et al (1997), Köchel (1996) and Tagaras (1999). Most of the literature cover N number of bases, which denotes a general number of bases. Identical bases share identical attributes, e.g. demand and cost. Conversely, non-identical bases do not have these attributes in common. Cost identical, refers to bases that share the same costs but do not share other attributes (Paterson et al, 2011; Axsäter, 1990).

Backorders vs. lost sales

Backorders refer to demand that cannot be met due to a shortage, this demand is then backordered and shipped out when the stock level is restored if the customer is willing to wait (Axsäter, 2006, p. 46). When taking this into account, either a shortage cost in the form of a backorder cost (see chapter 3.3.7.) or a service level constraint can be used. If the customer is not willing to wait, the order is lost. In such cases, costs associated with that loss has to be taken into consideration (Axsäter, 2006, p. 117; Dada, 1992).

3.3.5. Lateral transshipments

In an inventory system with a depot supplying several bases which cover an extensive geographical region, it is sometimes more time-efficient to restock a base from another neighboring base, instead of the depot, see Figure 3-3 (Axsäter, 1990; Wong *et al*, 2005a). The reason for this is that the distance between neighboring bases often is shorter than the distance between a base and the depot. Transportation of items made between bases is referred to as lateral transshipments.

There are several advantages to lateral transshipments, one being the avoided cost connected to satisfying a backordered demand faster. However, there are also some additional costs related to lateral transshipments such as transport costs and the cost of issuing the lateral resupply order. By using lateral transshipments, the total accumulated inventory level can be reduced, hence lowering holding costs (Lee, 1987). Tagaras *et al* (2002) suggest that lateral transshipments only reduce the total costs when the demand variability is high. This should be considered while analyzing demand data for the products a company wants to transship (Tagaras *et al*, 2002).

Several authors have contributed to the literature of lateral transshipments with some deviations regarding the assumptions and simplifications that they have made. In Paterson *et al* (2011), there are four characteristics related to the use of lateral transshipments that differentiate existing models. The four characteristics are:

1. Type – proactive, reactive or both
2. Pooling – complete, partial or both
3. Decision making – centralized or decentralized
4. Cost – per item, per transshipment, both or none

Type

A company can choose between utilizing either a proactive or a reactive approach to lateral transshipments. A proactive approach means that lateral transshipments are used to restock a base even when the base is not out of stock. Conversely, a reactive approach means that a lateral transshipment is made between two bases only when a base is completely out of stock. Literature developing models for proactive lateral transshipment include e.g. Agrawal *et al* (2004), Bertrand & Bookbinder (1998) and Gross (1963). Models for reactive lateral transshipment are developed by e.g. Lee (1987), Axsäter (1990) and Archibald *et al* (2008).

Pooling

When two or more bases enter a collaboration to utilize lateral transshipments, they can choose between sharing all of their stock with each other, or only parts of it. When bases choose to share all their stock, the term complete pooling between the bases is used. When companies only share part of their stock, the term partial pooling is used. In some cases, complete pooling exists between some bases in the network while partial pooling exists between other bases. There seems to be an even distribution of literature covering complete pooling and partial pooling respectively while a combination of the two is rarer (Paterson *et al* (2011).

If there are several bases across a larger area, it may be preferable to put the bases in pooling groups. The size of the group and the number of bases in them are determined by factors such as distance and transportation cost. If a base in a pooling group is out of stock, an emergency transshipment is issued to restock it and satisfy the demand. The base that sources the transshipment will issue a restocking order to the depot. If several bases are available to issue the lateral transshipment, a set of rules it utilized to prioritize which base should satisfy the demand. These rules vary between different authors, the three rules presented by Lee (1987) are the following:

- Random source rule. The source base is chosen randomly from among the members of the pooling group with stock on hand.
- Priority source rule 1. The base with the maximum stock on hand is chosen as the source base. If there are ties, then the source base is chosen randomly among the ties.

- Priority source rule 2. The base with the maximum stock on hand is chosen as the source base. If there are ties, then the base with the smallest number of outstanding orders waiting at the depot is chosen. If there are still ties, then the random rule is used to break the tie (Lee, 1987).

Decision-making

In order to use lateral transshipments in an inventory system, the type of decision-making needs to be specified since it affects how the model is constructed. If there is a unit in the organization that controls all other bases, then the organization is centralized, and decision-making is centralized. This is critical because the central unit can decide that bases should share all their stock or give them other instructions. A decentralized organization will add even more complexity to the modeling of lateral transshipments. Most literature on lateral transshipments assumes centralized decision making such as Agrawal *et al* (2004), Gross (1963) and Archibald *et al* (2008). Articles developing models for decentralized decision making include Sosic (2006) and Slikker *et al* (2005).

Cost

This category is related to what cost structure is applied to the lateral transshipments. The cost can be set at item level, which means that the company pays for the lateral transshipment based on the number of items that is sent. The cost can also be set as fixed per transshipment, or a combination of fixed and item-based cost models can be used. The last alternative is to assume that the cost is negligible compared to the cost savings made from reduced inventory levels or penalty costs (Paterson *et al,* 2011; Wong *et al,* 2005a).

3.3.6. Demand characteristics

Demand does not necessarily have to be constant over time. There are often uncertainties tied to the demand complicating predictions about the future (Lumsden, 2007, pp. 232-234). In such situations, it is appropriate to assume stochastic demand. The different types of demand distributions can be categorized into continuous demand and discrete demand and are used in different contexts. Distributions like the normal distribution and gamma distribution are examples of continuous distributions. Distributions like the compound Poisson distribution, logarithmic compounding distribution and geometric compounding distribution are examples of discrete demand. Since demand almost exclusively is a non-negative integer, it is a discrete stochastic variable. When the demand is low, it then makes sense to assume that the demand follows a discrete demand distribution. However, when the demand is large, there are benefits of assuming a continuous demand distribution (Axsäter, 2006, p. 77). Brief descriptions of some of the most common distributions for demand are presented below.

Normally distributed demand

Assuming the demand is normally distributed is fairly common among practitioners for a number of reasons. It is relatively easy and intuitive to handle. When there are many independent variables, the sum of said variables can be assumed to follow a normal distribution according to the central limit theorem. Contexts where there is a large number of independent discrete demand events are well suited to be approximated with a normal distribution. The major drawback of assuming a normal demand distribution is the probability of negative demand. In Figure 3-8, a normal distribution with the mean value 2 and standard deviation 1 is plotted. One can clearly observe that the probability of negative demand is greater than zero. In practice, the coefficient of variation (the ratio between the standard deviation and the mean value) may be significantly smaller than in this illustrative example, but the principle still holds.

The left-hand end of the tail of the bell curve approaches infinity, which means that the probability of negative demand will always theoretically exist. While negative demand can exist in practice (Browne & Zipkin, 1991), demand is almost always positive (Axsäter, 2006, p. 77).

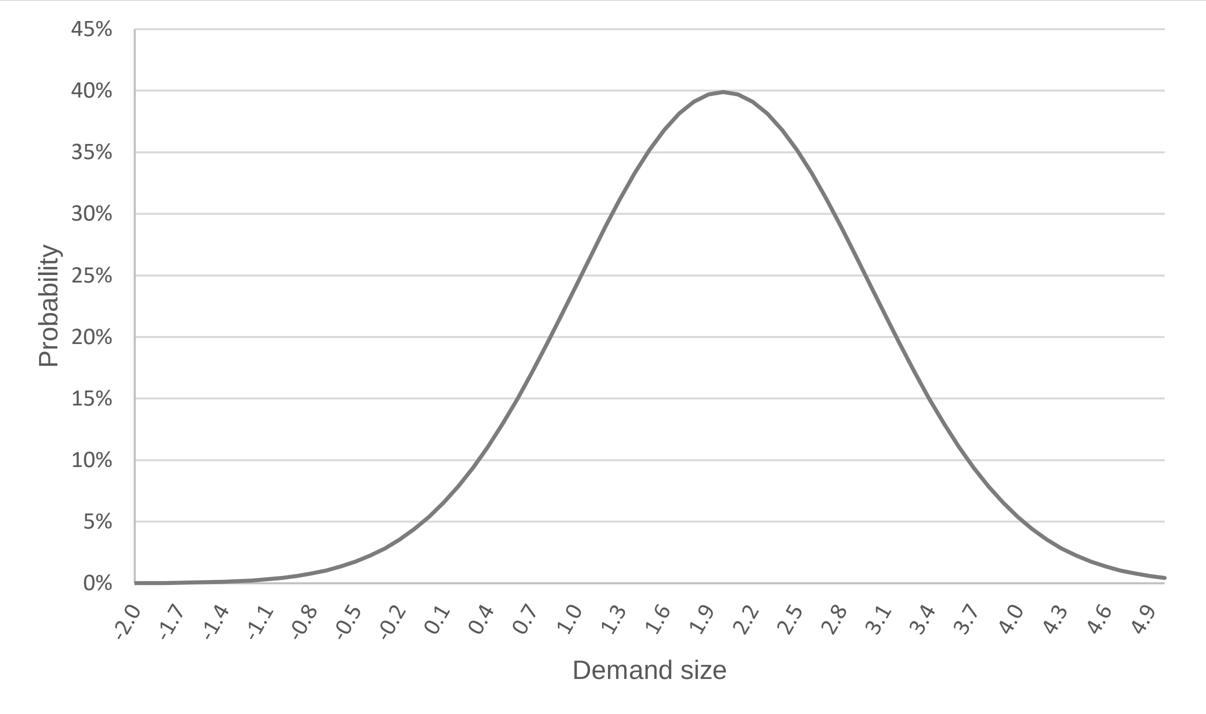

Figure 3-8: An example of a normal distribution to illustrate the probability of negative demand.

The density function and cumulative distribution function are

$$f(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}, \qquad -\infty < x < \infty$$

and

$$F(x) = \int_{-\infty}^{x} \frac{1}{2\pi} e^{-\frac{u^2}{2}} du$$

respectively.

Gamma distributed demand

Not all continuous distributions have the same problem with negative demand as the normal distribution does. The probability of negative demand for normal distributed demand increases when the coefficient of variation increases. In such situations, it might be suitable to use a gamma distribution (Axsäter, 2006, pp. 86-87). The density function for the gamma distribution is

$$g(x) = \frac{\lambda(\lambda x)^{r-1} e^{-\lambda x}}{\Gamma(r)}, \qquad x \geq 0.$$

where $\Gamma(r)$ is the gamma function

$$\Gamma(r) = \int_{0}^{\infty} x^{r-1} e^{-x} dx.$$

The mean and variance of the gamma function are r/λ and r/λ^2 respectively. With given μ' and σ' from the demand data, r and λ can be determined with

$$r = \left(\frac{\mu'}{\sigma'}\right)^2,$$

$$\lambda = \frac{\mu'}{(\sigma')^2}$$

Poisson distributed demand

A Poisson process is, in essence, a counting process in which the time intervals between events are independent (Ross, 2014, p. 297). Poisson distributed demand is assumed when the inter-arrival times between customers (demand events) are exponentially distributed and each demand size is 1. The computational efficiency of using a Poisson method makes it attractive but it is only appropriate in certain situations. Typically, Poisson distributed demand is used when the demand is low (Ramaekers & Janssen, 2008). As a rule of thumb, if the ratio between the variance and the mean value is above 0.9 and below 1.1 i.e.

$$0.9 \leq \frac{\sigma^2}{\mu} \leq 1.1$$

then it is appropriate to assume Poisson distributed demand. A Poisson distribution is often used for $\frac{\sigma^2}{\mu} < 0.9$ as well even though the variance is overestimated as a result. For $\frac{\sigma^2}{\mu} > 1.1$ it is more suitable to use a compound Poisson demand with a compound logarithmic distribution (negative binomial distribution) (Axsäter, 2006, p. 85). Assuming Poisson distributed demand, the probability for k customers is

$$P(k) = \frac{\lambda t^k e^{-\lambda t}}{k!} \qquad (Eq. 1.1.)$$

where λ denotes the arrival rate.

Compound Poisson distributed demand

Using compound Poisson distribution demand assumes that the customers arrive according to a Poisson process (see Eq. 1.1.) but are allowed to order more than one item (Axsäter, 2006, p. 77-79). The demand size is a stochastic variable distributed according to the compound distribution. Assuming that each customer orders an integral number of units, the compounding distribution is

$$f_j = \text{probability of demand size } j \ (j = 1, 2, \ldots).$$

The special case where $f_1 = 1$ (the probability that the demand size is 1 is 100%) is a pure Poisson process. In general, however, the demand sizes vary. Let

$$f_j^k = \text{probability that } k \text{ customers demand } j \text{ units},$$

$$D(t) = \text{stochastic demand in the time interval } t.$$

With the constraints $f_0^0 = 1$ and $f_j^1 = f_j$ the convolution of f_j, f_j^k can be obtained recursively as

$$f_j{}^k = \sum_{i=k-1}^{j-1} f_i{}^{k-1} f_{j-1}.$$

Combined with (Eq. 1.1.), this results in

$$P(D(t)=j)=\sum_{k=0}^{\infty}\frac{\lambda t^{k}}{k!}e^{-\lambda t}f_{j}^{k}.$$

Usage of demand distributions in spare part inventory models

For the sake of this thesis, it is interesting to understand the usage frequency of different demand distributions for spare part inventory models. A selection of articles and their corresponding demand distribution used is listed in table 3-2 below.

Table 3-2: List of demand distributions assumed in models by various authors

Article	Demand distribution
Axsäter *et al* (2013)	Compound Poisson/Gamma/normal
Boucherie *et al* (2018)	Poisson
Costantino *et al* (2018)	Zero-inflated Poisson
Díaz & Fu (1997)	Poisson
Huo & Li (2007)	Poisson
Jaarsveld *et al* (2015)	Poisson
Kukreja *et al* (2001)	Poisson
Thonemann *et al* (2002)	Poisson
Wang (2012)	Poisson
Wong *et al* (2005a)	Poisson
Wong *et al* (2005b)	Poisson

Table 3-2 suggests that the most common demand distribution used for spare part inventory models is the Poisson distribution. Variations of the Poisson distribution exist to handle more specific cases, such as using zero-inflated Poisson distribution while working with data sets who include an excess amount of zeros.

3.3.7. Relevant costs

When optimizing stock levels, minimizing costs is often a natural objective function. Costs can take many different shapes or forms depending on the model and its assumptions as well as the context. Some of the most common costs include holding cost, shortage cost, ordering cost and shipment cost (Axsäter, 2006, pp. 44-45). When allowing lateral transshipments, costs related to the transshipments are of interest as well.

Holding cost

This cost is related to the tied-up capital in the inventory. Handling, storage, obsolescence and interest are also often parts of the holding cost albeit less significant. In essence, the holding cost is meant to capture the cost incurred by stock keeping such as capital costs, rent, storage equipment costs, insurance, depreciation costs, administrative costs and costs tied to the risk of stock keeping (SILF, 2020). The holding cost is often defined as a percentage of the unit value. Depending on what type of item it is, the percentage varies (Axsäter, 2006, p. 44).

Shortage cost

When an item is demanded and said demand cannot be satisfied due to unavailability, there are several different costs that can occur. If the customer is willing to wait, the order is backordered meaning that it will be fulfilled at a later point in time. Backorder costs can include costs such as extra administration or loss of income due to discounts offered for late deliveries. In the case where the customer is not willing to wait and chooses another supplier, the revenue of a sale is lost altogether. There are also implicit costs related to shortages such as damage to reputation affecting future sales. Shortage costs are often difficult to quantify. One approach to counter this is to put service level constraints on the model instead of using shortage cost (Axsäter, 2006, p. 45).

Ordering cost

There is a cost associated to ordering a certain item or a batch of items, the cost is often a fixed cost per unit or per shipment. For this reason, it may be preferable to minimize the number of orders to avoid the ordering cost if the ordering cost is more significant than the holding cost (Axsäter, 2006, p. 7). A commonly known heuristic exists to determine the optimal number of orders and when to place them, called the Silver-Meal heuristic. The algorithm seeks to minimize the total cost while considering holding costs and ordering costs (Axsäter, 2006, p. 66).

Shipment cost

Shipment costs, or transportation cost, refers to the costs connected to shipping the products including freight, custom fees etc. These costs could be lowered by e.g. using full truckloads or using the same freight company for all orders, which could mean that there is a discount (Axsäter, 2006, p. 149).

Transshipment cost

Transshipment costs are related to the transportation costs for the lateral transshipment, as well as the cost for issuing the transshipment order. If the configuration allows for both proactive and reactive lateral transshipments, the cost for the proactive shipments and the emergency shipments are differentiated (Lee, 1987; Wong *et al*, 2005a; Hochmuth & Köchel 2012).

3.3.8. Mathematical solution methods

Different authors choose different ways of modeling their inventory systems, consequently the solution methods also differ. An overview of the models described below is listed in Table 3-3. The categorization is identical to the one presented in Paterson *et al* (2011) and has been explained in previous chapters.

Lee (1987) introduces two notations, α which is equal to the fraction of demand satisfied by emergency lateral transshipments and β, which is the fraction of demand satisfied directly by stock on hand. To find β, Lee (1987) first finds the steady state distribution of the number of outstanding orders at a base e.g. the number of orders in emergency transshipment or in transport from the depot. Based on that equation, an equation is set up to describe β and later an expression for N, the number of emergency lateral transshipments at pooling group i. Lee (1987) uses the above variables as input to a minimization problem with the goal of minimizing the total cost consisting of holding cost, backorder cost and transshipment cost. The result of the optimization are optimal inventory levels for the bases (Lee, 1987).

Axsäter (1990) extends on Lee (1987) by introducing non-identical bases, which not only is more adaptable to real-life situations but also models the demand more correctly. Axsäter (1990) develops a model, which, like Lee (1987), can be used to determine α, and β. However, Axsäter (1990) does not provide a model for finding optimal stock levels, but since he determines α and β one can use Lee (1987) to find optimal stock levels. Kukreja *et al* (2001) and Wong *et al* (2005b) propose similar solution methods to Axsäter (1990), modeling the state transitions of the bases with an $M/M/\infty$ queue (Markov chain). Wong *et al* (2005b) provides an algorithm for solving the steady state probabilities which are used for determining α and β. The approaches used by Lee (1987), Axsäter (1990), Kukreja *et al* (2001) and Wong *et al* (2005b) are all single-item models. Some studies have chosen a multi item-approach. One of them is by Wong *et al* (2005a) who develop a model where every single spare part has independent demand (Lee, 1987; Axsäter, 1990; Wong *et al*, 2005a).

The model described by Wong *et al* (2005a) is solved by determining four different transitions between states the system can be in. Using the transitions, Wong *et al* (2005a) form a Markov process. Wong *et al* (2005a) determine optimal stock levels by minimizing a cost function consisting of holding cost, transhipment cost and emergency shipment cost. The optimization problem is subject to a criterion which specifies the maximum waiting time a location can endure. Wong *et al* (2005a) solve the problem by utilizing a greedy heuristic which chooses an arbitrary solution and tries to improve it by making small changes until a local minimum is reached (Wong *et al*, 2005a).

The models described by the authors above all have one thing in common – they use analytical methods to solve their models. However, when models get more complex and some assumptions or simplifications are not made, the problem becomes a lot harder to solve. In these cases authors choose to solve the issue by using a simulation approach. For example, Hochmuth & Köchel (2012) develop a general model which can be fitted into many different inventory systems. Their model can be adapted to describe both continuous and periodic review systems, multi-location systems and one and two-echelon systems. Due to the flexibility of the model, an analytical solution would be extremely complicated and for this reason, Hochmuth & Köchel (2012) use simulation to solve their model (Hochmuth & Köchel, 2012).

Similar to Hochmuth & Köchel (2012), a simulation approach is used by Tiacci & Saetta (2011) who use a two-echelon model for non-repairable spare parts. They also include an analysis of what impact the introduction of lateral transhipment has on the mean supply delay of spare parts. Tiacci & Saetta (2011) base their model on a model developed by Banerjee *et al* (2003) who argue that a majority of the analytical approaches in the literature are too simplified to be able to capture the full complexity of inventory systems.

Chang & Lin (1991), which use a single echelon approach, provide an expression for the total costs to minimize including holding costs, transportation costs as well as a penalty cost for backorders. Worth noting is that the cost function is based on the total amount of stock across the bases rather than specifying the amount of stock at each base. The purpose of their paper is not to go in depth in the actual optimization process but rather show that an inventory system allowing for transshipments can experience lower total costs than one that does not.

Herer *et al* (2006) also uses a single echelon approach and uses a simulation-based method with Infinitesimal Perturbation Analysis (IPA) optimization. Holding costs, penalty costs and transshipment costs are considered. They assume an order-up-to policy and prove that the cost function is convex in the order-up-to level while also determining optimal transshipment sizes. The main idea of the IPA procedure is that the cost for the different paths the goods can take in the goods flow (including transshipments) are accumulated. The average cost for the goods can then be computed and adjustments be made to the up to order levels. This procedure is iterated multiple times until an optimal solution is found.

Table 3-3: Overview of the characteristics of the above-mentioned models (based on Paterson et al 2011).

	No. item	No. echelon	No. bases	Identical bases?	Backorder or Lost sales	Timing	Policy	Type	Pooling	Decision making	Cost
Axsäter (1990)	1	2	N	No	Backorders	Cont.	(S-1,S)	Reactive	Complete	Cent	Item
Lee (1987)	1	2	N	Yes	Backorders	Cont.	(S-1,S)	Reactive	Complete	Cent	Item
Kukreja *et al* (2001)	1	1	N	No	Backorders	Cont.	(S-1, S)	Reactive	Complete	Cent	Item
Wong *et al* (2005a)	M	1	N	No	Lost sales	Cont.	(S-1,S)	Reactive	Complete	Cent	Item
Wong *et al* (2005b)	1	1	N	No	Backorders	Cont.	(S-1, S)	Reactive	Complete	Cent	Item
Hochmuth & Köchel (2012)	1	-	N	-	Lost sales	Period	General	Both	Both	-	-
Tiacci & Saetta (2011)	1	2	N	-	Backorders	Period	-	-	Complete	Cent	Item
Banerjee *et al* (2003)	1	2	N	No	Backorders	Period	(S-1,S)	Proactive	Partial	Cent	Item
Chang & Lin (1991)	1	1	N	No	Backorders	Period	General	Reactive	Partial	Cent	Both
Herer *et al* (2006)	1	1	N	No	Backorders	Period	(S-1,S)	Reactive	Partial	Cent	Item

3.3.9. Classification based solution methods

As noted above, the task of determining stock levels for spare part flows is complex and has many inputs and developing a mathematical model that considers all the complexities is difficult (Braglia *et al*, 2004). An alternative to using mathematical modeling is developing a classification method, in which different inventory policies can be applied to different segments of products. Braglia *et al* (2004) has developed such a model, with spare parts in mind. They present four classification categories (criticality, supply characteristics, inventory problems and usage rate) with 17 different attributes. The main idea is that contrary to mathematical modeling, classification based methods can utilize a mixture of quantitative and qualitative factors that affect stock level decisions in a relatively simple manner. Using an analytic hierarchy process (AHP) model, the different attributes are compared to each other in a structured way, taking judgement by maintenance experts into consideration. The quantified results from the AHP model are then used to determine which policy that is to be used for a certain product segment. Braglia *et al* (2004) proposes four different policies:

1. *No stock* – the impacts of unavailability is outweighed by the cost and other implications of keeping it in stock.
2. *Single item inventory* – the risk of unavailability calls for the stock keeping of a single unit of the product.
3. *Just-in-time deliveries* – given predictable maintenance needs and supply characteristics, availability can be ensured even without keeping products in stock.
4. *Multi item inventory* – the result of high critical impact of unavailability and uncertainties in supply and demand. These methods are often advanced and expensive.

Most of the articles that a firm possesses are not feasible subjects for sophisticated mathematical modeling from a resource perspective. When Braglia *et al* (2004) applied this method for a paper industry company's spare parts flow, stock levels could be reduced by utilizing just-in-time deliveries for some segments, seizing stock keeping of some slow moving segments and reducing the stock levels where there had been obvious overstocking.

3.4. Spare parts performance measurement

The majority of supply chains are highly complex, which also makes measuring their performance a challenge. Quantitative methods are preferred to describe the performance of a supply chain, but many times the numerical measure may not adequately describe the performance, which is why a reliable model needs to be chosen (Beamon, 1999). When measuring the performance of the flow of spare parts for the operating machines in a manufacturing industry, one way is to measure the degree to which the demand for spare parts is satisfied. In this context, it is interesting to look at the service level of the spare parts. There are different ways to define service level and the most common ones are described in 3.4.1. The service level is affected by numerous factors. One key factor is the lead-time, see chapter 3.4.2.

On the other hand, according to Sherbrooke (2004, pp. 19-41), the performance of a flow of spare parts for manufacturing equipment is implied by the availability of the equipment. The reasoning is that ensuring high availability of equipment is the purpose of the spare parts flow. In other words, if the spare parts flow is under-performing, it will be detected through the loss of productivity from having broken down machines with no spare parts. He proves that maximizing the availability is equivalent to minimizing the number of backorders, if no parts are backordered, it means that the demand is satisfied directly and thus the availability is maximized. Availability of the equipment can be defined in a number of ways and is further explained in chapter 3.4.3.

Another optimization criterion is perhaps also the most common one – cost, costs that vary when the inventory level changes should ideally be considered. Since it is difficult to track all costs that are affected, some sort of delimitation may be present. Examples of costs to include are ordering costs, holding costs and shortage costs, defined in 3.3.7. To what extent these costs are broken down and considered differs between companies. Louit *et al* (2010) present a cost model for non-repairable spare parts where stock levels are determined based on a cost minimization problem that considers the costs discussed above. The model provides an analytical approach to solving the problem of choosing optimal inventory levels to minimize costs. Since no downtime is allowed, the model also maximizes the availability with the prerequisite that emergency orders are possible to issue (Louit *et al*, 2010).

3.4.1. Service level

Since one of the key purposes of an inventory system is to keep the cost down, performance of the system will be dependent on its ability to do so. Costs indicate where there are issues to solve. Appropriately defining the costs is therefore of importance. As mentioned in 3.3.4. and 3.3.7., it is often difficult to estimate the shortage cost given the complex nature of it. A common strategy to overcome this difficulty is to use service level constraints. Setting service level constraints can also prove challenging but not as arbitrary as setting a cost (Axsäter, 2006, p. 45). The service level may not only be used as an equivalence to shortage costs but also as a means to create value for the customer and serve as a strategic competence (Jiang *et al*, 2019). Furthermore, it is an intuitive way to assess whether the logistics flow satisfies customer demand. In academia and practice, the service level concept is often divided into three main definitions, $SERV_1$, $SERV_2$ and $SERV_3$.

$SERV_1$

The definition of this service level is the probability of experiencing no stockouts during the order cycle. It can be determined by calculating the probability of the demand during the lead-time being less than the re-order point:

$$SERV_1 = P(D(L) \leq R)$$

It is commonly used among practitioners due to its simplicity and ease of use. The limitation of this method is that it does not consider batch size. In practice, this can mean that if the batch size is considerably large, one batch can satisfy demand over a long period of time while the $SERV_1$-value is low. Conversely, if the batch size is small, the $SERV_1$-value can be high while experiencing a limited number of long stockouts resulting in poor service (Axsäter, 2006, pp. 94-95).

$SERV_2$

The second definition $SERV_2$, which is also called fill-rate, is the fraction of the demand that can be satisfied by the stock on hand.

$$SERV_2 = \frac{\mathrm{E(satisfied\ quantity)}}{\mathrm{E(demanded\ quantity)}} = 1 - \frac{\mathrm{E(backorders)}}{\mathrm{E(demanded\ quantity)}}$$

$SERV_3$

The final definition $SERV_3$, which is also called ready-rate, is the fraction of time with positive stock on hand:

$$SERV_3 = P(IL > 0)$$

In the case of continuous demand, $SERV_2$ and $SERV_3$ are equivalent. This is also true in the case of Poisson demand since only one unit can be demanded at a time. In the case of discrete demand where there is a possibility of demanding more than one unit at a time, the two definitions are not equivalent. For example, the stock on hand may be positive, but if the order is large enough, it might not be possible to satisfy it from the stock on hand. To illustrate this, consider an inventory system where the stock on hand often is low but positive and the customer order sizes are large. In such a system, the $SERV_3$-value would be high, but the $SERV_2$ value would be low (Axsäter, 2006, p. 95).

Other service level definitions

The service level is not always measured in probability-terms. For example, in some cases, it might be more suitable to measure the service in terms of time or waiting time. In such cases, it is common to either use metrics such as the average speed of answer (ASA) or percentiles of the waiting times which tracks how many of the customer that have waited more than an acceptable amount of time. Using the waiting time percentile to measure the service level is often opted for rather than ASA as the information is less aggregated (Legros, 2016).

3.4.2. Lead-time

The lead-time refers to the time from when an order is placed to when it has been delivered (Lumsden, 2007, p. 203). There are several dimensions that comprise the lead-time including time for order handling, planning, adjustments to product/service, throughput and transportation (Lumsden, 2007, p. 203). Lead-time affects stock levels, not only due to the length of it but also due to the variance tied to it. The variation of the lead-time in combination with the variation of the demand are examples of uncertainties that call for the need of safety stock (Lumsden 2007, p. 234). In the case of spare parts for machines, lead-times can be of special importance when there is a need for unplanned maintenance since the down time caused by the breakdowns can be costly.

3.4.3. Availability

Availability refers to the fraction of time during which a machine is operational. It is integral for a company to maximize the availability of their machines to avoid lost production, which many times can become quite expensive. Sherbrooke (2004, pp. 37-38) presents three different types of availability: inherent, achieved and operational availability. The definitions for the three types are presented below:

$$\text{Inherent availability} = \frac{100 \cdot \text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

Where MTBF stands for "mean time between failures" and MTTR stands for "mean time to repair". Inherent availability is not related to maintenance, only breakdowns.

$$\text{Achieved availability} = \frac{100 \cdot \text{MTBM}}{\text{MTBM} + \text{MCMT} + \text{MPMT}}$$

Where MTBM stands for "mean time between maintenance", MCMT stands for "mean corrective maintenance time" and MPMT stands for "mean preventive maintenance time". Achieved availability is more accurate since it incorporates time spent on preventive maintenance.

$$\text{Operational availability} = \frac{100 \cdot \text{MTBM}}{\text{MTBM} + \text{MDT}}$$

MDT stands for "mean downtime due to spares", which includes both corrective and preventive maintenance as well as other delays due to maintenance. Operational availability attempts to capture all possible disturbance and provide the staff with an accurate, reliable way of quantifying the availability. A simpler way of determining the operational availability is to firstly determine the maintenance availability, which is the same as achieved availability, and secondly the supply availability whose definition follows below (Sherbrooke, 2004, pp. 37-38):

$$\text{Supply availability} = \frac{100 \cdot \text{MTBM}}{\text{MTBM} + \text{MSD}}$$

Where MSD is the "mean supply delay". In order to obtain the operational availability, simply multiply supply availability with maintenance availability. The operational availability is used since it captures both factors connected to maintenance and to supply (Sherbrooke, 2004, pp. 37-38).

3.4.4. Frameworks for performance measurement

To improve productivity within a company, one needs to consider the performance indicators. A way of doing this in a structured manner is to use a predetermined framework and try to apply it to the industry which is considered. Muchiri & Pintelon (2008) argue that in order for a company to stay competitive, they should continuously work to improve the availability and productivity of their machines. The only way for a manufacturing company to do this is to first be able to identify where the losses occur so that they can be eliminated. The concept of total productive maintenance (TPM) includes a quantifiable indicator called overall equipment effectiveness (OEE), which measures the productivity of individual equipment in the factory. OEE considers availability, performance and quality rate and multiplies these three indicators to obtain the final OEE (Muchiri & Pintelon, 2008).

Losses which can occur in the production can either be chronic or sporadic. Chronic losses are small, difficult to detect and usually have multiple causes. Sporadic losses are larger and more obvious. In Table 3-4 there is a list of six different losses, their definition and their type.

Table 3-4: Six types of losses in production (Muchiri & Pintelon, 2008).

Loss	Description	Type
Equipment failure	Caused by a breakdown due to failing equipment. Leads to lost time and production.	Sporadic
Setup and adjustment	When changing production to produce something else.	Chronic
Idling and minor stoppage	Minor breakdowns causing losses, could be significant if the frequency is high.	Sporadic
Reduced speed	Differences in design for different machine and equipment could result in a slower production.	Chronic
Defects in process	Malfunctioning production equipment results in quality defects.	Sporadic
Reduced yield	Losses which occur while a machine is starting up before it is up to speed.	Chronic

Since the focus of this master thesis is to consider performance indicators related to the spare parts of the machine, the main loss subject to further discussion is the first one, equipment failure due to breakdowns. Kennedy *et al* (2002) discuss a model which considers expensive, critical spare parts. Unavailability of such spare parts result in excessive down time costs, but at the same time the demand rate for the parts is low and sporadic which makes predicting the failure rate a difficult task (Kennedy *et al,* 2002). RQ2 in this thesis also asks about how the performance of the spare parts flow should be evaluated when considering the cost of handling the spare parts, not only their availability. The literature review conducted for this master thesis revealed that a majority of performance measurement frameworks consider the whole supply chain, or only manufacturing in isolation (Martin & Patterson, 2009; Olivella & Gregorio, 2015). Since the focus of this thesis is to measure performance of spare parts management, the literature found was limited. This conclusion is supported by Jouni *et al* (2011).

Jouni *et al* (2011) discuss the challenges of trying to adapt to changes and instead argue that a company should try to work on these changes and instead make them fit the company. For a company to be able to identify where the most action is required, Jouni *et al* (2011) show how to develop a categorization framework which can be used to analyze areas which require most attention. A company is divided into three parts: demand aspects, internal process aspects and supply aspects and the links between these parts are analyzed to obtain the overall performance for the whole distribution chain (Jouni *et al,* 2011).

The link between supply and internal processes consist of factors such as availability risk, lead-time variance and accuracy of delivered quantity. A framework to categorize purchased spare parts is provided by Kraljic (1983) who divides items based on their market availability and purchasing volume. Jouni *et al* (2011) realized in their case study that the low annual turnover, which leads to low quantity and irregular purchase orders, means that it would be inaccurate to calculate any variance. For this reason, the availability risk was chosen as the best factor for categorization and the parts were categorized in three categories according to Figure 3-9. Key parts only have a few suppliers and remain critical for production to proceed. Industry-specific parts have more suppliers available with shorter lead-times, and commercial products are the easiest to find because of their generic nature (Jouni *et al,* 2011; Kraljic, 1983).

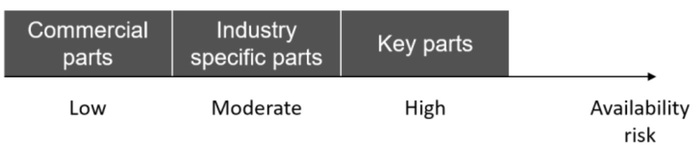

Figure 3-9: Supply categorization (Jouni et al, 2011).

For the demand link aspect, Jouni *et al* (2011) identify two factors which they consider to be most important: material price and demand variability. For spare parts, the prices usually differ significantly which has an impact on stocking policies when inventory value is considered. Figure 3-10 shows how to categorize spare parts based on the two factors, placing them in groups. Characteristics for spare parts in each group are presented in Table 3-5 (Jouni *et al,* 2011).

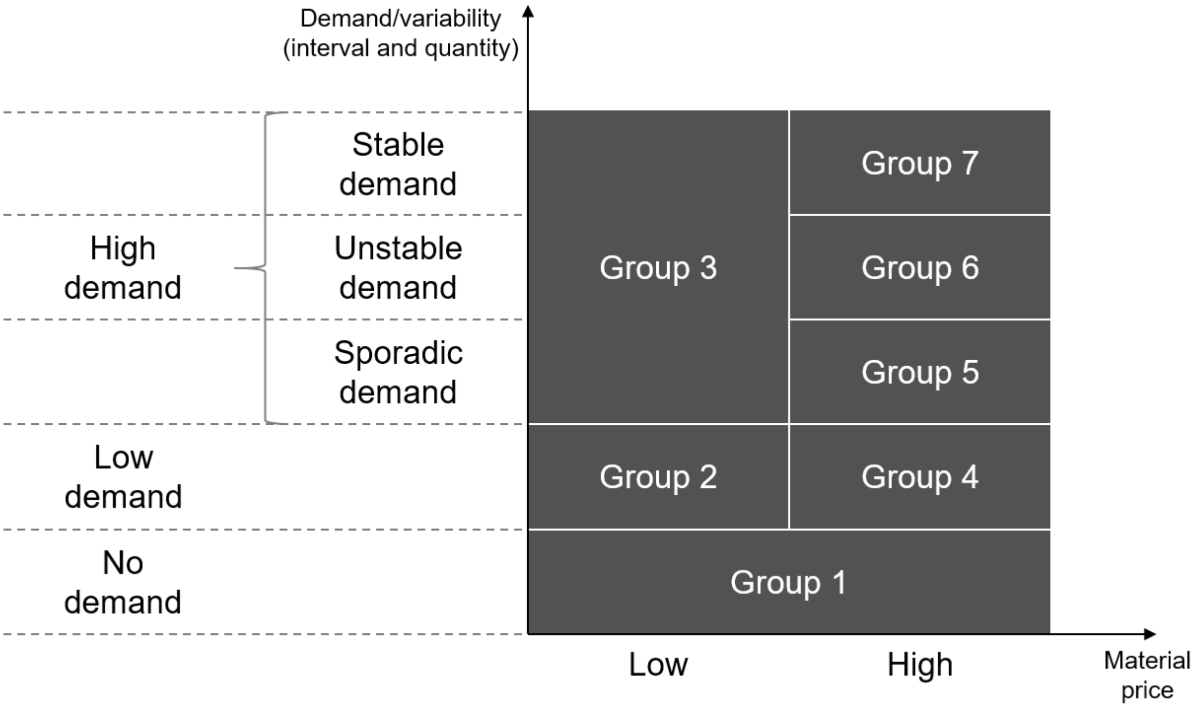

Figure 3-10: Demand categorization (Jouni et al, 2011).

Table 3-5: Group descriptions.

Group	Description
1	Spare parts which have no demand for the last two years, regardless of the price. Sometimes these parts could be of value but in most cases they should be scrapped.
2	Low value parts with low demand.
3	Low value parts with high demand. Only two groups for low value parts exist since management is thought to be more concerned with high value parts.
4	High value parts with low demand, the demand could be interpreted as stable from an inventory control point of view.
5	High value parts with sporadic and lumpy demand, usually most challenging to forecast. The demand is most likely coming from one or a few customers.
6	High value parts with unstable but continuous demand which can be determined by standard deviation, as in group 5 these parts are challenging to handle for inventory management.
7	High value parts with high, stable and continuous demand. Because of low variability, standard control methods should be used from an inventory management point of view.

The matrices in Figures 3-9 and 3-10 are combined to form the final framework which can be used to measure the performance of the spare parts distribution chain. The framework can be used to get a quick overlook of the current performance, and it works with many different KPIs. The performance measurement framework is presented in Figure 3-11 with the current service level of each group. The service level was determined by looking at individual sales order lines, if a part was not in stock when it was demanded the order line is considered to be late (see $SERV_2$ in chapter 3.4.1.). Note that the framework can be used with a number of different KPIs, it is up to the company to decide which KPI they want to monitor. Example of spare part related KPIs to monitor are (Jouni *et al*, 2011):

- Service level
- Stock-out costs
- Supply variance
- Product life-cycle

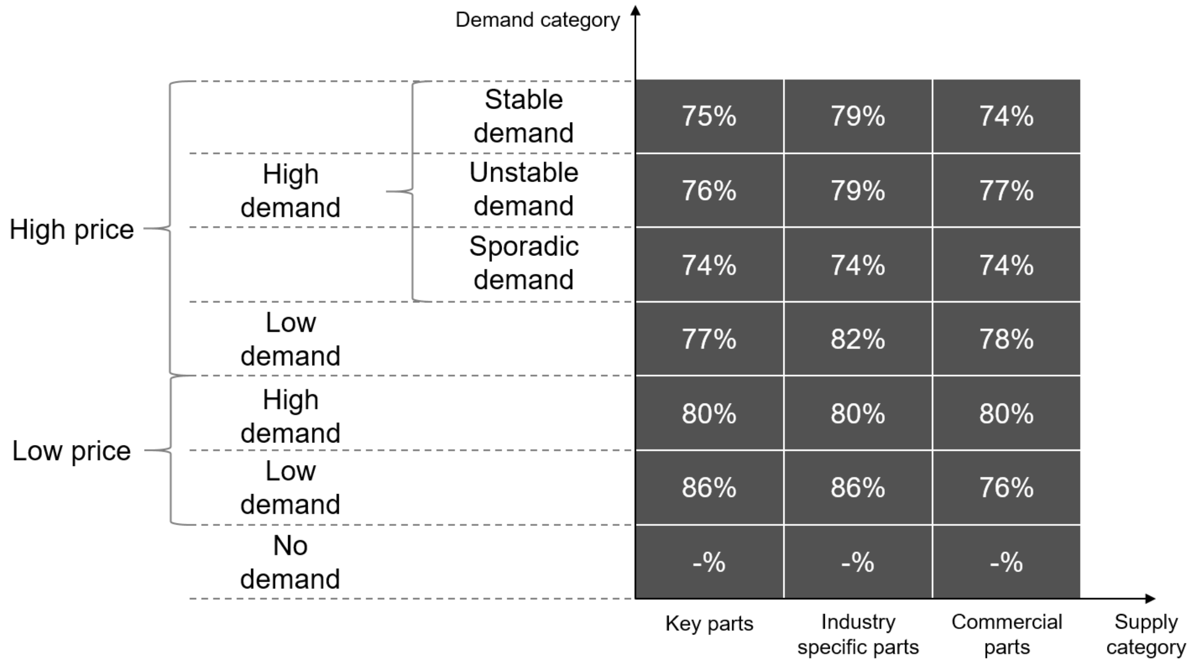

Figure 3-11: Service level performance distribution for the company studied by Jouni et al (2011)

3.4.5. KPIs for performance measurement

The literature on performance measurement for manufacturing is rich and this subchapter will present a number of KPIs relevant for manufacturing. Ahmad & Dhafr (2002) divide KPIs into financial, technical and efficiency indicators and argue that many companies fail to measure true productivity, considering all performance areas. They conducted a survey to identify what KPIs manufacturing companies are using, what levels they reach for those KPIs and how the results compare to world class manufacturing. Table 3-6 below presents some of the KPIs discussed by Ahmad & Dhafr (2002). The table also shows what target levels the KPIs should have in order to reach world class manufacturing. A batch plant outputs its products in batches while a continuous plant produces products with a steady flow (Ahmad & Dhafr, 2002).

Table 3-6: KPIs proposed by Ahmad & Dhafr (2002).

KPI	Definition	Target level batch plant	Target level continuous plant
Quality rate	$= \frac{\#\text{products passed QC}}{\#\text{ products passed QC} + \#\text{ products failed QC}}$	95%	99%
Product rate	$= \frac{\text{Products produced}}{\text{Most products produced ever}}$	95%	95%
Availability	$= \frac{\#\text{ hours plant is operable}}{\#\text{ hours in a year}}$	95%	99%
OEE	$= \text{Quality rate} \times \text{product rate} \times \text{availability}$	85%	95%
Adherence to production plan	$= \frac{\#\text{products produced}}{\#\text{planned products to produce}}$	99%	99%
Output	$\#\text{ products produced}$	-	-
Uptime	Uptime for plant in days	-	-

Note that the first three KPIs in table 3-6 serve as basis to calculate the OEE, this corresponds to the same measure discussed by Muchiri & Pintelon (2008). Chen (2008) explains how the work of Ahmad & Dhafr (2002) can be used by managers to identify what teams have performed best in the manufacturing process and reward them. The KPIs also cover both planning and production which makes it a complete set of KPIs for manufacturing performance measurement (Muchiri & Pintelon, 2008; Chen, 2008; Ahmad & Dhafr, 2002).

3.5. Summary of literature

Going forward into the empirical data collection chapter there are some key areas to be explored in order to answer the research questions. For RQ1 there are two main approaches defined by academia: mathematical and classification-based solution methods. While a classification-based method may be an easier way to set stock levels, it does not explicitly address the context of lateral transshipments. Mathematical solution methods are centered on formulating an expression for the total cost and minimizing it through analytical methods, heuristics or simulation methods. The total cost expression usually includes costs for holding inventory, transshipping parts and some sort of shortage cost (for loss of sales or backorders). Stock levels and the amount of parts transshipped are often determinants of the total costs. The mathematical solution methods can be categorized with respect to system configuration, ordering characteristics and transshipment characteristics. Input parameters for any type of solution methods include information about the demand, costs (sometimes implied by the criticality of the parts studied), lead-time and sometimes additional factors such as reparability. The frame of reference for RQ1 is summarized and illustrated in Figure 3-12.

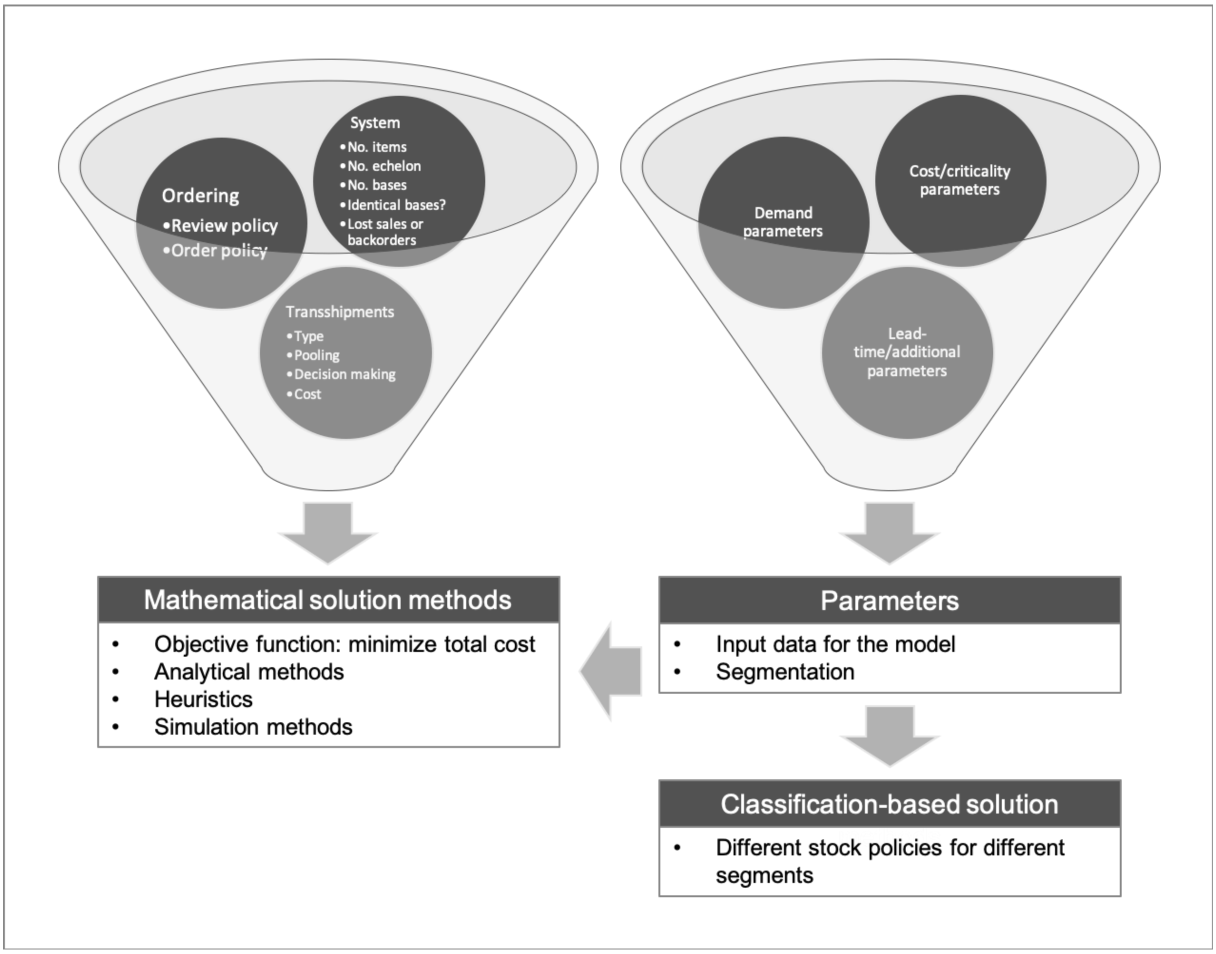

Figure 3-12: Frame of reference for RQ1.

For RQ2, there are two key approaches to be explored in order to answer the research question. Methods for measuring performance are divided into two categories: one that considers the supply chain as a whole and thus includes aspects from all parts of the business, and one that considers specific business functions in isolation, such as manufacturing or procurement etc. The existing frameworks for spare parts performance measurement were few. On the other hand, methods for performance measurement for manufacturing and supply chains in general are many (Muchiri & Pintelon, 2008; Chen, 2008; Ahmad & Dhafr, 2002). Since the focus of RQ2 is spare parts, the performance measurement systems considered should be related to spare parts or manufacturing. Many manufacturing performance measurement methods can be tied to the concept of OEE, since the three KPIs included in OEE (product rate, quality rate and availability) often are touched upon. The purpose of OEE is to get a sense of how the overall performance looks in a company.

The frameworks which consider spare part performance measurement focus on availability of spare parts and the stock value, presented in various ways. The goal of the frameworks is to identify spare part categories which are underperforming, in that way management will understand where they need to focus their efforts. Several authors argue that the introduction of a structured approach to performance measurement gives benefits to the company since it enables more efficient focusing of resources. The frame of reference for RQ2 is summarized and illustrated in Figure 3-13 and 3-14. Note that there are many other functions and KPI groups, the ones presented in Figure 3-13 are the ones relevant for RQ2.

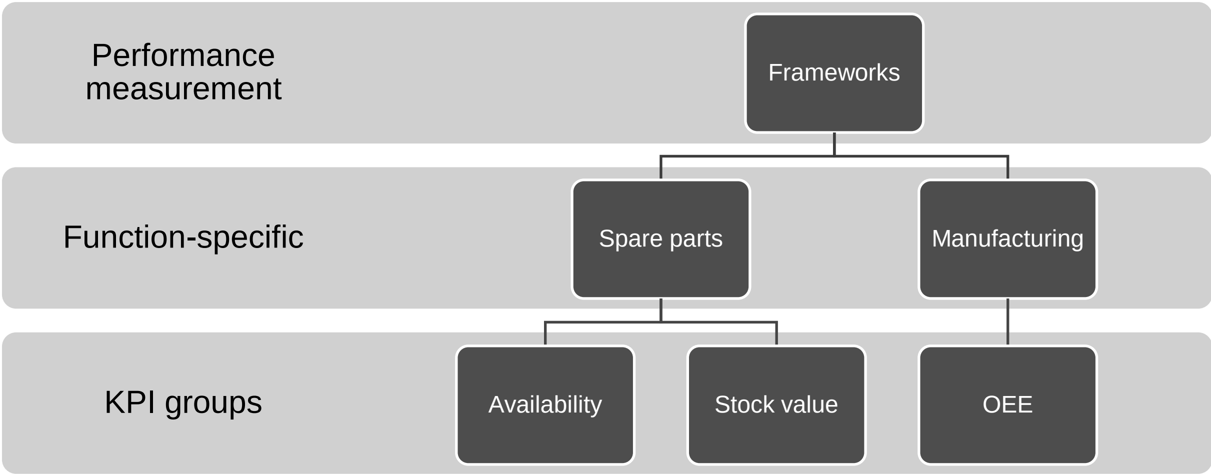

Figure 3-13: Frame of reference for RQ2.

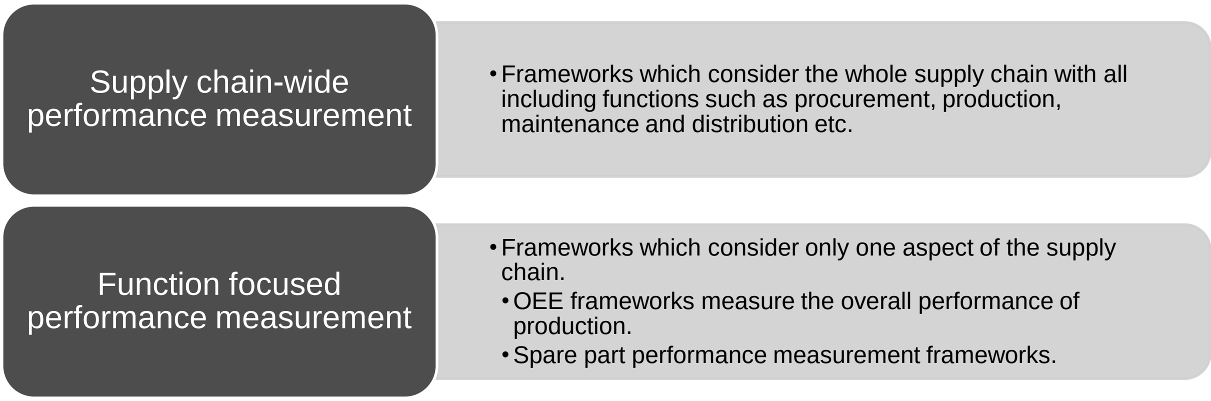

Figure 3-14: Supply chain-wide vs function focused performance measurement..

4. EMPIRICAL DATA

In this chapter, the study object IKEA Industry will be described more thoroughly. The purpose of the section is partly to give context to the research questions by providing descriptions of the supply chain and the current practices. The purpose is also to provide the data that is necessary in order to answer the research questions.

4.1. Supply chain of IKEA Industry

This sub-chapter will explain the flow of spare parts and products within IKEA Industry. Since this thesis revolves around the spare part handling, more emphasis will be put on presenting the spare parts flow in greater detail compared to the flow of products. The flow of products will be described in brief to provide the reader with a basic understanding for how the organization is constructed, while the more detailed presentation of the spare part flow is made to pave way for the introduction of a safety stock model.

4.1.1. Supply chain of IKEA products (direct material)

The process starts with raw material, such as timber and glue, being sourced and delivered to the production units that make boards and components, respectively. Components include products that are not flat, such as leg tables, arm rests etc. Some components are bought as finished components, which are used in the assembly of the furniture, such as hinges and door handles. During the final step of the production, boards and components are assembled into finished goods through two divisions, either Solid wood furniture or Flatline furniture.

The next phase in the supply chain revolves around transporting the finished goods to the warehouses. Depending on attributes such as distance and local set-up, the goods can be sent either directly to the warehouses, or to a distribution center, which then sends out the goods to the warehouses. Finally, the goods are sold in the stores and thus they reach their final destination – the customer. Figure 4-1 presents the general flow through which a product is manufactured and finally delivered to the customer. Something that is notable about the supply chain is that IKEA Industry has integrated vertically to a large extent, owning the process from the acquisition of raw materials to the production of finished goods.

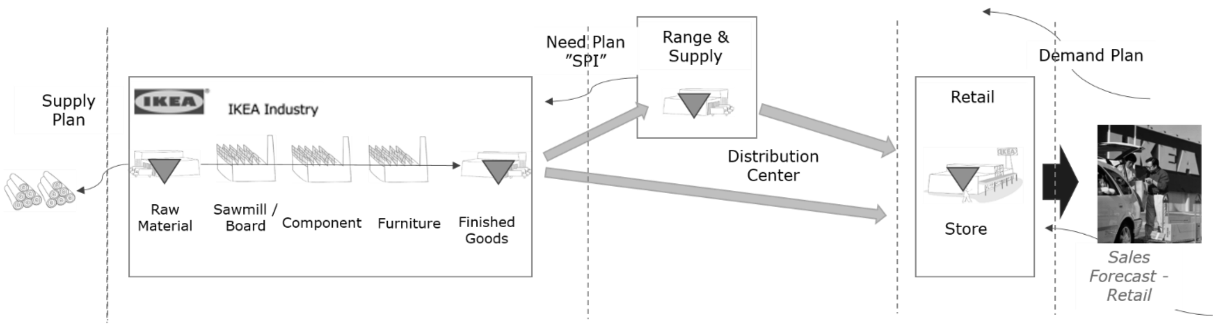

Figure 4-1: Illustration of the supply chain for the products of IKEA Industry (IKEA Industry, 2017).

4.1.2. Supply chain of the spare parts (indirect material)

The supply chain of the spare parts differs a bit from the supply chain of the products. Contrary to the product supply chain, IKEA Industry does not integrate vertically to a great extent. IKEA does not produce its own manufacturing equipment. Instead, the equipment is supplied by an array of suppliers, which means that there is a diverse catalogue of spare parts suppliers as well. These spare parts are delivered directly from the suppliers to the different production units.

There is currently no central warehouse or distribution center that the spare parts pass by. For the most part, the distribution system can be viewed as a single-echelon system meaning that the spare parts are only kept in stock at one place (storage at the production unit) before it is used in the factory. Some units are multi-sites meaning that the production unit has multiple sites. This is the case for the Poland West unit, which consists of five sites. In this unit, stock is kept centrally at one location and then distributed within the units to the other sites, which each keep stock. The sites are located in relatively close proximity (15 minutes transportation time). In day-to-day operations, however, such lead-times are not always viable for every single part, hence the need for disaggregated stock keeping. Even though lateral transshipments do occur in the current setup, it is not an established or standardized method for distribution of parts.

Spare parts are sourced in a variety of ways resulting in a large supplier catalogue. The need for a spare part is normally created through either preventive maintenance or corrective maintenance (see chapter 4.2.). This need is communicated from technicians from the maintenance department who issue an internal purchase order for a spare part. Depending on factors such as whether it is preventive maintenance or corrective maintenance and the number of parts needed, the purchase department may have to find different suppliers in order to request proposals and quotations. Depending on the type of spare part, the lead-times may vary greatly ranging from a few days up to several months. In the case where the situation is critical and spare parts are needed as soon as possible, the factory may have to resort to purchasing the part from another warehouse (lateral transshipment), a local supplier such as a department store or even a competitor. By studying the configuration, it can be concluded that the network configuration that most accurately describes the spare parts flow is a *single-echelon* system with *non-identical bases* (Poland West which has multiple stock location can be viewed as one site in the system). Since the flow does not concern all spare parts and since all items cannot be considered simultaneously when making inventory control decisions, by definition the system is *single item*.

To varying degrees, there is also a return flow in the chain. At the Lubawa and Wielbark plants, whenever a part breaks, there are three main scenarios that can occur (see Figure 4-2):

1. The part is sent to the workshop to be repaired. If required competence and resources are in place for the specific part, it can be repaired on-site. If not, the part is sent back to the supplier for repair. In both cases, the repaired part will be kept in the plant's workshop and not in the on-site spare parts warehouse which means that the repaired spare parts are not visible in the system. The value of the repaired article is only the cost of repair.

2. The part is directly sent back to the supplier and a *new* part is returned from the supplier at a reduced price meant to represent the repair costs.

3. The part is discarded.

At the Poland West and Goleniow plants, repair of parts is handled slightly differently (see Figure 4-2):

1. The part is sent to the workshop to be repaired. If required competence and resources are in place for the specific part, it can be repaired on-site. If not, the part is sent back to the supplier for repair. In both cases, the repaired part will be returned to the on-site spare parts warehouse with a new article number. The new article number is the old article number with an R at the end e.g. if the article C9005180 is repaired, the new article number is C9005180R. The value of the repaired article is only the cost of repair.

2. Same as for Lubawa and Wielbark.

3. Same as for Lubawa and Wielbark.

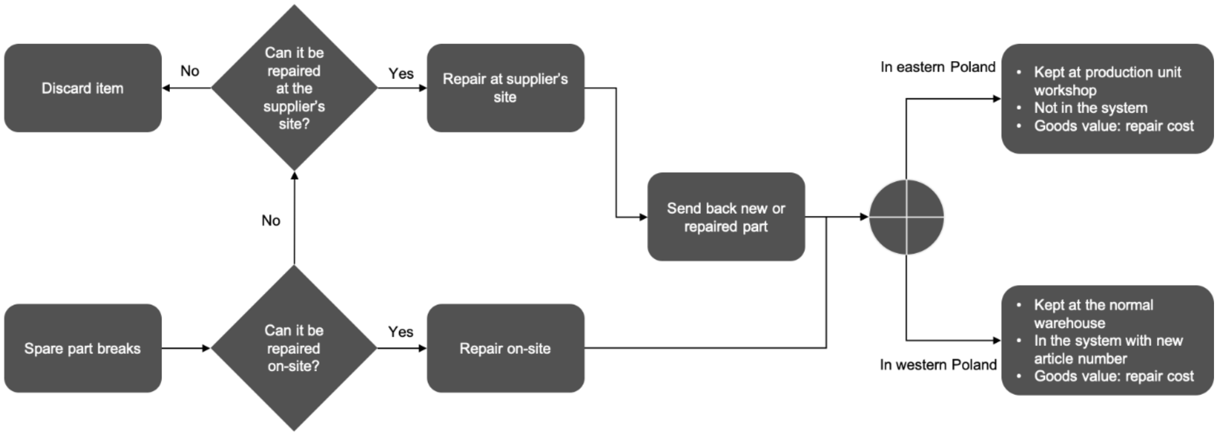

Figure 4-2: Repair process chart.

4.1.3. Harmonization project

The factories at IKEA Industry spend a significant amount of money every year to purchase spare parts, both for preventive and corrective maintenance. The spare parts portfolio is quite similar between different factories, especially for factories within the Flatline and Solid wood-division, and thus the spare parts come from the same suppliers or suppliers that are similar. The factories have been using individual spare part numbers for identical spare parts, and many duplicates have been found. There is no centralized control of purchasing since all factories have been buying their own spare parts, using their own budgets and their own agreements with suppliers.

IKEA Industry has initiated a harmonization project, aiming to standardize article numbers across factories. The project will enable harmonized statistics of purchases and provide division Purchase with stronger arguments during price negotiations with suppliers. Another benefit is that benchmarking between the factories will become possible and enable the factories to share the stock keeping effort, supporting each other with shipments between factories in cases of emergency. Administrative work will also be reduced since the factories will no longer need to upload individual items and price lists, which so far has taken a lot of time without adding any value to the business. It is important to note that the finalization of the project only included 40,000 spare parts out of approximately 200,000 in the global spare part catalogue.

The harmonization project is limited to a number of predetermined suppliers/item groups for divisions Flatline and Boards. For division Solid wood, the suppliers will be identified as part of the project in each factory individually. For division Boards, the item groups were chosen based on stock value which was above 50,000 EUR as of October 2016. For Division Flatline, five key suppliers were identified during a pre study.

The pilot project proved that a great benefit is gained since the project did not only bring order to the data, but also reliable information about which warehouses that use a certain spare part. A need for extensive change management was also recognized connected to the change of item numbers and how spare parts are created in the system. The efforts needed for conducting the project consisted largely of additional administrative tasks during the implementation. The implementation did not significantly disturb the daily operations. The time needed for harmonizing the 40,000 spare parts was roughly two years.

4.2. Maintenance management

Maintenance management is the basis for the spare parts flow. Throughout the production, there are different events that call for the consumption of spare parts. Maintenance is divided into two main categories: preventive maintenance and corrective maintenance, see Figure 4-3. In addition to this, there is a third category, "Improvements", which represents efforts taken to reduce the need for preventive and corrective maintenance.

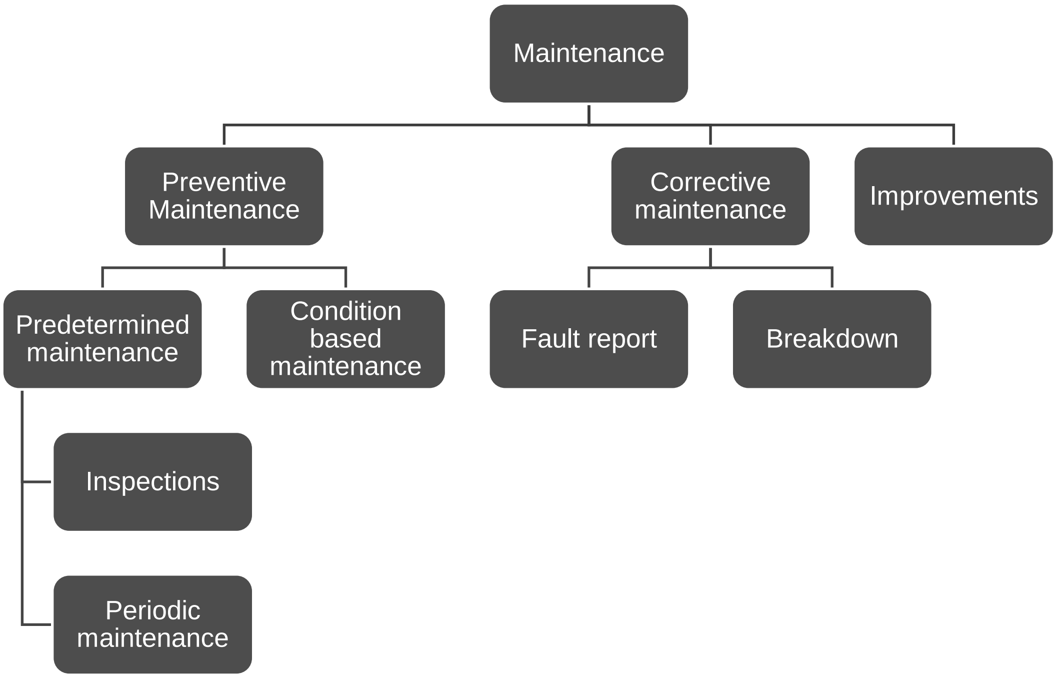

Figure 4-3: There are different categories of maintenance events (IKEA Industry, 2020).

Preventive maintenance

The activities that are related to preventive maintenance are the activities that are aimed to prevent the unplanned stops due to technical difficulties. These activities can be further divided into predetermined maintenance and condition-based maintenance. Predetermined activities are activities repeated with certain frequency. The frequency is commonly based on calendar time (e.g. maintenance every 12 weeks), machine running time (e.g. maintenance every 10,000 running hours) or production volumes (e.g. maintenance every 100,000 pieces produced). In addition to this, there are scheduled inspections to identify possible maintenance issues. Condition-based maintenance activities are based on the condition of the equipment, which is obtained from operating and condition measurements. There are varying degrees of automation in these activities, ranging from visual inspection to fully automated systems with sensor, data collection, monitoring, diagnosis and prognosis.

Corrective maintenance

The activities that are related to corrective management are the activities that are reactive and based on something that has occurred and where maintenance is needed as a result. Examples of this would be breakdowns in the production where sufficient preventive maintenance actions have not been taken.

4.3. Spare parts safety stock

Improvement of the process for determining stock levels requires an understanding of the current practices. Therefore, this chapter is devoted to ascertaining what IKEA Industry actually refers to when talking about safety stock for spare parts. It is also of great interest to understand how the stock levels are determined at the different production units currently.

4.3.1. Definition of safety stock at IKEA Industry

The purpose of safety stock is to hedge against uncertainties. IKEA Industry defines safety stock as the stock, which, ideally, only should be utilized for corrective maintenance. The preventive maintenance should be predictable enough that spare parts can be ordered for this specific purpose without having to worry about using the safety stock. However, in reality it has happened that the safety stock has been used for other purposes. This is because there are uncertainties tied to preventive maintenance as well. Such uncertainties include lead-time and demand variations. If a delivery for a planned maintenance event is delayed, items from the safety stock are used if available instead of delaying the maintenance event. For some planned maintenance events, the number of spare parts needed may exceed the planned quantity resulting in the utilization of the safety stock. It should be noted that for this thesis, the safety stock is only assumed to be used for corrective maintenance.

Some factories have reported having half of their stock being in storage for over four years which may indicate too high safety stock levels. The reason for this is that stock keeping is considered a small cost compared to experiencing a breakdown for a couple of days as a result of not having the necessary spare part on stock. Employees within the operations function have expressed that the fear for having low stock levels and risking prolonged breakdowns is much greater than the inventory costs resulting from high inventory levels. Especially management is interested in minimizing down time in order to meet budget targets, and thus it becomes even harder to motivate lowering the stock levels to decrease inventory costs. Another source of high experienced stock levels in relation to the set stock levels is the transition period when a safety stock level has been lowered but there is still stock on hand from orders placed when the safety stock level was higher. This is something that should be taken into consideration when assessing the current stock levels.

4.3.2. Current way of determining stock levels

Since there are many different production units, and the stock levels are set independently from each other (which means that the decision making is *decentralized*), it is difficult to present an entirely representative view of how the stock levels are set. As the focus of this thesis has been directed at Polish sites; the description in this chapter represents Polish sites best. It will be noted whenever something that is represented is exclusive to one site.

Segmentation

Not all articles have to be treated the same way when setting stock levels. At the Orla site (Boards division), articles are segmented by: article value, throughput volume and criticality. For segmenting with respect to article value, an ABC-analysis can be conducted. For example, the articles in the A category can represent 80% of the total stock value, B 15% and C 5%. The throughput segmentation describes the annual frequency of demand by categorizing spare parts into fast-moving items (F), slow-moving items (S) and non-moving items (N). The criticality segmentation is usually supported by some sort of failure mode and effects analysis (FMEA). The segments are vital (V), essential (E) and desirable (D). The criticality is dependent on both the production impact (e.g. a breakdown might cause the entire production to stop), lead-time (e.g. it might take a very long time to get the machine operating due to long lead-times) and safety.

Tools used

In general, the planners at the different plants have relied on experience and intuition rather than analytical tools. For parts that have been used for a long time, the staff is usually able to set levels given their experience. When a new piece of equipment or a new machine is purchased, the supplier (manufacturer of the machine) provides IKEA Industry with a recommendation of how many spare parts to keep in stock in order to avoid prolonged breakdowns. The manufacturer also recommends a schedule for preventive maintenance, which IKEA Industry should follow to avoid breakdowns. However, in IKEA's experience these recommendations have often resulted in stock levels being too high. In some cases, as little as 10% of the recommended amount of spare parts to keep in stock have actually been used. Situations like these vary depending on the manufacturers approach to after sales service. Some manufacturers choose to ship bill of materials (BOM) which is a number of spare parts the manufacturer considers that IKEA Industry should have present, in other cases IKEA can use original equipment manufacturer (OEM) numbers to order and store specific parts. This suggests that manufacturers have different incentives, which drives them to sell more spare parts by recommending customers to have more spare parts in stock. The difficulty around these situations are thought to be one of the reasons for the high spare part stock levels. The process is illustrated in Figure 4-4.

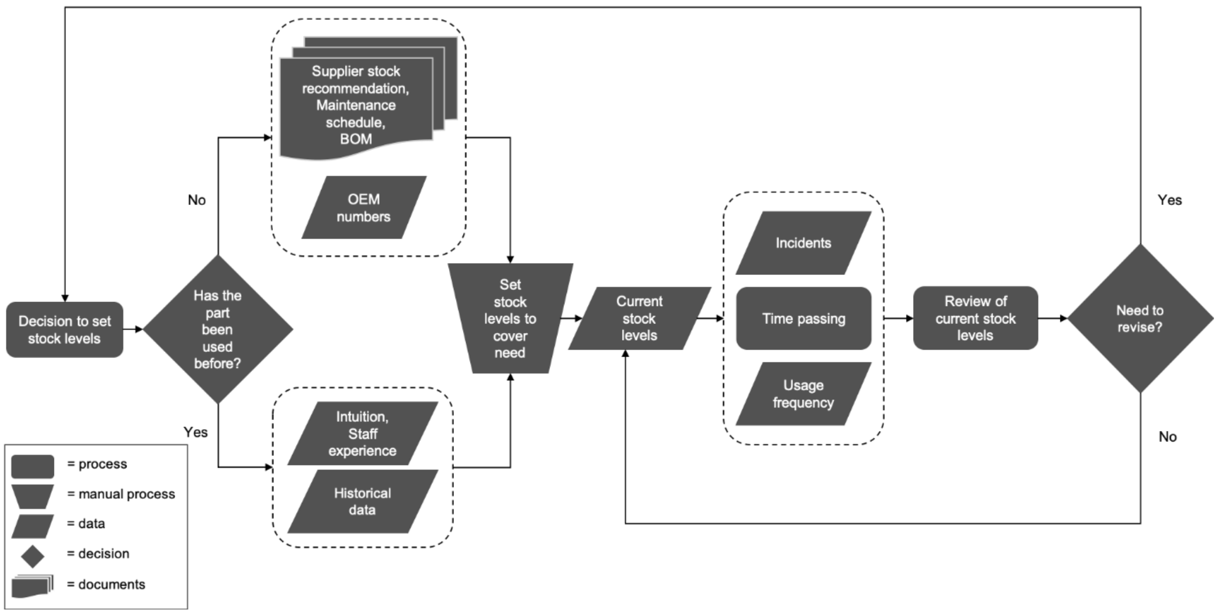

Figure 4-4: Map of the current process for determining stock levels.

One of the main concerns IKEA has is that the introduction of new equipment always seems to have a negative impact on the inventory level of spare parts. The reason for this is that IKEA does not have data to accurately forecast demand, thus they have to rely on information about spare parts life cycles from the manufacturers. This typically results in too high inventory levels. Once enough historical data has been recorded of the usage at IKEA, the reliance on supplier recommendations can be lifted.

At the Orla plant in eastern Poland, which is a part of the boards division, initiatives towards more structured methods for determining stock levels have been taken recently. *This method is still in its infancy and only used at this specific plant to a very limited extent*. Currently, it is being tested on articles that are being introduced at the Orla plant. This approach is based on Braglia *et al* (2004) (see 3.3.9.) and proposes that stock can be set in three different ways:

1. No stock.
2. One piece in stock.
3. Several pieces in stock.
    a. If the demand is constant, the EOQ-formula is used to set the level, where the stock level is implied by the batch size.
    b. If the demand is stochastic, other methods are used like asking technicians.

With the three segmentation methods described above, the model uses a multi-criteria classification, which considers all three segments and based on that determines the suitable safety stock level. The classification is done in Excel, which based on inputs for ABC, FSN and VED recommends a stock policy from the list in the beginning of this subchapter. Figure 4-5 shows what the interface in Excel looks like.

PARAMETERS			
	value [eur]		issues/year
A		F	4
	10 000		
B		S	1
	1 000		
C		N	0

	Spare part value [eur]	Yearly consumption frequency	Production impact (1-3)	Lead time (1-3)	Safety (1-3)
New item data	5	1	1	1	1

RESULTS				
ABC	FSN	VED	Suggested policy	
C	S	D		One piece/set in stock

Figure 4-5: Interface in Excel for determining safety stock policy.

The planner expresses the limits of the model by explaining that the input data for criticality and demand is not entirely reliable and that methods need to be put in place in order to quantify these attributes more accurately. He continues explaining that the model, in its current form, will not be applicable to big warehouses with many transactions, and that more reliable information from maintenance will be needed to utilize the model fully.

Order Policy

The policy which is used by IKEA Industry today when ordering new spare parts is for the most part an *(S-1, S)-policy*. Stock is ordered up to a pre-determined stock level, but there are cases where more than what is needed is ordered (as is the case at the Wielbark plant). IKEA's ERP-system M3 automatically reviews the stock levels once per day and places the orders necessary to reach the determined stock levels. However, the ERP is currently undergoing an update which will decrease the time between reviews to once per hour between 5 a.m. and 5 p.m., a change which is common for all production units. Thus, the review policy is *periodic* by definition. However, when comparing the review period length to the order cycles (the time from ordering until consumption of a spare part), the review period is so short that the review policy can be approximated as *continuous*, which opens up the possibility of using other models in the analysis.

Lateral transshipments

Due to high lead-times for spare parts needed urgently, sometimes IKEA conducts lateral transshipments. Currently, the number of transshipments conducted is relatively small (a few times per year at most sites) and the process is not standardized across different production units. The general flow is that an RFQ (Request for Quotation) is sent by the site in need to a site that has the needed part in stock. The site with the part in stock can then chose to sell the part to the other site. This is decided by the maintenance manager at the site which means that the pooling is *partial* as opposed to complete pooling where all of the stock should be available to all production units without the approval of the maintenance manager. Transport is often arranged with a freight company (TNT) who has a special agreement with IKEA, or using a local taxi firm, which also operates according to a previously agreed price model. The choice of what alternative to use is based on the urgency of the shipment. Taxi drivers are more flexible and available and can be used in critical situations. Freight companies on the other hand can be used when a 24h delivery time is acceptable, often for a lower price. Given that the transshipments are only conducted as a response to demand that cannot be met locally or by the supplier, the transshipments are *reactive*. Although the usage of lateral transshipment is sparse at IKEA Industry, three main characteristics that affect the probability of using lateral transshipments are mentioned by the planners:

- Supply lead-time. The lead-time for sourcing items varies to a great extent. If the lead-time is significant, the item may be viewed as critical per standard. Both preventive and corrective maintenance becomes more difficult to plan and as a result, IKEA Industry is more likely to laterally transship the goods.
- Usage rate. The usage rate matters because it is related to the usage of safety stock at all. Many items are slow movers and do not need safety stock as a result. If the items are rarely used, they are not likely to be transshipped since the probability of the item being at a nearby stock location is low.
- Criticality. Since transshipments are not something that is done as regular praxis, the trouble of manually contacting another production unit and coming to an agreement regarding sending the items needs to be outweighed by the negative effects of *not* doing it. Those negative effects will of course be more severe if the articles are critical. On the other hand, if the article is critical, it will be more difficult to source the article from another production unit since transshipping the article will put the other production unit at risk.

Relevant costs

From a cost perspective, the purchasers try to source items at the lowest possible cost but the current way of determining stock levels is not based on any total cost level like the literature suggests. Instead the focus is put on ensuring availability. Therefore, IKEA Industry’s perspective on the cost parameters typically used in inventory models have been dedicated a separate chapter (chapter 4.5.).

4.4. Selection of production units and spare part articles

Despite the spare part network configuration being fairly simple (see chapter 4.1.2.), the planning activities tied to spare parts are quite complex. This complexity derives from the vast array of spare parts and suppliers. The scope of this thesis does not allow for a model that can take all of these complexities into consideration. Therefore, clear boundaries in terms of articles for testing the model and sites taken into consideration have to be set. As far as site selection is concerned, not all production units should be considered at the same time as the lead-time will be too long and expensive to regularly ship between all sites. Instead, the network can be divided into clusters in which goods can be transshipped. As far as articles are concerned, the model will require extensive data about the articles (e.g. demand characteristics, holding costs and backorder costs). Not all of this data is readily available at the time and will require manual assessment. Such data includes information about the criticality and the backorder cost. In this model, the data needed for the model can be defined for a limited set of articles.

4.4.1. Selection of production units

The units that are chosen need to be in close proximity to each other in order to ensure reasonable transshipment distances and costs. Through discussions with the thesis supervisors at IKEA Industry, five units in Poland were chosen due to the high number of production units in proximity to each other. The chosen units (see Figure 4-6) are the following:

- Goleniow (Solid Wood)
- Resko (Solid Wood)
- Stepnica (Solid Wood)
- Pine sawmill (Solid Wood)
- Poland West (Flat Line)

Figure 4-6: Geographical map of the units considered in this thesis.

Transshipment lead-time will be of special interest within the cluster in order to determine the backorder cost. In order to identify distances and transportation times for transshipments between different production units, addresses of the production units were entered into Bing Maps and the shortest transportation times and distances were noted (see Table 4-1 and Table 4-2). Indeed, the transportation time does not equal the transshipment lead-time, but it provides a lower boundary for the lead-time. The time for accepting the order, picking and packing the goods is estimated to be 30 minutes which means that 30 minutes should be added to the transportation times in Table 4-1 to obtain the actual transshipment lead time (see Table 4-2). Note that transshipments are not initiated if delivery within 24 hours cannot be guaranteed.

Table 4-1: Summary of transportation times (by car) between the production units expressed in minutes.

Transshipment transportation times expressed in minutes					
	Resko	**Stepnica**	**Goleniow**	**Pine Sawmills**	**Poland West**
Resko	0	60	47	45	184
Stepnica	60	0	28	71	162
Goleniow	47	28	0	49	148
Pine Sawmills	45	71	49	0	166
Poland West	184	162	148	166	0

Table 4-2: Summary of transshipment lead-times between the production units expressed in minutes.

Transshipment lead-times expressed in minutes					
	Resko	**Stepnica**	**Goleniow**	**Pine Sawmills**	**Poland West**
Resko	0	90	77	75	214
Stepnica	90	0	58	101	192
Goleniow	77	58	0	79	178
Pine Sawmills	75	101	79	0	196
Poland West	214	192	178	196	0

Table 4-3: Summary of distances (by car) between the production units expressed in kilometers.

Distance between production units expressed in kilometers					
	Resko	**Stepnica**	**Goleniow**	**Pine Sawmills**	**Poland west**
Resko	0	73	55	44.5	254
Stepnica	73	0	20.8	81	222
Goleniow	55	20.8	0	47.4	200
Pine Sawmills	44.5	81	47.4	0	223
Poland west	254	222	200	223	0

4.4.2. Selection of articles

The articles need to fulfill two criteria: (1) the article should be used in at least two of the production units in the cluster of selected production units and (2) there needs to be non-zero current safety stock level at the production units.

Item commonality

The article should be used in at least two of the production units in the cluster. This is an obvious requirement, and it should not be ignored, since there are spare parts which are not used by all production units. Since the cluster in this thesis consists of five different production units, the number of combinations is

$$\sum_{n=2}^{5} \frac{5!}{n!\,(5-n)!} = 26.$$

In this thesis, the entire set of articles used in every production unit in the cluster is extracted from Navigation Portal respectively. Article matches in all of the 26 combination are highlighted. Matches were found in eight of these 26 combinations and are summarized in Table

4-4. It should be noted that since these matches are found in the Navigation Portal, it only represents the harmonized 40,000 articles. There are surely more matches in reality.

Table 4-4: Item commonality between the warehouses in the cluster. The 18 combinations not listed had no common articles.

Site combination	Number of common articles
Goleniow & Resko	8
Goleniow & Stepnica	12
Goleniow & Poland West	175
Resko & Stepnica	3
Resko & Pine Sawmills	6
Resko & Poland West	6
Stepnica & Poland West	16
Goleniow, Stepnica & Poland West	7

Non-zero current safety stock level

The reason for using this criterion is two-fold. For one, it implies *some* level of criticality, since the cycle stock should be able to cover the preventive maintenance in an ideal world. Non-zero safety stock levels then imply that there needs to be goods in stock in the event of corrective maintenance or if there is variation in demand or lead-time related to preventive maintenance. If the safety stock is zero, it is then implied that the likelihood or impact of such events is not significant enough to keep extra stock i.e. lower criticality. The other reason for this criterion is that the purpose of this model is to lower safety stock levels. If the safety stock is already zero, there is no need for using the model. A list of all articles with their current safety stock levels and supply lead-time was supplied by the maintenance solutions owner. By filtering with respect to the article numbers and warehouses of interest, the needed data could be extracted.

When considering these criteria, the resulting group of articles to be used was 43 articles that all are shared between Goleniow and Poland West. For 20 of the articles, both units keep a safety stock of two or more. In the case of the other 23 articles, both sites keep a safety stock of one or more. Since no significant reductions can be made to an article that only has one unit in safety stock, the 20 articles with two or more units in safety stock are used henceforth in this thesis. The articles are summarized in Appendix C.

Demand and supply lead-time characteristics of the selected articles

Most inventory models require some information about the demand events. Since the demand is a stochastic variable, the distribution that the demand follows was of interest. Ideally, this would be done with a statistical test (see chapter 2.4.2.). In the case of spare parts at IKEA Industry, however, the demand events are so few that the lack of data points would render the test completely void of any statistical significance. Instead, with reference to the summary of usage frequency of demand distributions in spare parts inventory models in the literature review, the dominant distribution was used. In this case, this means that a Poisson distribution was used (see Table 3-2). As mentioned in 3.3.6., Poisson distributed demand only allows for one article to be demanded at a time. This seems reasonable with the delimitation that the safety stock should only cover breakdown events. Realistically, the breakdown of an article should only result in the demand of one article to replace it. The intensity parameter λ (demanded units per day) was determined for the 20 selected articles with the help of maintenance staff at the selected production units going through the number of breakdowns per spare part in the last three years. During the identification of the demand rates it was discovered that for two of the 20 articles, more than one spare part are replaced in a single machine whenever there is a breakdown. This was the case for C9004677 “Custom tooth” and C9005180 “Bearing”. This means that the demand size during individual demand events can be larger than one which violates the assumption of Poisson distributed demand. The maintenance staff commented that this is a special case and does not apply to most articles. For this reason, these two articles were excluded from the thesis. Three of the remaining 18 articles did not have any data of breakdowns in Goleniow in the past years which means that no demand rate could be estimated in Goleniow. Therefore, these three articles were also excluded. This resulted in a final set of 15 articles to test the model with. The set of articles represent a variety of different spare parts including springs, bolts, motors and sprockets etc. The estimations of the demand rates are listed in Appendix C. Since the transaction history was so short for the articles, the uncertainty of the intensity parameters was high as well which means that the sensitivity of the intensity parameter will had to be analyzed. The supply lead-time for the different articles are contract-based and vary across the production units. The lead-times for the selected articles for both units are expressed in days and are listed in Appendix C.

4.5. Cost parameters

In this subchapter, different types of costs related to spare parts management will be presented. The current ways of determining the costs at IKEA will be presented, and the costs which will be used in the model will be highlighted.

4.5.1. Holding costs

Holding costs, i.e. the cost of keeping stock does not have a strong history at IKEA. Traditionally, high stock levels and large buffers have been viewed in a positive way and seen as an enabler of good service. The cost of keeping stock has been assumed negligible compared to benefits of good service. Nonetheless, there is a focus on a lean supply chain and the development of IKEA Production System (IPS). IPS is inspired by Toyota Production System, which among other things emphasizes the reduction of stock keeping. This means that stock levels cannot be arbitrarily high. If inventory for direct material is held for a year, the cost of holding that inventory is roughly 25% of the goods value. For indirect material (spare parts), there is no official figure, although the same principle should hold. At the Lubawa plant, these sorts of costs are included in the overhead costs which are estimated to be 17% of the goods value per year. As a compromise, 20% of the goods value per year is chosen as a starting point for this thesis. This will be assumed to be representable for the other production units in Poland.

Since there is such a degree of uncertainty to the holding cost, it will be subject to sensitivity analyses in later parts of the thesis. The current way IKEA evaluates the stock levels from a financial point of view is to estimate the tied-up capital. In terms of spare parts, an average unit value is defined by calculating the average price IKEA has paid for all parts of a specific kind in stock. An average value is needed since the same part will be purchased at different prices from time to time. The average price is different across the different production units. The differences are, however, small enough between the production units that an overall average price can be calculated. This average price is also the goods value that is used for calculating the holding cost. The average purchase prices of the selected 20 articles along with their corresponding holding cost are presented in Appendix C.

4.5.2. Ordering costs

Ordering costs that are common for the affected units are not easy to estimate since the order handling is different at different sites and there are varying degrees of automation when it comes to the administrative work related to order management. Most production units when posed with the question do not regularly track this sort of cost. In one production unit, the ordering cost is estimated with the personnel cost for staff responsible for order management. The personnel cost is the salary, social cost as well as training etc. and is estimated to be 105,000 PLN as average cost in Poland for this kind of job. Divided by the number of orders for calendar year 2019 which was 4,200 orders the cost per order was 25 PLN. The staff responsible for order management estimated that 20-25% of their time is devoted to order management which means that the ordering cost is around 5 PLN or 1 EUR per order. It is assumed that this is representable for the production units in Poland.

4.5.3. Shipment costs

Shipment costs depend on what supplier is used. There are different price mechanisms for this such as:

- Fixed cost per shipment. This is the most basic type of cost. IKEA Industry and the supplier agree upon a specified order amount. If the amount is adhered to, the cost will be the agreed upon price. Small packages that weigh less than a few kilos will cost approximately 5 EUR.
- No shipment cost. In this case, the supplier takes all of the cost and can be the case when the supplier is in close proximity and the purchase volumes are large and regular.
- Variable cost per shipment. The cost may vary between deliveries depending on size, weight, number of items/packages, type of delivered material (e.g. fragile materials may need special packaging) and country of origin. The price can vary from a few EUR to thousands.

4.5.4. Shortage costs

Relating to chapter 3.3.7., the demand is represented by a breakdown and the customer is the maintenance staff requesting a spare part. The shortage happens when the maintenance requests a spare part and there is none in stock. This implies a shortage cost. Shortage costs are the most difficult costs to quantify since they essentially, in the case of spare parts, represent the cost of not being able to have the equipment up and running. The immediate effect is the loss of revenue that would have been generated by the goods that are not being produced as a result of the downtime. However, the effect on production of a machine breakdown heavily depends on which machine it affects. For example, at the Orla plant which belongs to division “Boards”, the production configuration is a single production line. This means that a breakdown in any of the machine will eventually make the entire production come to halt (once buffers and slack has been consumed). Shortage costs in such production units is therefore relatively easy. For plants that belong to divisions “Solid Wood” and “Flatline”, however, there are multiple parallel production lines which means that in many cases, the breakdown will not cause the entire production to stop. Even in the “Solid Wood” and “Flatline” units there are bottleneck machines where breakdowns do greatly impact the production. Ideally, the items that have significant safety stock levels today, are only items that in some way is critical and greatly affects the production.

The shortage cost used for this master thesis is 140 EUR/h (or 3,381 EUR/day). This figure was estimated for one of the factories. There is likely a high uncertainty tied to this number and it will need be revised in the future when a more representative number can be determined. It will serve as an placeholder in the meantime. The exact method used for determining this number remains undisclosed due to confidentiality.

4.5.5. Transshipment costs

Transshipment costs have occurred in Lubawa, Goleniow and Poland West when the factories have sent spare parts between each other. The two different situations using either a forwarder or a taxi firm have different costs tied to them. When using a forwarder, the fee depends on the size and weight of the spare part in question but is usually between 100-500 PLN (although for some complex parts it could cost thousands). The fee for taxi drivers is paid based on the number of kilometers the spare part will be transported. Usually there is a starting fee of around 9 PLN (2 EUR) plus 3 PLN (0.66 EUR) extra per kilometer. The transshipment cost which will be used in the model is the rate for the taxi driver (2 EUR + 0.66 EUR/KM). Note that this cost varies depending on local agreements, IKEA should adjust the cost when using the model in practice. As for taking the down-time during the transshipment into consideration, the transshipment lead-time between Goleniow and PL West is around 2.5-3 hours (see Table 4-2) which will be multiplied with the hourly shortage cost of 140 EUR. The total transshipment cost per transshipment between Goleniow and PL West is then

$$C_T = 2 + 0.66 \cdot 200 + 3 \cdot 140 = 554\ EUR/transshipment$$

Realistically, the transshipment costs are not the same for every article. Some articles that are larger are not feasible to send by car and would require a forwarder instead which could cost more than a taxi. In this thesis, a categorization of the selected articles with respect to size and weight was made. The idea was to estimate the transshipments for each category individually, since the price varies depending on these attributes. However, no rates were obtained from Poland West or Goleniow, which is why the fee of 554 EUR will be used going forward.

4.6. Spare parts performance measurement

Like the other parts of the spare parts flow, performance measurement varies depending on the production unit. The common theme across the units is that some form of availability of the machine equipment is regularly reported.

4.6.1. Production unit Lubawa

The maintenance department in Lubawa utilizes a number of KPIs to monitor the production performance, these include technical availability which indicates the percentage of time the production is up and running. Lubawa also monitors the preventive maintenance effectiveness (PME) which shows the fraction of the total maintenance time that is spent on preventive and corrective activities respectively. Mean time between failure (MTBF) and mean time to repair (MTTR) are also monitored. These KPIs are discussed during daily and weekly meetings when the maintenance department follows up on breakdowns and planned maintenance.

4.6.2. Production unit Wielbark

In Wielbark, the maintenance department has been improving the whole process around managing spare parts. An effort was taken to clean the spare parts data by taking new pictures of the parts and updating the descriptions. The team has also started to utilize new cost centers, documenting exactly which machine a specific purchase of a spare part is related to. However, the only spare part performance measure used by the team in Wielbark is the current stock value of all parts in the spare part inventory. The reports are generated on a monthly basis and are discussed during maintenance meetings. Wielbark is currently not using any other KPIs related to spare parts inventory management.

4.6.3. Production unit Goleniow

At the Goleniow site, monthly and weekly reports of the machine failure rates are submitted. In these reports, the failure rate for all machines are presented both in terms of percentage of time standing still as well as the loading time (where loading time is the is the time the machine should be scheduled). The three machines with the highest failure rates are rated as critical and more detailed information is reported about these. Such information includes a detailed list of the failures of the past week. The list includes the date of the incident, machine number, area of the machine that failed, a short notation describing what happened and what shift. It also includes the down time of each failure/breakdown expressed in minutes. With this information illustrative diagrams are constructed highlighting the major causes for the failures. Furthermore, time spent on preventive and corrective maintenance, number of reports in M3 and the historical failure of the machine are reported.

4.6.4. Production unit Poland West

The production unit in Poland West monitors the performance of machines via a number of KPIs related to maintenance. Similarly to the other Polish plants, they do not monitor the performance of the spare parts in particular. The KPIs connected to production in Poland West are listed below:

- Availability of machines
- MTBF (Mean time between failure)
- MTTR (Mean time to repair)
- Breakdown time (in hours)
- Losses of loading time with stop codes

The maintenance department in Poland West also measures the costs for repairing machines, buildings and forklifts. Another factor which is measured is the amount of open work orders. A work order is a document which specifies what the reason is for a stoppage, who is responsible and other technical details. The number of open and closed work orders the last 24 hours, together with the cost tied to them, is also monitored by the maintenance department.

4.6.5. Global performance measurement

The performance measurement approaches presented above are all individually used at each production unit, with methods and definitions differing between production units. In order for managers who work centrally in IKEA to get an overview of the overall performance of all production units, global performance measurement is used. This is done by QlikView reports extracting information from the ERP about the production units and summarizing it in global performance measurement reports. These reports serve as a way of alarming central management when a specific production unit is underperforming, or as a way to show central managers issues which are common for several production units. The reports include information about current stock levels, stock value and breakdowns for all production units connected to the system. The reports are overseen to make sure that the desired uptime is achieved. IKEA also utilizes OEE-measurement in the factories, dashboards are used to present the current performance levels, see Figure 4-7.

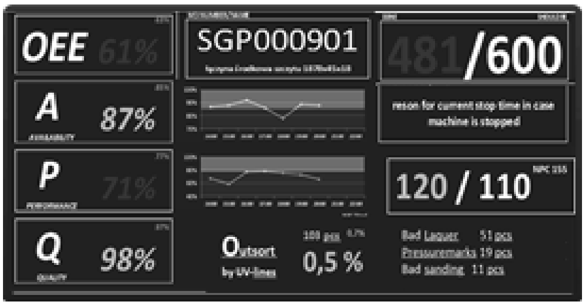

Figure 4-7: Performance measurement dashboard used at the production units.

However, IKEA does not currently monitor the performance of the spare parts inventory itself, other than monitoring its value and stock levels. Some of the global performance measurement areas are presented in Table 4-5.

Table 4-5: Global performance measurement areas.

Performance measurement area	Description
Sourcing	Showing fractions of purchase orders delayed or delivered per purchase order line for the different production units.
Warehouse	Showing fraction of issues related to a work order, not related to a work order and planned/unplanned activities.
Make	Shows numbers and fractions of corrective and preventative maintenance, as well as overhauls and inspections.
Stock balance	Shows the total stock value per production unit, as well as the total stock value.

4.7. Summary of important characteristics of the flow

The characteristics of IKEA Industry’s spare parts flow with respect to the categorization in the frame of reference are listed in Table 4-6. In addition to the flow characteristics, there are input parameters for the model that are determined. These parameters are listed in Table 4-7.

Table 4-6: Summary of the characteristics of IKEA Industry's spare parts flow based on the categorization by Paterson et al (2011) presented in chapter 3.3.

IKEA Industry's spare parts flow		
System	No. item	1
	No. echelon	1
	No. bases	N (2 for the selected set of articles)
	Identical bases?	No
	Backorder or Lost sales	Production down-time (backorder)
Ordering	Timing	Period/Continuous
	Policy	(S-1,S)
Transshipments	Type	Reactive
	Pooling	Partial
	Decision making	Decentralized
	Cost	Item

Table 4-7: Summary of parameters that are of interest as input data for the model.

Model parameters	
Holding cost	20% of goods value per year
Shortage cost	140 EUR/h or 3,381 EUR/day
Transshipment cost	554 EUR/transshipments
Ordering cost	1 EUR/order
Demand distribution	$D_i \sim Po(\lambda_i)$ see Appendix C
Supply lead-time	See Appendix C

5. ANALYSIS

In this chapter, the data gathered will be analyzed with the help of the frame of reference with the goal of answering the research questions. The first sections of the chapter is devoted to the initial analysis of data, which is a prerequisite before the development of the safety stock model. Such steps include selection of articles and analysis of their properties such as demand characteristics. The remainder of the chapter is devoted to development of the safety stock model and suggestions for KPIs.

5.1. Safety stock model

Developing an easy-to-understand model for determining stock levels is no easy task. Therefore, the chapter is divided into five parts. First, the model is described in a conceptual way in order to concretize what the model should do in a brief way. Second, the model should be described in detail, specifying the scientific methods being used to achieve the goal. Third, the excel model is described in order for IKEA Industry to understand how the model works computationally. This will facilitate adjustments to and development of the model post-project. Fourth, the results of the testing of the model using the 15 selected articles are presented. Finally, since there are many uncertainties related to the input parameters and the assumptions being made, the last part is devoted to sensitivity analyses of said parameters.

5.1.1. Conceptualization

It is important to define what the model is supposed to do in order to subsequently define a scientific model that defines input variables and their causal relationships. As stated in chapter 3. and 4., there are different costs related to the inventory system that need to be weighed against each other. Specifically, the user of the model should be able to supply the model an article number, and the model should consider all the costs and suggest stock levels for the affected warehouses. In order for it to work, the model should be able to identify a number of different parameters using just the article number as a reference:

- Holding cost per unit and time unit
- Shortage cost per unit and time unit
- Transshipment cost
- Demand characteristics
- Supply lead-time
- Transshipment lead-time

The selection of cost parameters to include is based on the cost parameters which have an influence on order-up-to levels. Since the order policy is (S-1, S), the total ordering cost depend on the demand rather than the order-up-to level which is why it is not included (when an (S-1, S)-policy is used an order is placed for every unit that is demanded). The regular shipment costs are insensitive to the order-up-to-level for the same reason. Using these parameters, an expression for the total costs should be defined. The expression should be a function of the order-up-to levels in the system. The overall concept is illustrated in Figure 5-1.

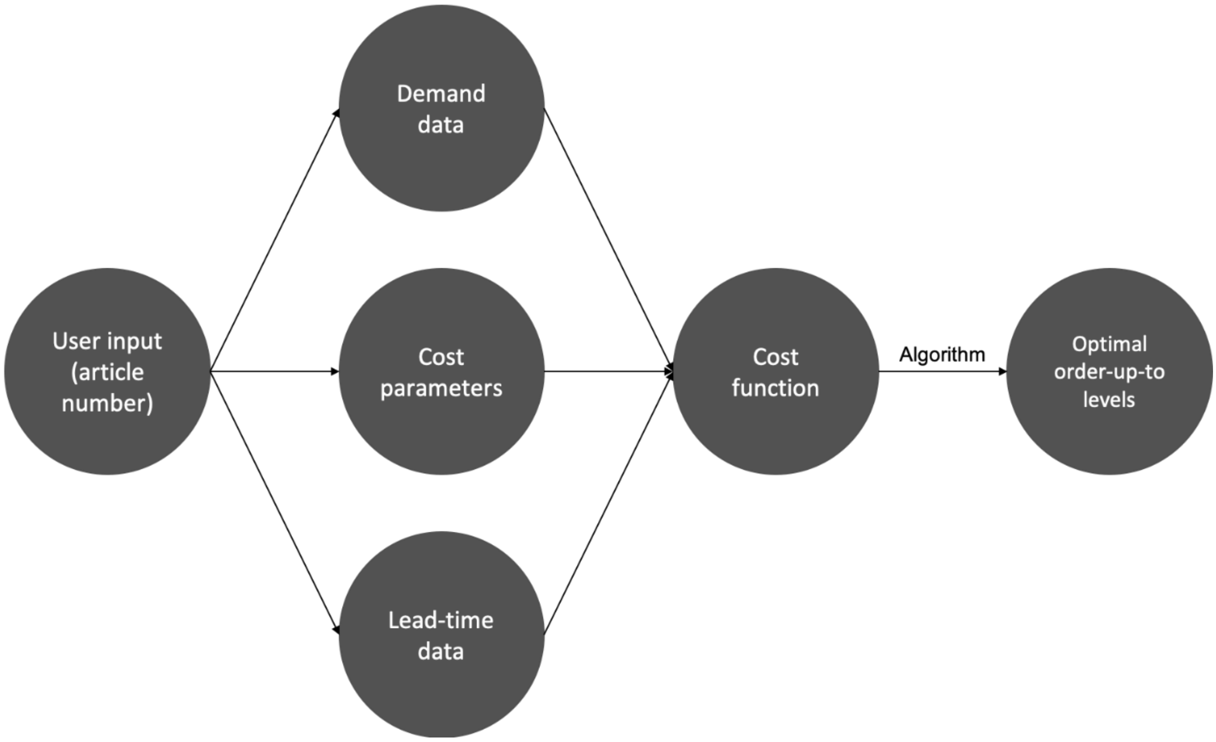

Figure 5-1: Illustration of the overall functionality of the model.

Looking back at the literature of solutions methods, this concept mathematical solution method rather than a classification-based method. The reason for this choice is that the mathematical solution methods more directly addresses the transshipment context than the classification-based method presented in 3.3.9. In this thesis, algorithms are used instead of simulation methods to obtain the order-up-to level. A simulation model may have a better ability to be adapted to reality but may also be slower and more difficult to use at a large scale. That would not be an obstacle in this case since the set of articles used is quite small. However, the inexperience of any simulation software present at IKEA Industry the authors have makes analytical/heuristic solutions more reasonable to use.

5.1.2. Modeling technique

In this thesis, Wong *et al* (2005b) will be the basis of the model. The technique is divided into three main parts: (1) determining the order-up-to level (safety stock level) of the system at an aggregated level, (2) allocating the order-up-to levels to the production units proportionally to the demand and (3) using perturbation analysis to find the optimal order-up-to levels with respect to holding costs, shortage costs and transshipment costs. Like any other model, a number of assumptions are necessary.

Assumptions and denotations

The demand is assumed to follow a Poisson distribution. As stated earlier, this is the dominant assumption in similar contexts (see Table 3-2).

The supply lead-time is assumed to be exponentially distributed in accordance with both Wong *et al* (2005b), Wong *et al* (2005a), Lee (1987) and Axsäter (1990). Some of these papers note that while the assumption of exponentially distributed lead-time may not describe reality well (Wong *et al*, 2005b), Alfredsson & Verrijdt (1999) have shown that the choice of lead-time distribution does not affect the results significantly. As seen in Appendix C, the lead-time is not the same for the different production units. The model assumes one common supply lead-time across the entire system. To accommodate this, a weighted average lead-time is selected with respect to the demand. In other words, the average supply lead-time will be

$$\mu = \mu_{Goleniow} \cdot \left(\frac{\lambda_{Goleniow}}{\lambda^0}\right) + \mu_{PL\,West} \cdot \left(\frac{\lambda_{PL\,West}}{\lambda^0}\right)$$

Note that the lead-time expressed in days is $1/\mu$ while the model uses μ which technically is the supply rate per day. This means that in order to get $\mu_{Goleniow}$ and $\mu_{PL\,West}$, the inverse of the lead-times are used to calculate μ. The reason for using a weighted average rather than a total average is that it will ensure that the supply lead-time chosen will more closely resemble the system's average supply lead-time. The supply rates for each article in the model are listed in Appendix E. The possibility of repairing the spare parts is neglected since it is assumed that the most common way of replenishment is through an order to the supplier.

Complete inventory pooling and no transshipment lead-time are two major assumptions as well. Complete inventory pooling means that all of the bases share their entire inventory with each other. While this is not the case at IKEA Industry today, it is a necessary assumption to make in order to have a reasonably efficient and easy-to-understand model. The results of such a model could also be used to incentivize moving towards (or away from) inventory pooling. The assumption of no transshipment lead-times is motivated by the fact that the transshipment lead-time is considerably shorter than the supply lead-time (Lee, 1987; Axsäter, 1990; Wong *et al*, 2005b; Herer *et al*, 2006; Kukreja *et al*, 2001). This is because the alternative, which is to wait for it to be delivered by the supplier has a much longer lead-time, the transshipment lead-time is almost nothing in comparison. If the transshipment lead-time is not negligible compared to the supply lead-time, lateral transshipments may not be an attractive alternative (Kukreja *et al*, 2001). In IKEA Industry's case, this assumption seems reasonable. It should be highlighted that the transshipment lead-time is only neglected when estimating the system's ability to deliver demanded spare parts (e.g. estimating one production unit's ability to supply the demand of another production unit does not consider any transshipment lead-time). The economic impact that the transshipment lead-time implies will be included in the total cost however. The cost implied by the transshipment lead-time will be the expected number of transshipments multiplied with the average transshipment lead-time and shortage cost.

Whenever a transshipment is initiated, the production unit will choose which other production unit to source the article from randomly. It is possible to define other sourcing rules as well such as ones based on transshipment cost, distance or stock level (Wong *et* al, 2005b; Lee, 1987; Kukreja *et* al, 2001; Axsäter, 1990). In this thesis, given that the production units within a cluster are at relatively equal distances from each other, the differences are not deemed to be significant enough to warrant the complexity and rigidity more complicated sourcing rules bring. Furthermore, the set of selected articles that will be tested are only used at two production units, rendering the results completely insensitive to the choice of sourcing rule (the production unit only has one other site to source from).

Finally, it is assumed to be possible to make delayed transshipments. This means that when the inventory level is zero for all productions sites and an item is demanded at production unit X, it may be possible to send an order to production unit Y. When the article is delivered to production unit Y, it will immediately be transshipped to production unit X. This may be favorable in situations when the inventory is zero at all production units but expected to arrive soon to a nearby production unit.

With all of these assumptions in mind, the following denotations can be summarized:

$I = \{1, 2, \ldots, N\} =$ Set of bases

$S_i =$	Order-up-to level at base *i*
$S^0 = \sum_{i=1}^{N} S_i =$	Aggregated order-up-to-level
$\lambda_i =$	Demand rate at base *i*
$\lambda^0 = \sum_{i=1}^{N} \lambda_i =$	Aggregate demand rate
$\lambda_{gh} =$	Lateral transshipment rate from base *g* to base *h*
$g_i =$	Demand rate at base *i* when inventory is positive
$h_i =$	Demand rate at base *i* when inventory is zero or negative
$1/\mu =$	Average supply lead-time
$TL =$	Transshipment lead-time
$\rho_x =$	Probability that the average inventory level is *x* (*x<0* represents backorders)
$\pi_x^i =$	Probability that the inventory level at base *i* is *x*
$\beta_i =$	Probability that the demand at base *i* is met by stock on hand
$\alpha_i =$	Probability that the demand at base *i* is met by a lateral transshipment
$\theta =$	Probability that a demand is backordered
$\varepsilon_i =$	Probability that a delayed transshipment is sent from base *i*
$\eta_i =$	Probability that a delayed transshipment is received at base *i*
$IL_i^- =$	Expected number of backorders at base *i*
$W_i =$	Expected down-time at base *i*
$T_i =$	Expected number of transshipments received at base *i* during a given time frame
$C_T =$	Transshipment cost
$C_{TL_i} =$	Cost incurred at base *i* by shortage during the transshipment lead-time
$C_H =$	Holding cost
$C_W =$	Shortage cost (downtime cost)

Determining the stock level of the system at an aggregated level

With all assumptions and denotations presented, the first part of the model can be explained. The idea here is to view the inventory system, not as many isolated units, but as one system that combines all of them. One way of visualizing this is to imagine the system as a warehouse, and the different production units as storage racks within the same warehouse. If an article is demanded, you can supply from any storage rack (production unit) that has it. From a customer satisfaction purpose, it does not matter from where you supply it. This is ensured by the complete pooling and no transshipment lead-time assumptions. Another result of these assumptions is that an item is only backordered if *no production units* have it. Depending on the aggregated order-up-to level S^0 and aggregated demand rate λ^0, there will be a specific expected stock on hand and number of backorders. The objective here is to determine which aggregated stock level S^0 that results in the lowest combination of holding cost and shortage cost (see Eq. 5-1).

$$\min(C) = IL^+ \cdot C_H + IL^- \cdot C_W \qquad (Eq. 5-1)$$

Where

$$IL_0^+ = \sum_{x=0}^{S^0} x \cdot \rho_x \qquad (Eq. 5-2)$$

and

$$IL_0^- = \sum_{x=1}^{\infty} x \cdot \rho_{-x} \qquad (Eq. 5-3)$$

Where ρ according to Palm's theorem (Sherbrooke, 1968) is

$$\rho_{S^0-m} = \frac{\left(\lambda^0/\mu\right)^m}{m!}\left(e^{-\lambda^0/\mu}\right), \qquad m = 1,2,\ldots \qquad (Eq. 5-4)$$

Since (Eq. 5-4) is just the definition of the density function for a Poisson distribution, (Eq. 5-4) can be calculated in Excel using the built-in Poisson function. Note that transshipment costs are not considered in (Eq. 5-1). This is because the number of transshipments does not affect the choice of aggregated order-up-to level. The transshipments will however affect the allocation of the order-up-to levels which will be addressed in the final part. The algorithm to find the optimal S^0 is to first start with $S^0 = 1$ and then add one incrementally. Between each S^0 the difference in the cost is compared. At first, the cost will decrease for every unit S^0 is increased since the shortage costs will decrease. At some point the costs will start to increase for every unit S^0 since the holding costs will be dominant instead. This is illustrated in Figure 5-2 which is based on input data from Wong (2005b). The turning point will be the optimal S^0. Therefore, computationally, the S^0 will be increased until the cost difference with the two most recent S^0-values is positive (indicates a relative total cost increase when increasing the order-up-to level).

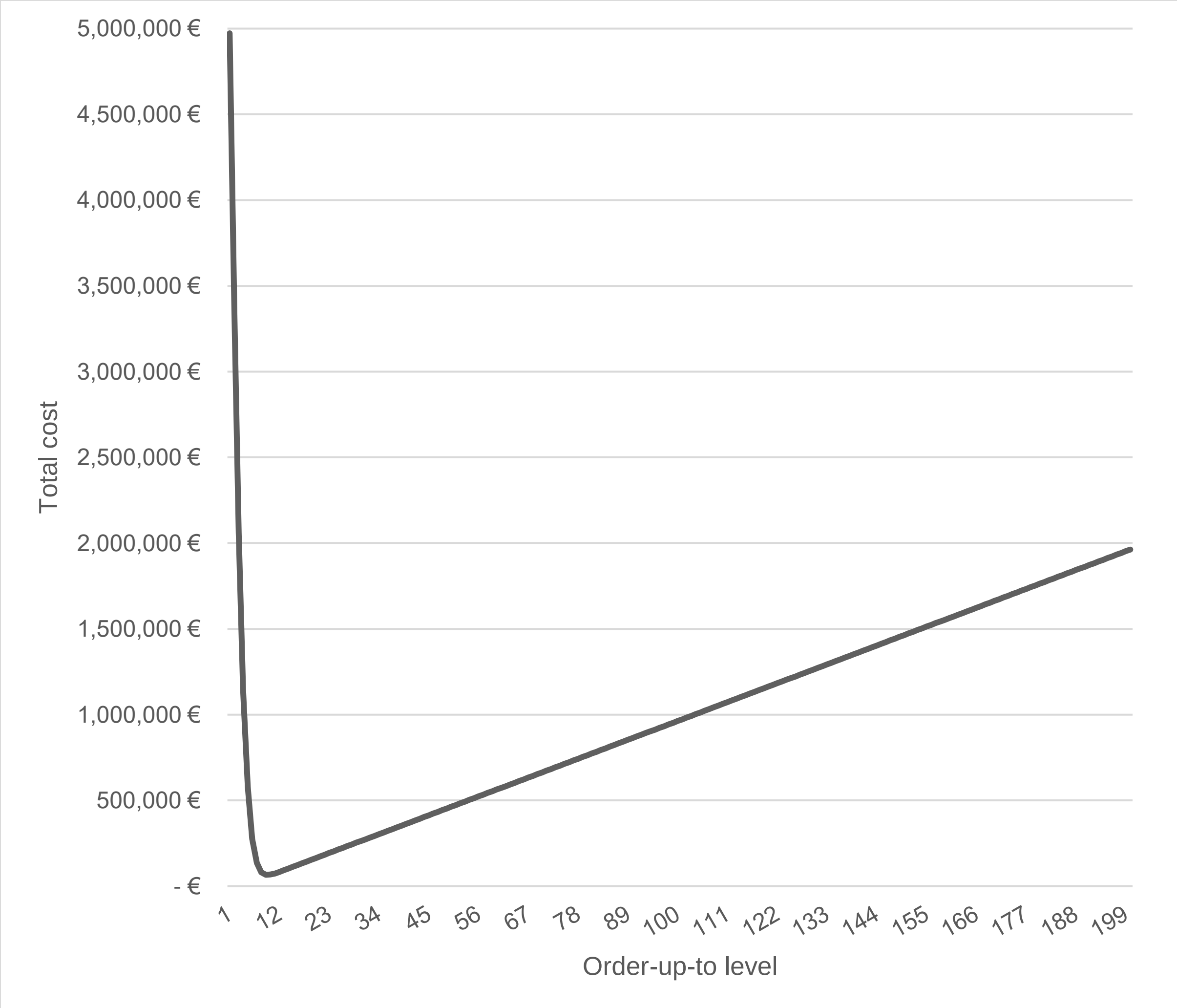

Figure 5-2: Illustration of holding cost vs shortage cost w.r.t. order-up-to levels.

Allocating the stock levels to the production units proportionally to the demand

To get an initial allocation of the order-up-to levels for the perturbation analysis, an intuitive place to start is to allocate them proportionally to the demand. Consider an example of two production units where the aggregated order-up-to level is 9, the aggregated demand is 0.6, the demand for production unit X is 0.4 and the demand for production unit Y is 0.2. In this case the demand at production unit X is two thirds of the aggregated demand which means that the order-up-to level at production unit X should be 6. Conversely, the demand at production unit Y is one third of the aggregated demand which means that the order-up-to level at production unit Y should be 3. In mathematical terms, the order-up-to level at base i S_i can be expressed as

$$S_i = \frac{\lambda_i}{\lambda^0} S^0. \qquad (Eq. 5-5)$$

This often results in S_i being a fractional number. In order to round the numbers to integers and making sure that $\sum_{i=1}^{N} S_i = S^0$, Kukreja *et al* (2001) present a simple heuristic which will be implemented in the excel model.

Finding the optimal stock levels

The final part of the model can be divided further into two sub-parts: (1) determine a number of different order-up-to level allocations to compare and (2) determine the quantities IL_i^+, W_i and T_i to calculate the total cost in order to compare the different allocations. The allocation with the lowest total cost is chosen.

Different perturbations of allocations will be defined. If there are N number of bases, at most $N(N-1)$ perturbations are checked. The heuristic for defining the perturbations to check is best explained using an example (Kukreja *et al*, 2001). Consider a situation where there are three production units that have an article in common. Suppose that the allocation obtained when allocating proportionally to the demand is $S_1 = 4$, $S_2 = 2$ and $S_3 = 3$. One unit is then taken from one of the production units and given to the other production units, one at a time. The first perturbation would then be to take one unit away from production unit 1 and give it to production unit 2. The next one would be to take the same unit given to production unit 2 and then give it to production unit 3. This procedure is repeated for all production units. The complete list of perturbations for this example is presented in Table 5-1.

Table 5-1: Example of perturbation list.

Perturbation	S_1	S_2	S_3
Proportional to demand	4	2	3
1	3	3	3
2	3	2	4
3	5	1	3
4	4	1	4
5	5	2	2
6	4	3	2

In order to determine T_i, the probabilities θ, β_i and α_i have to be determined. The probability of the demand being backordered θ is the sum of all probabilities of aggregated stock levels below zero i.e.

$$\theta = \sum_{x=1}^{\infty} \rho_{-x} \qquad (Eq.5-6)$$

Obviously, $\theta + \beta_i + \alpha_i = 1$ which means that in order to determine α_i, β_i must be determined. In order to determine β_i, the different states the different production units can be in, can be modeled as an M/M/∞ queue. An illustrative diagram of these states and the transition rates between them is presented in Figure 5-3.

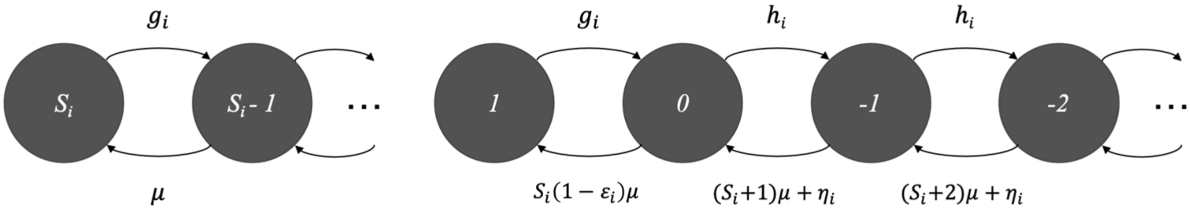

Figure 5-3: State transition diagram at the production unit level (Wong et al, 2005b).

The arrows between each state show at which rate the system will move towards another state. For example, if the current stock level at a production unit is four, the arrow pointing towards the state where the stock level for the production unit is three represents the rate at which the production unit goes from having four units in stock to having three units in stock. The opposite arrow represents the opposite transition. At this stage it becomes relevant to define the different rates that are possible. Starting with the transitions of removing units from the stock, there are two different rates: the demand rate at base *i* when the inventory level is positive g_i and when the inventory level is negative h_i. When the inventory level is positive, the demand rate at base *i* is its local demand plus the demand that is transshipped to other bases i.e.

$$g_i = \lambda_i + \sum_{k \epsilon I, k \neq i} \lambda_{ik} . \qquad (Eq. 5-7)$$

In a network containing *N* bases, there are (*N* – 1) alternatives to source from when a transshipment is made. Given the random sourcing rule, the probability of selecting any base is 1/(*N* – 1). The average transshipment rates are defined as:

$$\lambda_{gh_{average}} = \frac{1}{N-1} \lambda_h \beta_g (1 - \beta_h) = \frac{1}{N-1} \lambda_h \beta_g (1 - \beta_h)$$

However, this is not the rate that is needed for the M/M/∞ queue. The rate that is of interest is the rate sender base *g* has positive inventory. This is because the transshipment rate is used to describe the total rate for transitioning between states (g_i). Therefore the transshipment rate from base *g* to base *h* when base *g* has positive inventory is

$$\lambda_{gh} = \frac{1}{N-1} \frac{\lambda_h \beta_g (1 - \beta_h)}{\beta_g} = \frac{1}{N-1} \lambda_h (1 - \beta_h) \qquad (Eq. 5-8)$$

When the inventory is negative, the only demand that the base will face is the backordered demand i.e.

$$h_i = \frac{\theta \lambda_i}{1 - \beta_i} . \qquad (Eq. 5-9)$$

As for the arrows in the opposite direction, ε_i and η_i represent the probability of sending and receiving a *delayed* lateral transshipment respectively and are defined as (using a random source rule):

$$\varepsilon_i = \frac{1}{N-1} \sum_{k \epsilon I, k \neq i} 1 - \beta_k - \pi_0^k \qquad (\mathrm{Eq.} 5-10)$$

and

$$\eta_i = \frac{1}{N-1} \sum_{k \epsilon I, k \neq i} \pi_0^k S_k \mu \qquad (\mathrm{Eq.} 5-11)$$

respectively.

With this in mind, the steady state probabilities can be described. There are several different states the production units can assume. For states where the inventory is positive, the steady state probabilities are

$$\pi_{S_i-m} = \pi_0^i(1-\varepsilon_i)\frac{S_i!}{m!}\left(\frac{\mu}{g_i}\right)^{S_i-m}, m = 0,1,2,\dots,S_i-1 \qquad (Eq.5-12)$$

For states where the inventory is negative, the steady state probabilities are

$$\pi_{S_i-m} = \pi_0^i\frac{h_j^{m-S_i}}{\prod_{p=m}^{S_i+1}(p\mu+\eta_i)}, m = S_i+1, S_i+2,\dots \qquad (Eq.5-13)$$

The steady state probability of having the inventory level zero is

$$\pi_0^i = \left((1-\varepsilon_i)\sum_{m=0}^{S_i-1}\frac{S_i!}{m!}\left(\frac{\mu}{g_i}\right)^{S_i-m} + \sum_{m=S_i+1}^{\infty}\frac{h_j^{m-S_i}}{\prod_{p=m}^{S_i+1}(p\mu+\eta_i)}+1\right)^{-1} \qquad (Eq.5-14)$$

Finally, the probability β_i which is the probability of satisfying demand with stock on hand is the sum of all the positive steady state probabilities i.e.

$$\beta_i = \sum_{x=1}^{S_i}\pi_x^i \qquad (Eq.5-15)$$

In order to solve the steady state probabilities (Eq. 5-12) - (Eq. 5-14), an algorithm is formulated. This algorithm was developed by Wong *et al* (2005b). The idea is to choose arbitrary values of β_i and π_0^i and use them to calculate new values with (Eq. 5-12) - (Eq. 5-15) and keep going until the equations return the same values every time i.e. when the system is in steady state. The algorithm is summarized in Figure 5-4.

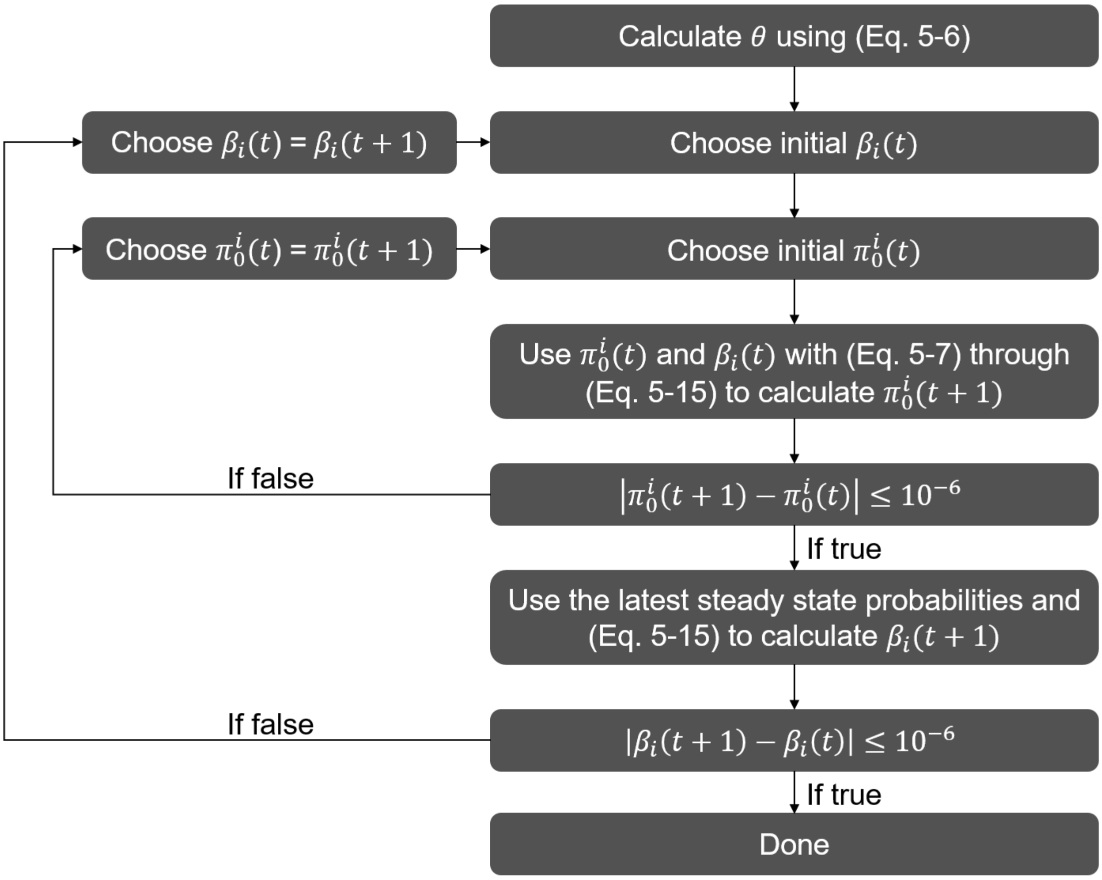

Figure 5-4: Algorithm for finding the steady state probabilities (based on Wong et al, 2005b).

When the algorithm is done, α_i can be calculated using

$$\alpha_i = 1 - \theta - \beta_i. \qquad (Eq. 5-16)$$

With a given α_i, the expected number of transshipments per production units T_i can be calculated using

$$T_i = \alpha_i \lambda_i t \qquad (Eq. 5-17)$$

where t is a pre-determined timespan expressed in days e.g. 365 days. W_i can be calculated using Little's Law

$$W_i = t \cdot IL_i^- \qquad (Eq. 5-18)$$

where

$$IL_i^- = \frac{\lambda_i}{\lambda^0} IL_0^- = \frac{\lambda_i}{\lambda^0} \sum_{x=1}^{\infty} x \cdot \rho_{-x}.$$

The cost implied by the transshipment lead-time will also be considered

$$C_{TL_i} = T_i \cdot C_w \cdot TL \qquad (Eq. 5-19)$$

Finally, the total cost is then expressed by

$$TC = C_H \cdot IL_0^+ + C_W \cdot W_i + C_T \cdot T_i + T_i \cdot C_w \cdot TL \qquad (Eq. 5-20)$$

Since only two production units are used in the model, the cost per transshipment will be constant and the same for all articles. If the model would include three production units, the transshipment cost would depend on between which units the item is being transshipped.

The modeling technique described above does not require any complex software or programming language. Microsoft Excel is readily available at any business laptop at IKEA Industry and therefore seems like an attractive choice of program to build the model. Unfortunately, the model is not simple enough to build directly into the worksheet and has to be programmed in the programming language VBA (Visual Basic for Applications) available in Microsoft Office. This means that a basic understanding of programming is needed in order to adjust or develop the model further. A description of the Excel model as well as a picture of the model user interface are available in Appendix D.

5.1.3. Results

Using the techniques described in 5.1.2. for all the 15 selected articles, order-up-to-levels are found for each one. As seen in 5.1.2., it is necessary to define a time horizon in order to calculate (Eq. 5-17) and (Eq. 5-18). In this study, the time horizon of 365 days is chosen since it seems like an appropriate time horizon from a budget perspective. The input data used in the model is listed in Appendix C. The complete results including aggregated order-up-to levels, allocated order-up-to levels, service level, expected stock on hand, expected number of transshipments, expected down-time and total cost are summarized in Appendix E. The current order-up-to levels are compared with the order-up-to levels suggested by the model. These comparisons are visualized in Figure 5-5. It can be noted that the model suggests similar order-up-to levels compared to the current order-up-to levels.

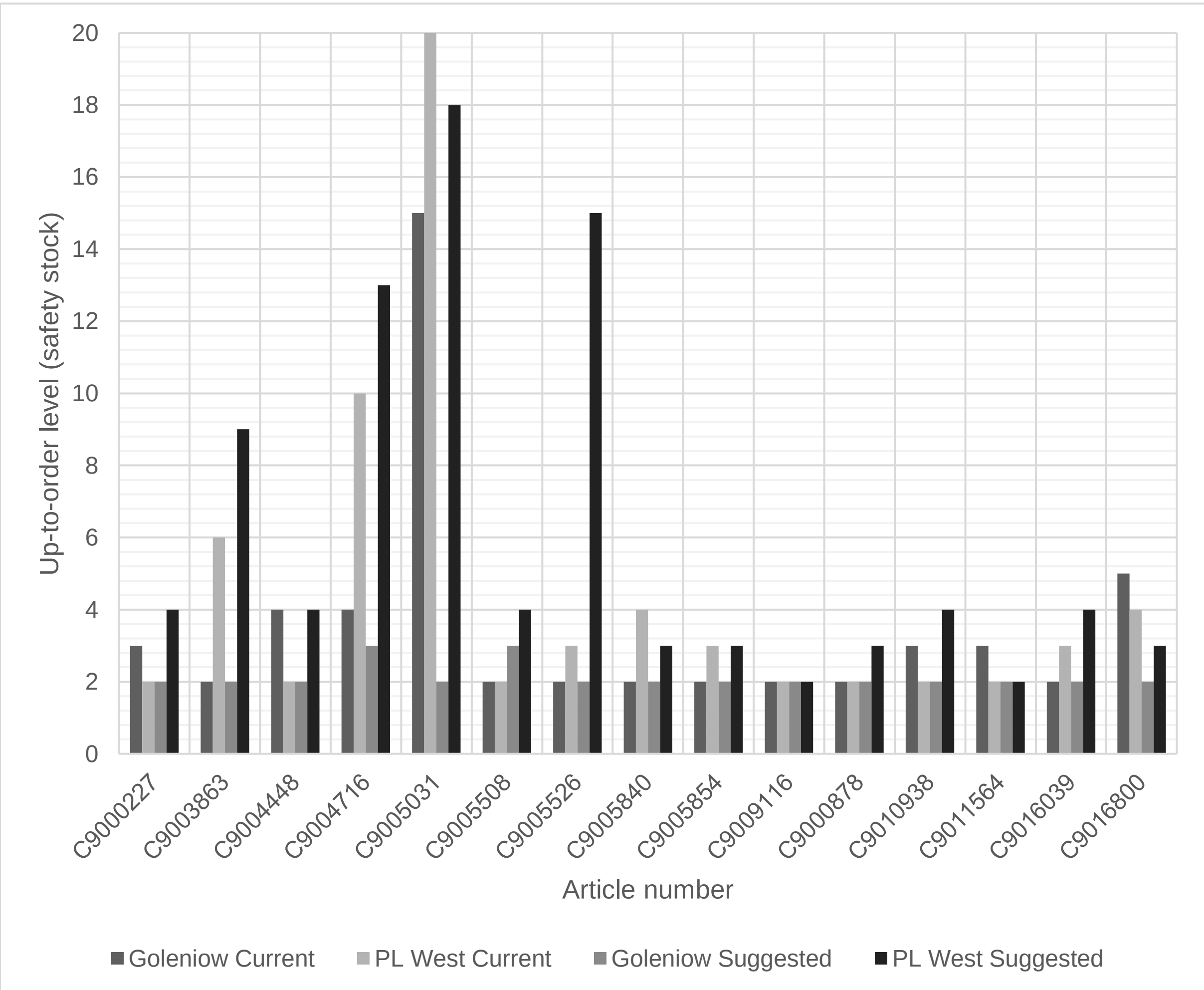

Figure 5-5: Current and suggested order-up-to levels respectively.

The relative order-up-to level differences are illustrated in Figure 5-6. Out of the 15 articles, the model suggests that the aggregated demand should be lowered for four articles, increased for eight articles and unchanged for three articles.

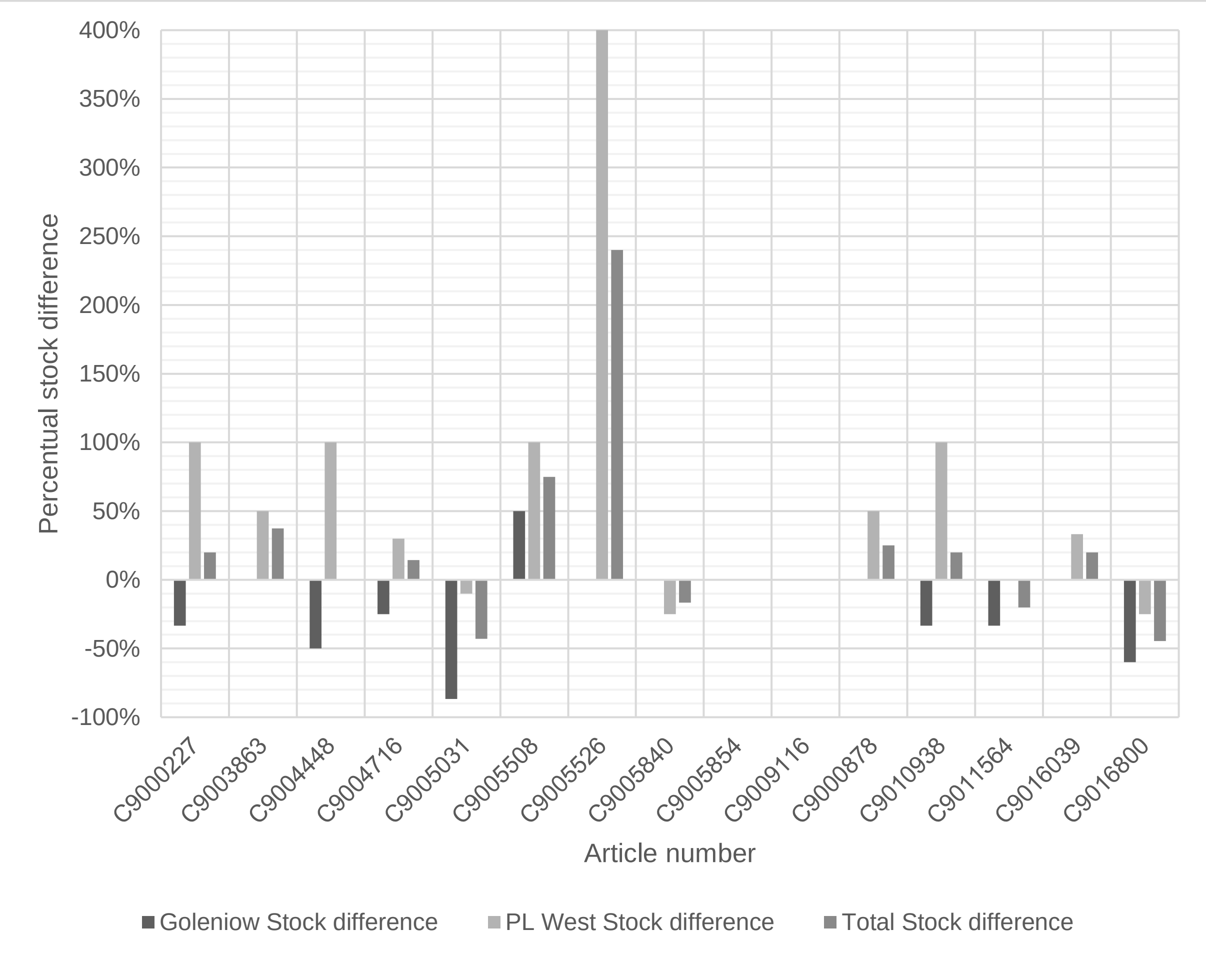

Figure 5-6: Relative differences between current and suggested order-up-to levels.

Furthermore, the total cost incurred by the suggested order-up-to-levels (at a system level, not the individual production units) are compared to the total cost incurred by the current order-up-to-levels (see Figure 5-7). It should be pointed out that the total cost incurred by the current order-up-to levels for article C9005526 is not 700 EUR. In fact, this cost is so high that it is not feasible to visualize it in the graph since the scale would make the other costs unreadable. The current costs for this article are so high because the specified safety stock level is low in relation to the demand rate and supply rate which results in high shortage costs. It is unlikely that IKEA Industry has experienced such high costs. The demand may have been met by previous overstock. Once again, it is pointed out that the total cost represents the costs that are *influenced* by the order-up-to levels at IKEA Industry during a specific time horizon. It does not represent all of the costs that are related to spare part inventory.

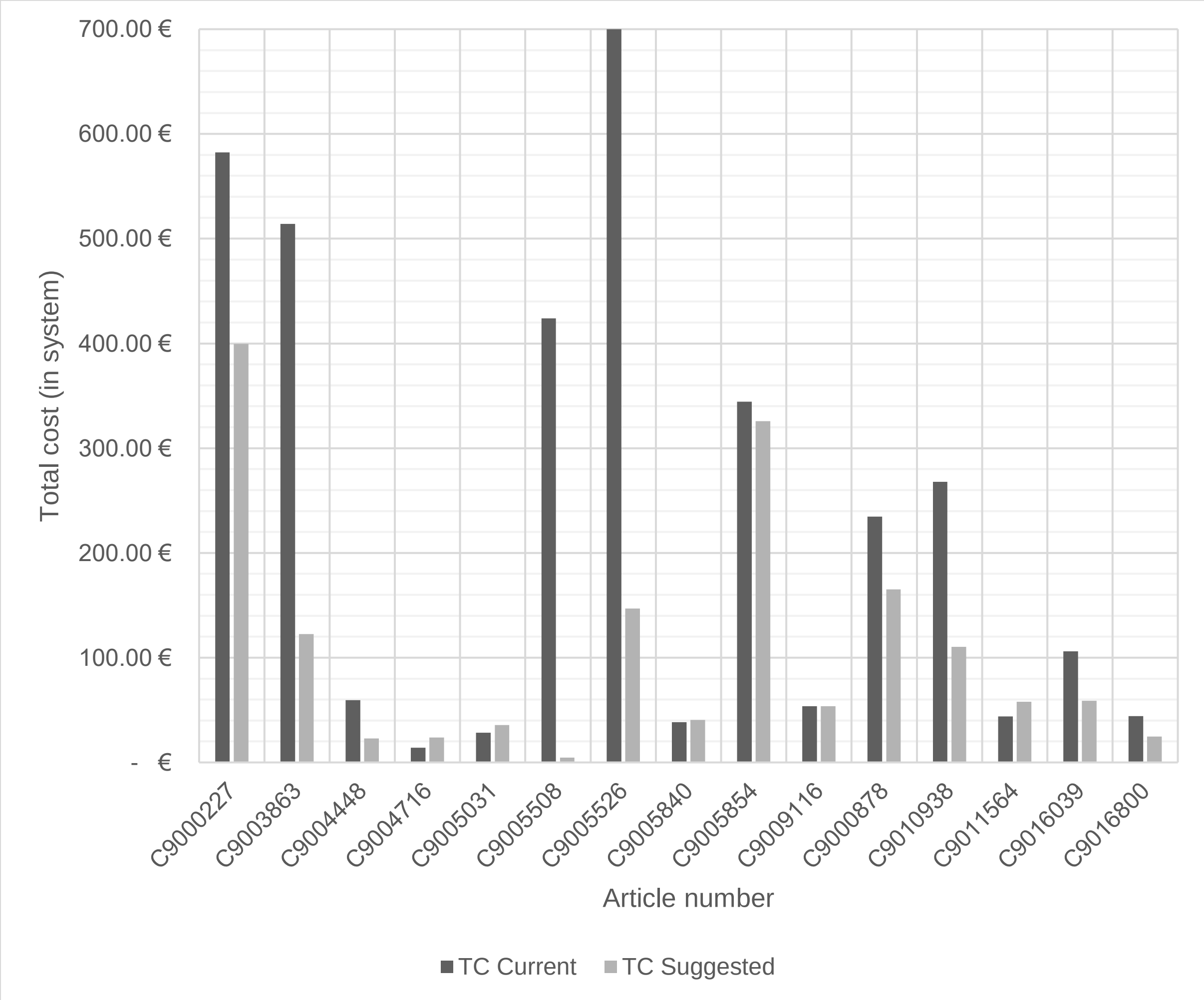

Figure 5-7: Total cost incurred by the current and suggested order-up-to levels respectively.

The relative cost differences are visualized in Figure 5-8. It can be noted that for nine of the 15 articles, the model's suggestions incur significantly lower costs than the current order-up-to levels. For one article, the suggestion incur somewhat lower costs. For one article, the order-up-to-levels were identical. For one article, the model's suggestions incur somewhat higher costs and for three articles, the model's suggestion incurs significantly higher costs. However, for two of these three articles (C9004716 and C9005031), there exists allocations of the model's suggested aggregated order-up-to-level with lower costs than the current order-up-to-levels. Those allocations result in cost decreases of 48% for both articles respectively. The reason these solutions are not found automatically and the reason the models suggestion incurs higher costs for C9011564 are discussed in chapter 6.1.4. The average cost saving per article was 28% (125 EUR).

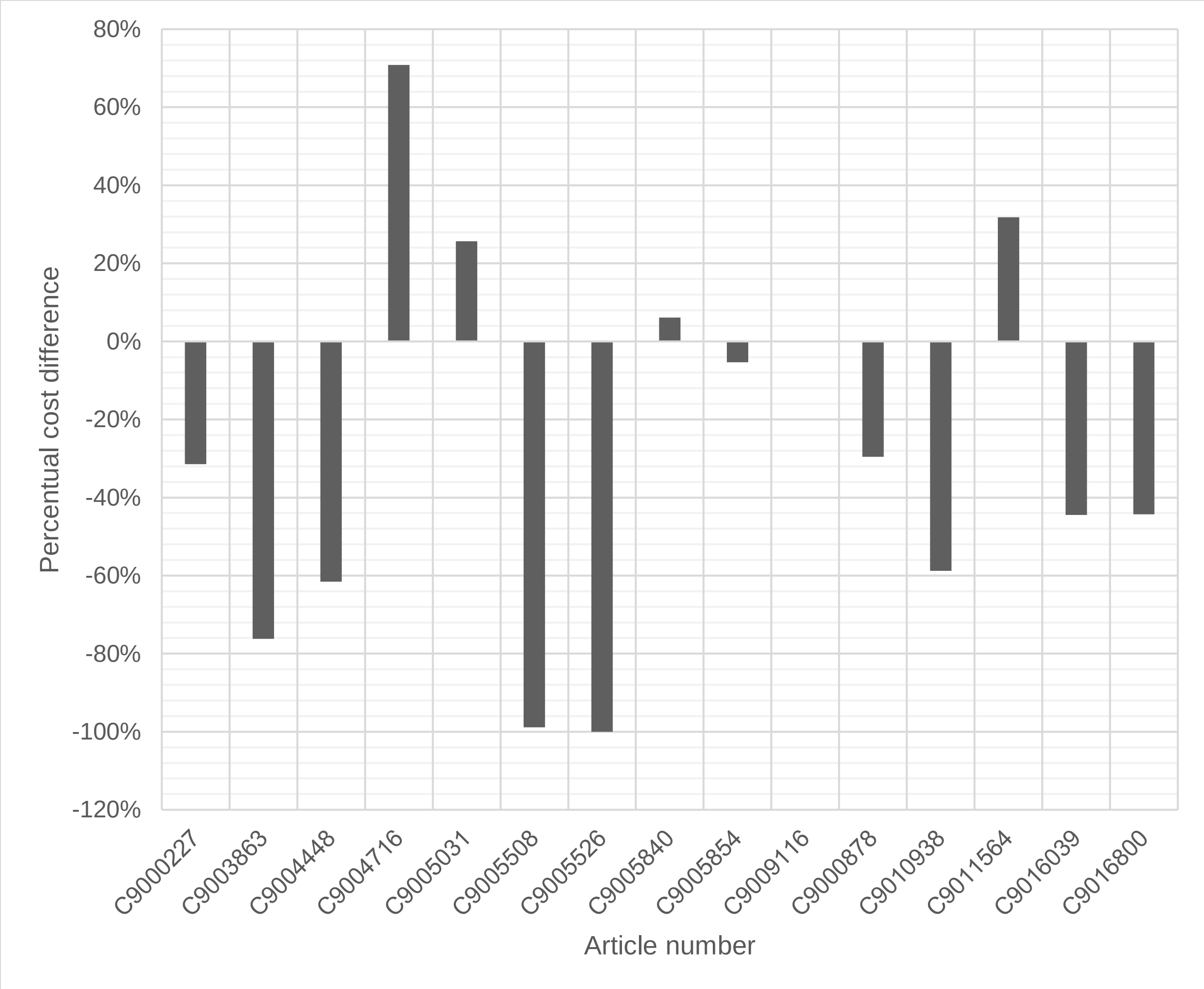

Figure 5-8: Relative differences between the total cost incurred by the current and suggested order-up-to levels.

5.1.4. Sensitivity analysis

The output data of a model is only as good as the input data. There are uncertainties tied to all of the input parameters of the model. Therefore, tests are carried out with one of the selected articles (C9000227) as the basis. It does not matter which article is chosen for the sensitivity analysis; C9000227 is chosen randomly. Each one of the uncertain parameters are tested individually while keeping the other parameters constant to see how greatly they affect the order-up-to levels and the incurred total cost. The original inputs of C9000227 are listed in Table 5-2.

Table 5-2: Original input values for article C9000227 subject to sensitivity analysis.

Parameter	Value
Supply lead-time rate per day	0.0399
Demand rate per day Goleniow	0.0059
Demand rate per day Poland West	0.0237
Holding cost per year and unit	69.89 EUR (20% of goods value)
Shortage cost per day and unit	3,381 EUR
Transshipment cost per transshipment	554 EUR

These input parameters result in order-up-to levels of 2 in Goleniow and 4 in Poland West in the model.

Supply lead-time

Naturally, the lead-time can be altered for either Goleniow or PL West but since a weighted average lead-time is used, whether the lead-time is increased for Goleniow or PL West does not influence the order-up-to level distribution among the production units. Therefore, it is only interesting to see how the average weighted supply rate per day influences the order-up-to levels and total cost which is visualized in Figure 5-9.

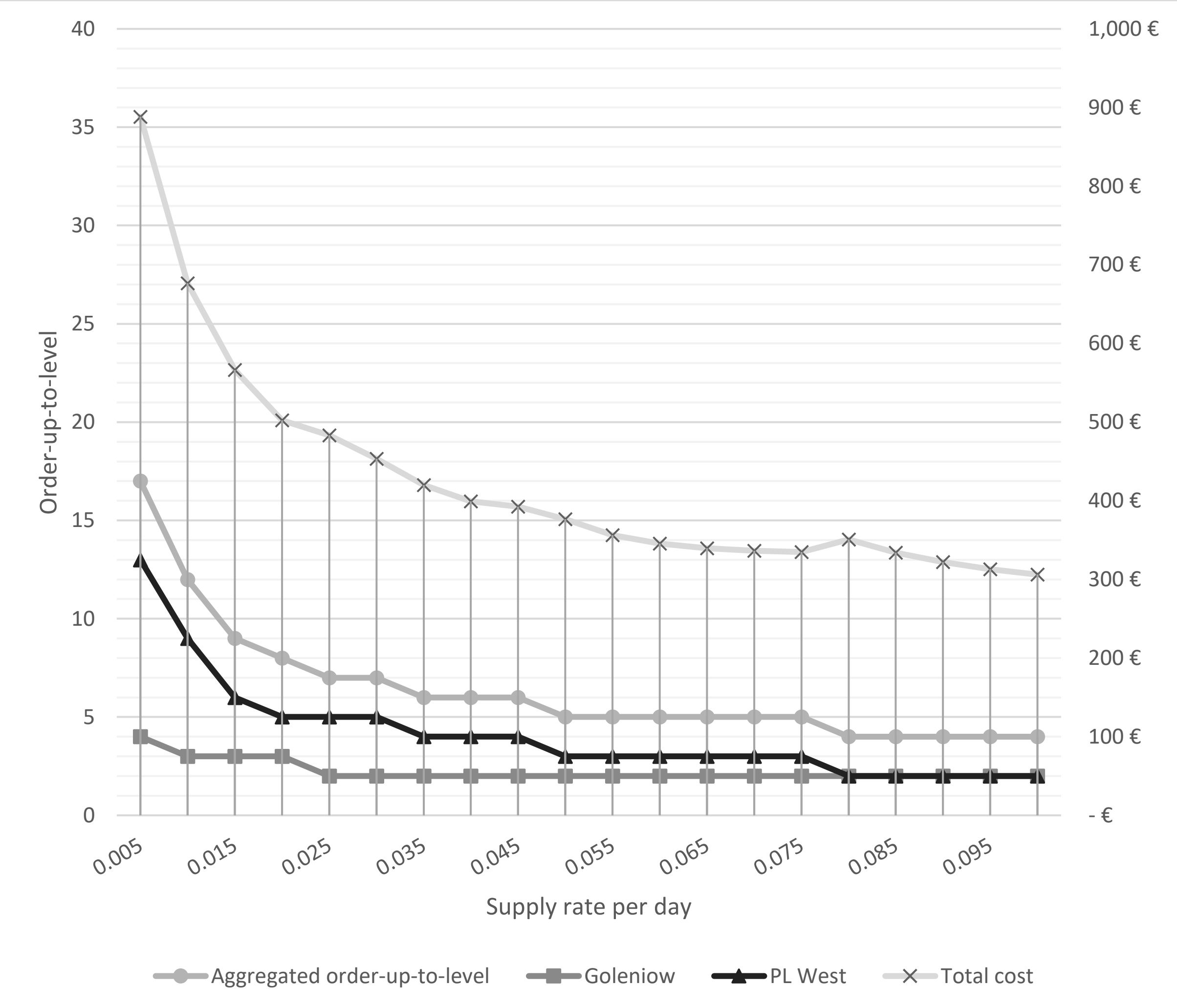

Figure 5-9: The influence the supply rate per day has on the order-up-to levels and total cost.

Demand rate

In this analysis, it is interesting to see both how the results are affected by the aggregated demand rate and the production units individually. Therefore, three tests are made: (1) changing the demand rate of Goleniow (2) changing the demand rate of PL West and (3) changing the demand rate of Goleniow and PL West simultaneously. Since the supply lead-time is calculated as a weighted average w.r.t. to demand, the supply lead-time will not remain constant when changing the demand rate for only one of the production units. However, when changing both of the demand rates simultaneously, the weights will remain constant which means that the supply lead-time will remain constant as well. When changing the demand rates for the production units individually, fixed intervals are tested. When changing the demand rates for both production units simultaneously, percentages of the original demand rates in Table 5-2 are tested. For example, in the first test, the demand rates are 10% of the original demand rates in Table 5-2. The next test is 20% and so on. Figure 5-10 visualizes the impact of changing the demand rate of Goleniow, Figure 5-11 visualizes the impact of changing the demand rate of Poland West and Figure 5-12 visualizes the impact of changing the demand rate of both production units simultaneously.

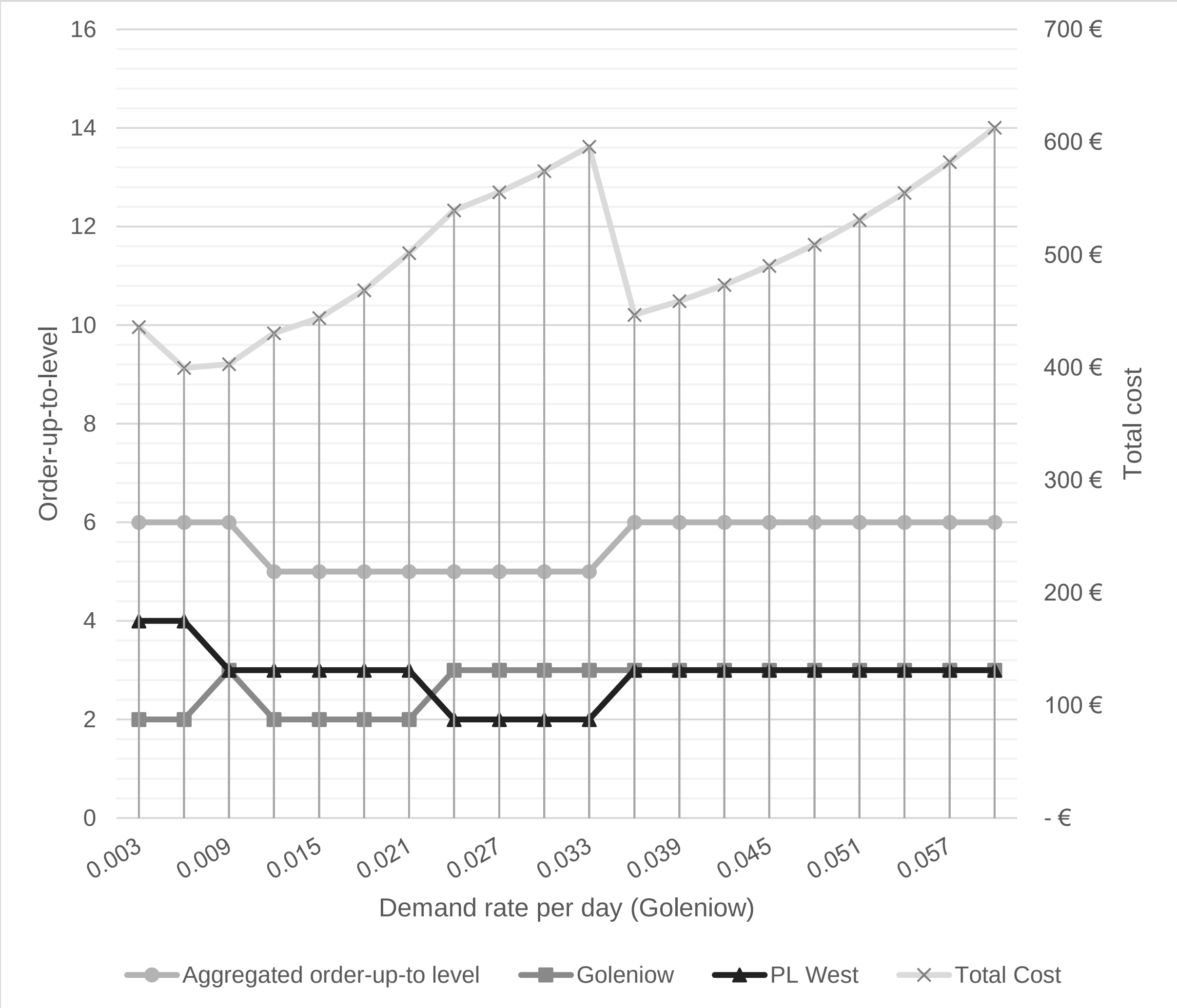

Figure 5-10: The influence Goleniow's demand rate per day has on the order-up-to levels and total cost.

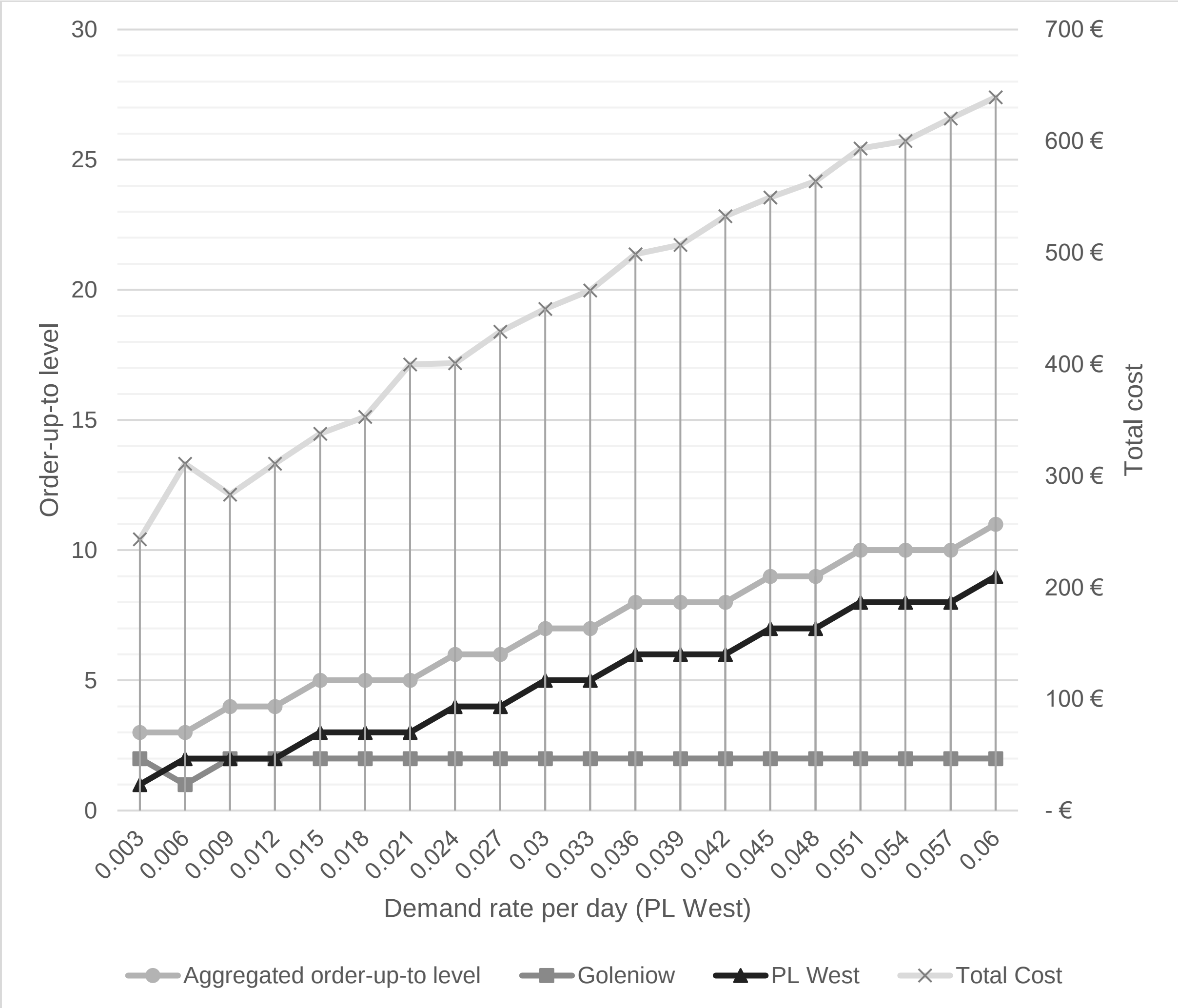

Figure 5-11: The influence PL West's demand rate per day has on the order-up-to levels and total cost.

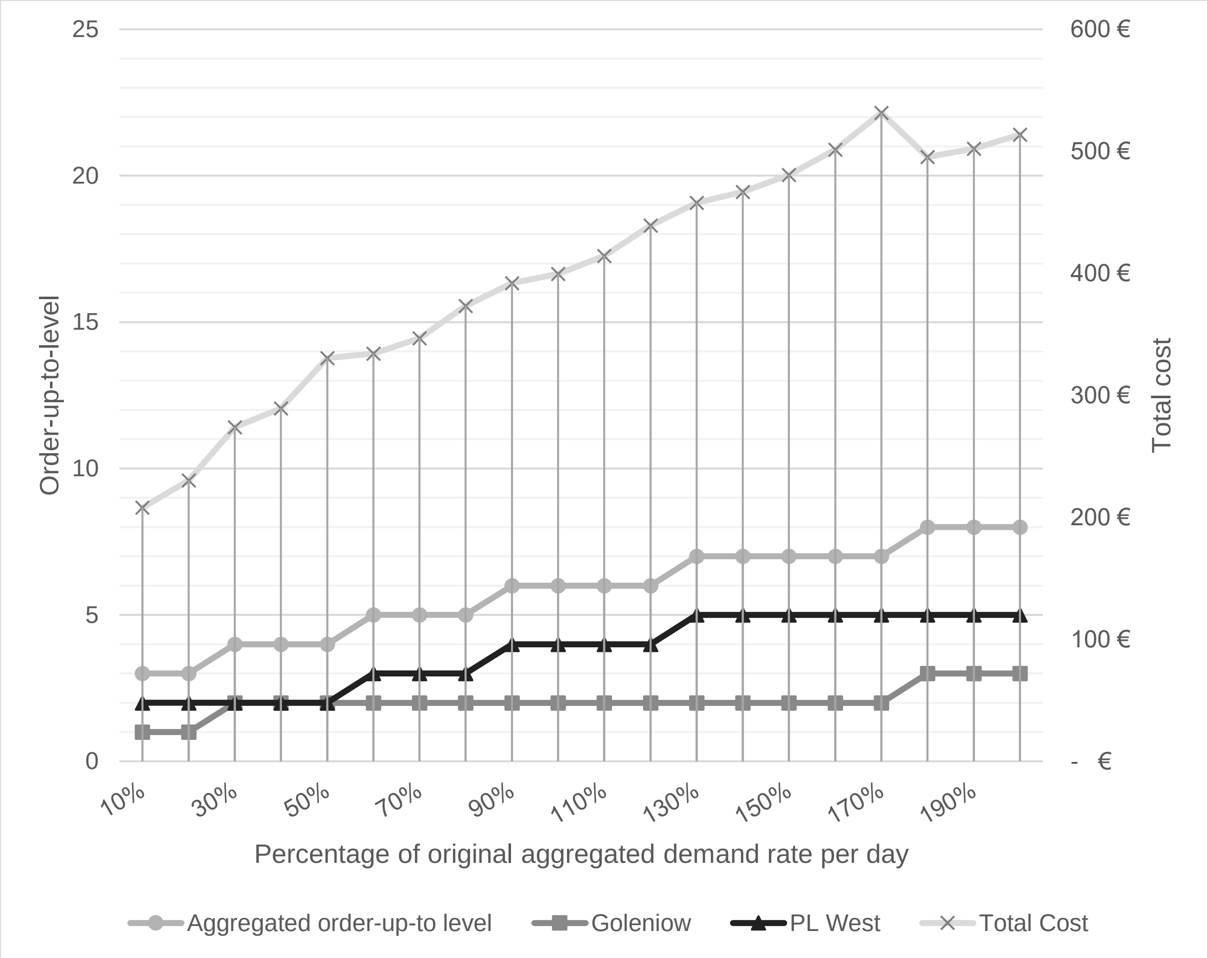

Figure 5-12: The influence the aggregated demand rate per day has on the order-up-to levels and total cost.

Holding cost

There are two factors that affect the holding cost: the good's value and the percentage of the good's value that is used to estimate the holding cost. The uncertainty of the percentage is high while the uncertainty of the goods value is fairly low. However, it is still interesting to see how the goods value impacts the order-up-to levels since there may be articles outside of this thesis that have substantially higher goods values. Therefore, two different sensitivity analyses are set up for the holding cost. One of them uses the goods value for C9000227 specified in Table 5-2. In this test, the percentage used for calculating the holding cost varies between 10% and 30% with 1%-intervals. The lower and upper boundaries are based on encapsulating the different figures that have surfaced during interviews and searching internal documents at IKEA Industry. The results from this test are visualized in Figure 5-13. Note that all holding cost percentages within 10% and 30% results in the same order-up-to-levels. In order to get the aggregated order-up-to level to decrease from six to five, a holding cost percentage of 45% is needed. No percentage will result in an aggregated order-up-to level that is lower than five. This is different for different articles and depends on the goods value.

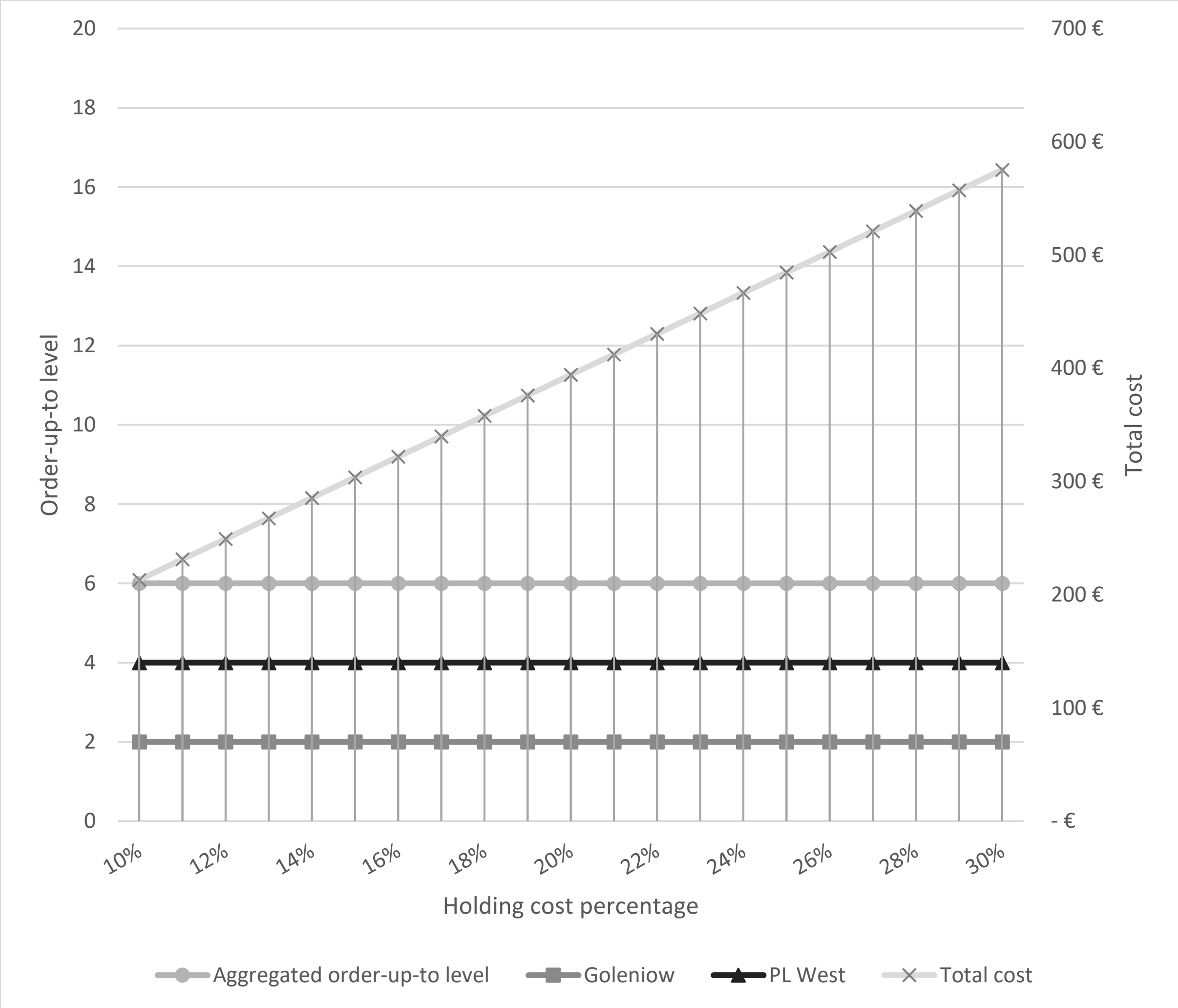

Figure 5-13: The influence the holding cost percentage has on the order-up-to levels and total cost.

The other sensitivity analysis tests different absolute holding cost values and is visualized in Figure 5-14. The aggregated order-up-to level decreased to four when the holding cost was more than 1,300 EUR. It dropped to three if the holding cost was more than 8,200 EUR and it dropped down to two when the holding cost was more than 50,500 EUR. Higher holding cost values than that were not tested since it is unlikely that IKEA Industry has a significant amount of spare part with such high holding costs.

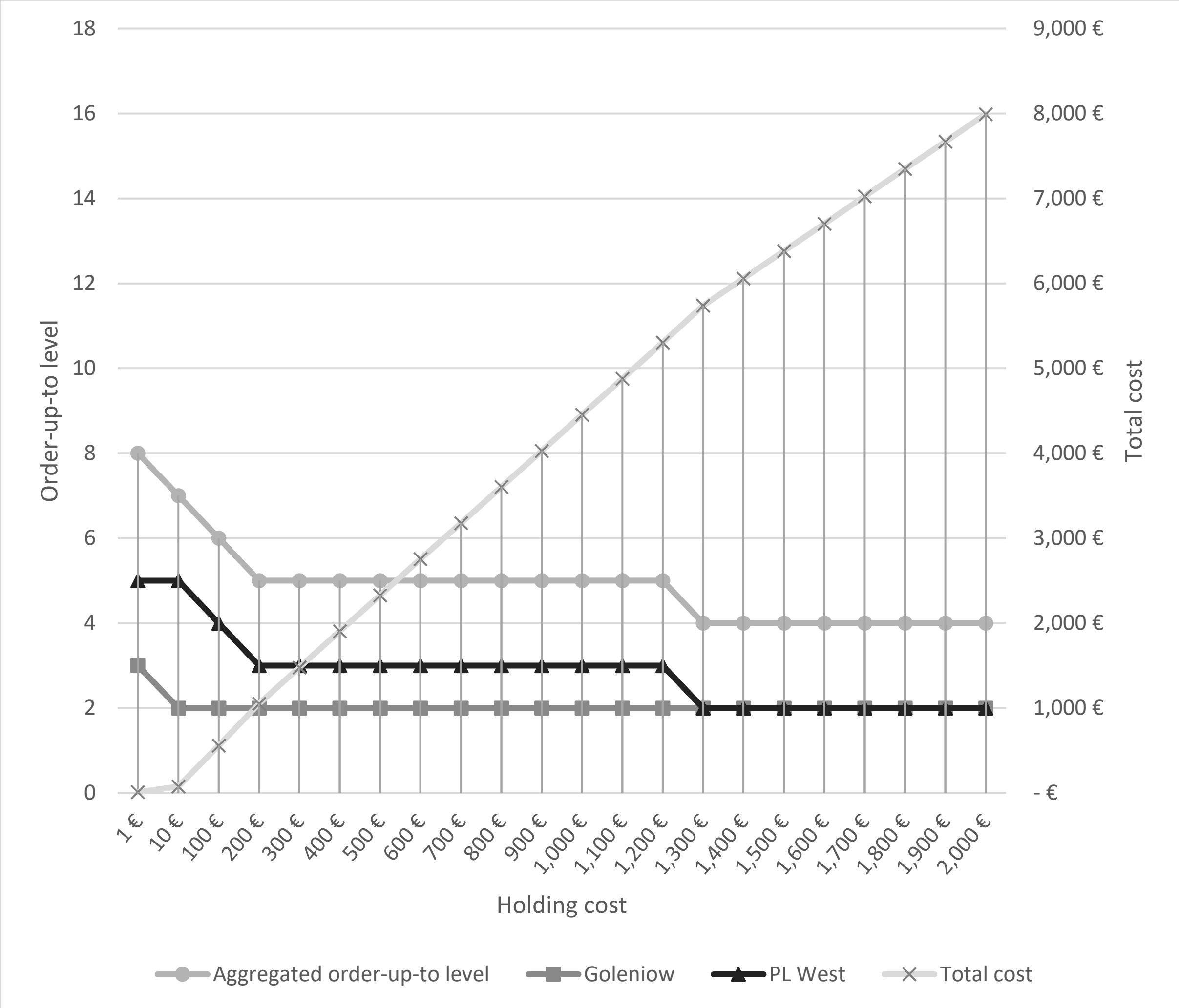

Figure 5-14: The influence the holding cost has on the order-up-to levels and total cost.

Shortage cost

The shortage cost influences two of the three cost parameters (shortage cost and transshipment cost). The results of the sensitivity analysis is visualized in Figure 5-15. Once the shortage cost is more than 2,000 EUR, the model proposes an order-up-to level that maximizes the service level ($SERV_2$ > 99%). In other words, it does not matter if the shortage cost is 2,000 EUR or 2,000,000 EUR, the order-up-to level will be six for this article.

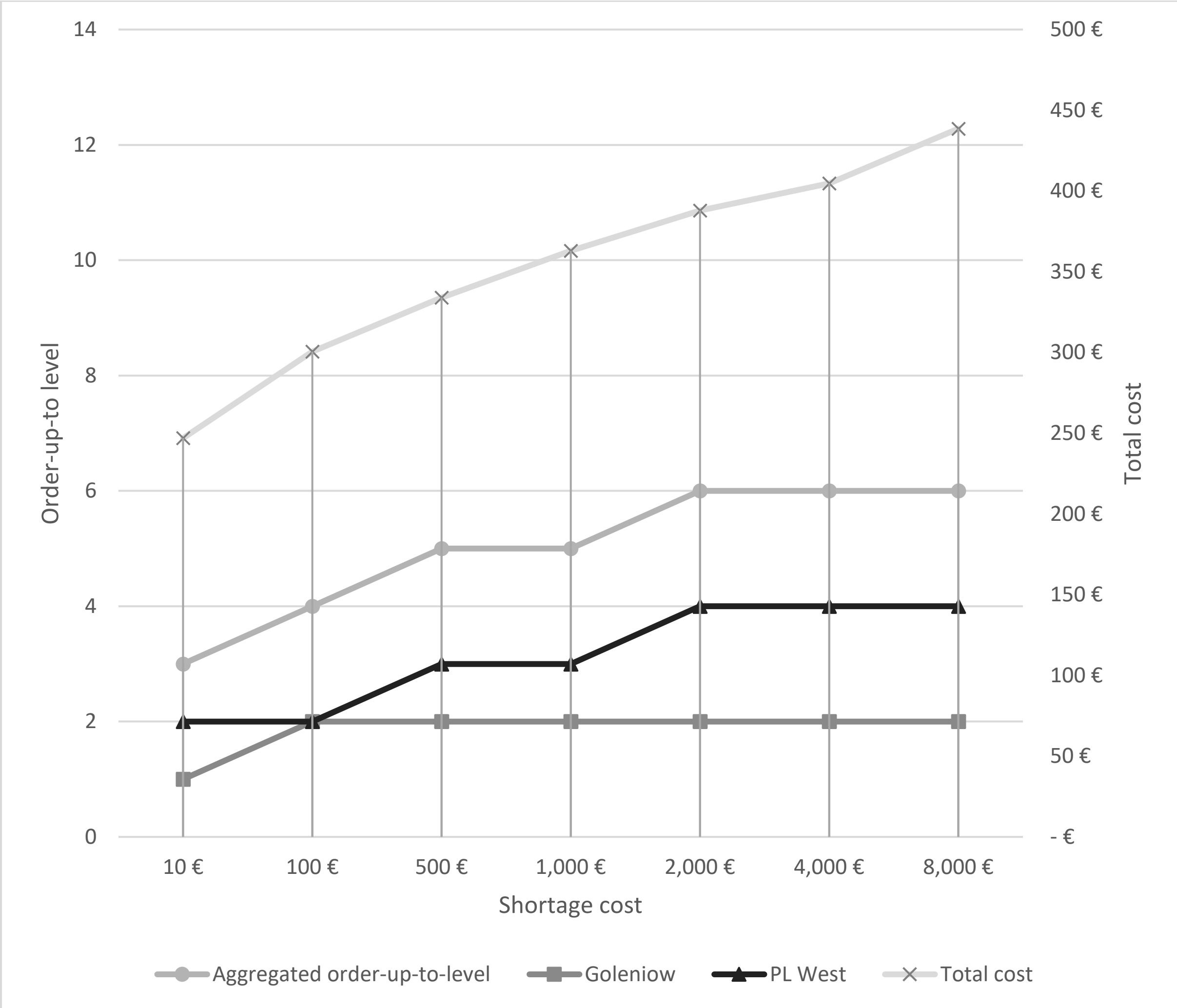

Figure 5-15: The influence the shortage cost has on the order-up-to levels and total cost.

Transshipment cost

The last parameter to be tested in the sensitivity analyses is the transshipment cost which is tested with absolute values. The results are visualized in Figure 5-16. Since the aggregated order-up-to level is only dependent on the holding cost and the shortage cost, it will be constantly six. Given the heuristic for generating the perturbations of order-up-to level allocations (see chapter 5.1.2.), only three different perturbations are tested in the transshipment cost sensitivity analysis: (1) one in Goleniow and five in PL West, (2) two in Goleniow and four in PL West, (3) zero in Goleniow and six in PL West. The first allocation is only chosen when the transshipment cost is 1 EUR. For all other transshipment costs, the second allocation is chosen. The third allocation is never chosen. This is discussed in chapter 6.1.4.

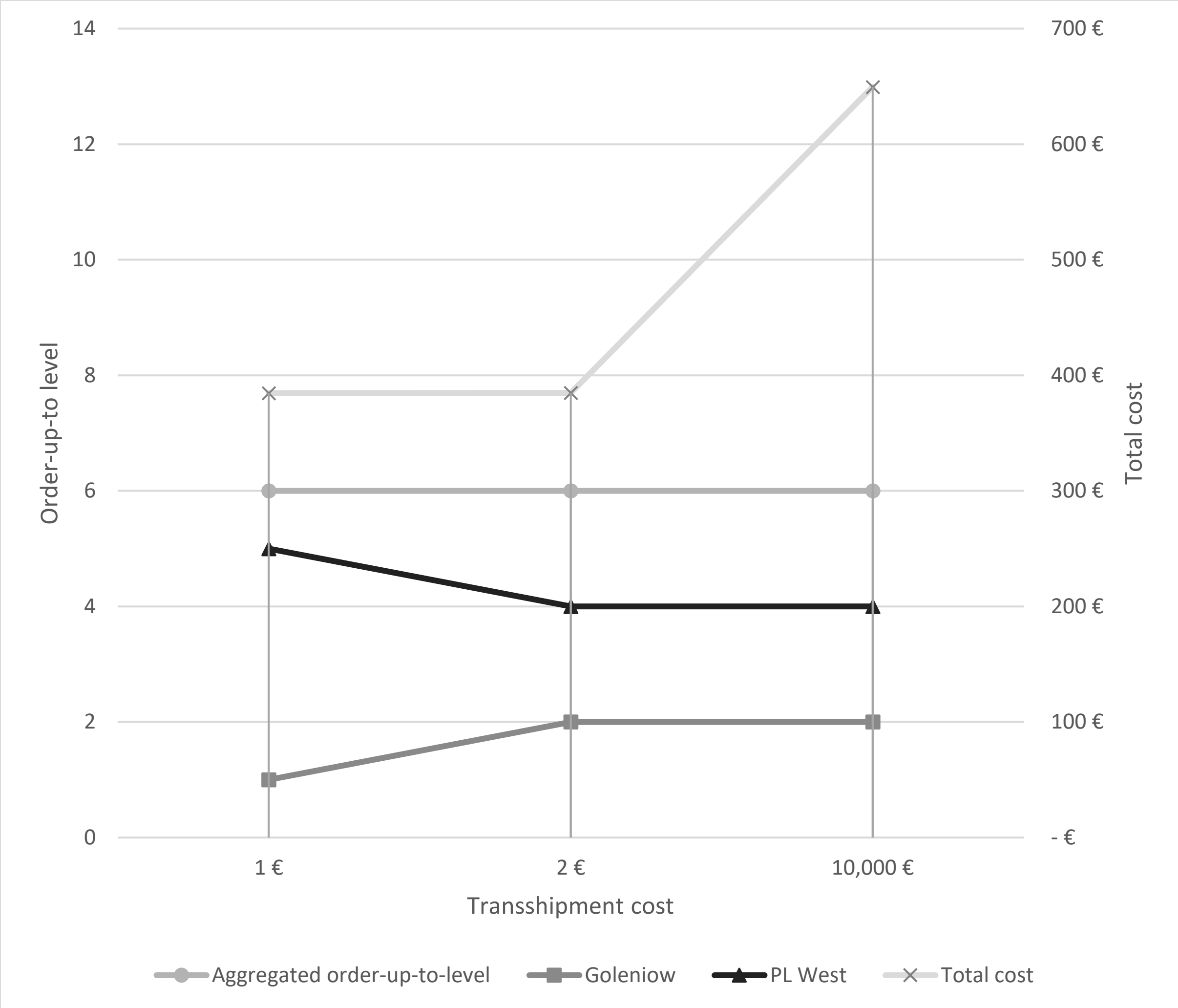

Figure 5-16: The influence the transshipment cost has on the order-up-to levels and total cost.

5.2. Performance measurement

Interviews with employees at IKEA, together with the studying of internal documentation regarding performance measurement, have showed that the current performance measurement at IKEA is somewhat lacking. This specifically applies to the measurement of spare part performance. In this subchapter, the possibility of implementing a spare parts performance measurement framework will be investigated. This will be done by comparing similarities between production units to see if it is plausible to implement a framework company wide and by identifying what benefits can be gained.

5.2.1. Similarities between production units

The collection of empirical data has showed that all production units which were studied choose to measure aspects of production performance. The measurements are connected to the performance of the machines, e.g. by looking at MTBF and MTTR in Lubawa and Poland West. Wielbark monitors the fraction of time machines are up and running, which is referred to as availability. In Goleniow, failure rates for the machines are monitored together with the time spent on corrective and preventive maintenance. The failure rates are directly related to availability, which means that Goleniow also measures availability. Table 5-3 below summarizes the main KPIs used by the different production units. Overall, it can be concluded that neither of the production units is measuring performance connected to spare parts management in a greater extent. However, performance measurement for production and maintenance is utilized.

Table 5-3: KPIs at the production units

Site	Machine KPIs	Spare part KPIs	Description
Lubawa	MTTR, MTBF, availability, PME, OEE	None	Lubawa has not confirmed the usage of any spare part KPIs
Wielbark	Availability, MTTR, MTBF, OEE	Stock value, rotation rate	
Goleniow	Availability, downtime per breakdown, OEE	None	Goleniow has not confirmed the usage of any spare part KPIs
Poland West	MTTR, MTBF, availability, OEE	None	Poland West has not confirmed the usage of any spare part KPIs

5.2.2. Performance measurement at IKEA vs. in academia

When comparing how IKEA is measuring their performance with how academia suggests that it should be done, there are a couple of differences. According to the framework developed by Muchiri & Pintelon (2008) to calculate the OEE, there are six losses a company can experience and hence measure. IKEAs performance measurement within maintenance is mainly connected to two of those losses which are equipment failure and idling and minor stoppage, which they monitor by looking at availability and breakdowns. IKEAs measurement of equipment failure is however not connected to the spare parts, but the machines themselves. The production units in Orla and Wielbark have made attempts at categorizing spare parts based on criticality, demand and lead time but these efforts are in their infant stage and there is no centralized performance measurement framework currently utilized. A framework which potentially could be used is presented by Jouni *et al* (2011).

The most significant match between IKEA and academia is within availability performance measurement. All of the production units which have been studied (Lubawa, Wielbark, Goleniow and Poland West) work with measuring availability of their machines. Some of the production units choose different approaches (see table 5-3), but the common denominator is that the uptime of the machines is monitored to calculate the availability. In order to understand the differences between how IKEA utilizes KPIs compared with how academia suggests it should be done, a comparison is done between the two. Table 5-4 shows a comparison between KPIs used at IKEA and KPIs presented in literature.

Table 5-4: Comparison between KPIs at IKEA and in academia

KPI	IKEA	Academia
Quality rate	IKEA monitors the number of failed products but has not confirmed to calculate quality rate.	In academia, the quality rate is used to later calculate the OEE.
Product rate	Not confirmed to be measured by IKEA.	In academia, the product rate is used to later calculate the OEE.
Availability	IKEA monitors production availability, not spare part availability	Several ways of monitoring availability with the main one being machine availability for OEE and spare parts availability for the framework developed by Jouni *et al* (2011).
OEE	IKEA works with OEE	Academia suggests that OEE is a powerful performance measurement tool
MTTR	Monitored by IKEA.	Used to calculate availability.
MTBF	Monitored by IKEA.	Used to calculate availability.

Quality rate is measured indirectly at IKEA since the number of failed products is measured, in academia the quality rate is used as a component in determining the OEE. The product rate is not confirmed to be used by IKEA. However, availability is measured by looking at the uptime of the production. In academia, all three components (quality rate, product rate, availability) are used to determine the OEE. IKEA uses a different approach to calculate OEE, but the definition and usage of it is outside of the scope for this thesis. The two KPIs MTTR and MTBF have identical definitions at IKEA and in academia

5.2.3. Benefits for implementing spare parts performance measurement

Literature which discusses performance measurement for spare part inventories suggest that there is significant advantage to gain from utilizing and monitoring KPIs for spare parts inventories. The performance measurement framework presented by Jouni *et al* (2011) shows how a company can find inefficiencies in their spare part inventory handling by applying the suggested framework. One benefit gained from utilizing a standardized approach to spare part performance measurement is that management efforts can be focused more efficiently (Jouni *et al*, 2011). This can ultimately mean that management is able to focus their efforts on minimizing or mitigating the causes for a disturbance before they become critical. Without a standardized approach to enable a company to recognize failing parts in their production or operations, it is almost unavoidable to end up in a prolonged breakdown. Since the framework created by Jouni *et al* (2011) divides spare parts into groups, management is able to identify underperforming groups by comparing the same KPI between the different groups.

Jouni *et al* (2011) continue explaining how the overall performance in the company can be increased by conducting internal process improvement. The case study performed in their article showed how a company increased service levels and overall performance by implementing the framework developed by Jouni *et al* (2011). It is reasonable to assume that IKEA could gain similar benefits from implementing a spare parts performance measurement framework, increasing service levels and lowering costs. The main benefits for a framework implementation are summarized in table 5-5.

Table 5-5: Benefits for implementing a performance measurement framework

Benefit	Explanation
Better management effort focus	By identifying what group of spare parts is underperforming, management can focus their efforts more accurately and efficiently.
Higher performance levels	The study conducted by Jouni *et al* (2011) has showed that usage of the framework can result in higher overall performance levels in the company.
Categorization benefits	Implementation of a framework requires a thorough spare part categorization effort, once this is done it can be utilized in other projects as well.

6. CONCLUSIONS AND RECOMMENDATIONS

This is the final part of the thesis and is aimed to draw conclusions from the analysis and its results in order to answer the research questions. Moreover, the chapter should also give propositions to how IKEA Industry should use these results and conclusions going forward. Finally, suggestions for further research about aspects that have been outside of the thesis' scope are directed both at IKEA Industry and academia.

6.1. Interpreting the safety stock model output

The initial hypothesis was that the safety stock levels for spare parts were too high, mainly since the possibility of transshipping items was not considered. This perception was also shared by both management at IKEA Industry and part of the maintenance staff. Additional contributing factors were mentioned e.g. the fact that intuition and experience is used to set the levels rather than analytical methods. Scenarios other than machine breakdowns have also traditionally been taken into consideration when setting the safety stock levels which realistically should result in higher safety stock levels than the model which does not consider such scenarios. Despite of this, for the selected 15 articles, there does not seem to be any significant safety stock level reductions to be made. If anything, the model seems to recommend an overall increase of the safety stock levels. It should be noted that the selection of spare parts for the results is very limited and does not represent the entire spare parts catalogue. It is therefore impossible to draw any conclusions for the *overall* spare part safety stock situation. Such conclusion can only been drawn once the entire spare parts catalogue is visible (all the articles must be harmonized) and categorized in such a way that all groups of spare parts can be tested. Despite of this, it is important to understand the results for the selected articles and why the model comes up with them. In order to do that, the dynamics between the parameters and their uncertainties must be explained and put into the context of the model. It is also appropriate to discuss the validity of the results and the limitations of the model.

6.1.1. Parameter dynamics

The initially unintuitive result can partly be explained by the imbalance between the holding cost and the shortage- and transshipment costs. The cost of keeping a few extra articles in stock is simply negligible compared to the cost of not having a spare part in stock when there is a breakdown, regardless of how the missing spare part is sourced. The article with the highest holding cost tested in this thesis had an annual holding cost which is only 2% of the daily shortage cost or 50% of the hourly shortage cost. In other words, if the transshipment lead-time is more than 30 minutes, the cost of the down-time alone is higher than just keeping an extra unit in stock per year. That does not include the cost of the actual shipment. To understand how this dynamic influences the model's decision, the model is broken down to three parts. In the first part, the model determines the aggregated safety stock level. The only cost parameters that are considered are the holding cost and the shortage cost. Since the shortage cost is so high compared to the holding cost, the model will maximize the system's availability (ensuring $SERV_2$ = 99-100%) which will result in a relatively high aggregated safety stock level. The cost parameters do not influence the second part of the model which determines which stock allocations to investigate. In the third part, since the transshipment cost is so high compared to the holding cost, the model will choose the allocation which results in the fewest number of transshipments per year.

The cost parameters are not the only factors that influence the safety stock levels. The relation between the supply rate and the demand rate is also of interest. Given the cost parameter dynamics, the objective of the first part of the model is in practice to maximize the availability. If the supply rate is high in relation to the demand rate, the safety stock level needed to achieve the high availability will be lower than it would be if the supply rate is low in relation to the demand rate. This is a rather intuitive behavior. If the supply lead-time approaches zero, the supply rate approaches infinity (since there is an inverse relation between the two). If the supply rate is infinite (zero lead-time), there is no need for keeping safety stock at all. If the supply rate is low (long lead-time), there is a need for high safety stocks. The way of determining if a supply rate is low or high is to compare it to the demand rate. The behavior is also confirmed by Figure 5-9 which demonstrates a negative correlation between the supply rate and the safety stock levels and Figure 5-11 which demonstrates a positive correlation between the demand rate and the safety stock levels.

The results of this raises the question of whether or not articles with a current safety stock of zero should also have been tested. The model could have helped identifying articles that currently have no safety stock, but ideally should. When the articles have been identified, it should be investigated whether or not IKEA Industry are experiencing unnecessary down-time as a result of not keeping any safety stock of the article.

6.1.2. Parameter uncertainties

As for the uncertainty of the holding cost, the percentage used for estimating the cost does not matter much if it is between 10% and 30% since the goods value is low compared to the shortage cost. This is likely the case for many of the spare parts. Even though there might be some articles with more significant holding costs, the results from the sensitivity analysis showed that very high holding costs are needed in order to affect the safety stock level recommendations (see Figure 5-13). There is not a high uncertainty tied to the goods value since it is based on the average purchase price of the spare part. In other words, the uncertainties tied to the holding cost is assumed to be relatively low.

Regarding the uncertainty of the shortage cost, it is probably not realistic that every article has the same shortage cost. Investigating the cost of not having a spare part when it is needed because of a breakdown is in and of itself a large project that falls outside of this project’s scope. As of the current situation, the cost of down-time has only been estimated for when the entire production is standing still. Furthermore, it has only been estimated at one production unit. Since down-time due to machine breakdowns is important from a maintenance perspective (not only in this thesis) and a production perspective, there should be a way to relatively accurately describe the cost of one machine standing still. Indeed, this will prove more difficult for divisions Flat line and Solid Wood which have parallel production flows. From a maintenance perspective, it would also be interesting to see if it matters which machine a given spare part breaks down in; are the shortage costs different if C9000227 breaks in one machine or another? Such complexity would probably be difficult to add to a stock-decision model but it could raise relevant discussion about the model’s validity. Even though there is a non-negligible uncertainty related to the shortage cost, the shortage cost is likely high compared to the holding cost of most articles which contributes to the low sensitivity of the holding cost.

When it comes to the transshipment cost, there are two different uncertainties. One of them is related to the cost of down-time during the transshipment lead-time and the other one is related to the cost of the actual transshipment. The down-time cost has already been discussed and the lead-time is the sum of the shipment time and picking and packing time. The shipment time is fairly realistic since it is based on distance and average traffic. The picking and packing times are based on estimations from the purchasers. Even so, since the shortage costs are so high, small deviations in the transshipment lead-time will greatly impact the transshipment cost. A more appropriate way to estimate the transshipment lead-time would be to record the time for a number of transshipments. Unfortunately, time records of previous transshipments could not be found. As for the costs related to the actual transshipments, these are small compared to the shortage cost during the transshipment. In other words, the uncertainties tied to the transshipment costs are mainly related to the shortage cost and the transshipment lead-time. Similarly to the shortage cost, even when accounting for the uncertainties of the transshipment cost, the transshipment cost is likely to be large in comparison to the holding cost of most articles.

For both the supply rate and the demand rate, the uncertainties are relatively high. The supply rate is based merely on the agreed upon lead-time values found in M3. A better way of determining the supply rate would have been to observe actual lead-times and estimating the values based on that. Due to the limited transaction history of the articles, there would still be uncertainty to such estimations, but it would be more representative of the reality. The demand rate was estimated with the help of maintenance staff. The estimations were based on the number of breakdowns that had occurred the last three years for each article. This parameter also has the limitation of having a limited set of historical data.

6.1.3. Validity of the results

To fully trust the results requires some form of validation of how the model works. Ideally, a comparison with simulation results would be done. Time constraints did not allow for the development of such a simulation model. Another means of validation would be to compare results with the scientific article of which the model is based; in this case, Wong *et al* (2005b). Wong *et al* (2005b) validate their results against a simulation model and other more complicated analytical models which means that validating the results of this thesis' model with Wong *et al* (2005b) would indirectly validate the model. The differences between this thesis' model and Wong *et al* (2005b) is the sourcing rule (random vs nearest neighbor) and the number of production units (bases) to include. The first two parts of the model have been verified to output the exact same results as Wong *et* al (2005b). However, the computational examples in Wong *et al* (2005b) include bases with equal distances between some of the bases. They do not specify which sourcing rule is used in those cases which hinders the replication of their results in the third part where the sourcing rule matters. The model still shows the same patterns as the reference (e.g. bases that are further away receives fewer transshipments as a result of the sourcing rule), but the transshipment probabilities deviate enough that the results cannot be interpreted as a validation.

As an alternative, the validity is checked by observing how the model is behaving when altered with. An example of this was the sensitivity analysis. The model does not seem to output any unreasonable results. Given that the aggregated safety stock level is validated, only the allocation of the safety stock levels is subject for discussion. It is difficult to confirm the cause for the deviations between the model and the reference, but the hypothesis is the most likely given that it is not fully specified in the reference and assumptions had to be made. If that is the case, then the deviations neither confirm nor reject the thesis' model since a random source rule is used.

6.1.4. Limitations of the modeling technique

There are a few assumptions, techniques and limitations in the model which must be considered when interpreting the results. The sourcing rule is one of those assumptions. Perhaps the most fitting sourcing rule for IKEA Industry's context would be the nearest neighbor rule (source from the production unit that is the closest) since this would minimize the down-time cost during the transshipment. A random sourcing rule was chosen since it is much easier in the context where there are articles that only three or four out of five production units within the cluster share. Since the number of production units that are considered would not be the same for all articles, different sourcing rules would have to be programmed for every single set of production units that commonality could exist within. It is simply not realistic. If the set of all production units would be the same for all the articles, a nearest neighbor sourcing rule could be defined for that particular set to be used for all articles. In this thesis, only two production units were considered, so the sourcing rule did not matter. However, if for example Stepnica or Resko would be included, it would matter. The problem with the random sourcing rule is that it could choose to source from a production site with a higher transshipment cost. It should also be noted that if the model were to be expanded to use more than two production units, it is necessary to define different transshipment costs within the model to account for the fact that the model sources from different production units with different transshipment cost. Between Goleniow, Resko, Stepnica and Pine Sawmills, the transshipment cost is constant enough, but PL West is considerably further away and would result in at least a 1-2 hour longer transshipment lead-time.

Another limitation is the complete pooling assumption. In the first part of the model, it is assumed that if an item is in stock at one production unit, it can be transshipped to another one, no questions asked. As described in chapter 4, this is not the case at IKEA Industry at this stage. It was a necessary assumption to make in order to make the model work, but it should be kept in mind when interpreting the results. In reality, this would translate to the need of having a higher aggregate safety stock level in order to achieve a high system-service-level since maintenance managers can say no to transshipping an item.

The heuristic for generating stock allocation perturbations is flawed for a model that considers two production units. For such a model, only two additional allocation perturbations are tested in addition to the one that is proportional to the demand. This becomes an issue when one of the production units has a significantly higher demand rate than the other. To illustrate this problem, consider articles C9004716 and C9005031 in Figure 5-7 and Figure 5-8. The imbalance between the two demand rates resulted in allocations based on demand rates to be (2; 14) and (1; 19) respectively. Both of these allocations result in a fairly high number of transshipments. The model then chooses the allocation where the lowest number of transshipments occurs: (3; 13) and (2; 18). However, these allocations result in higher total costs than the current situation. By going through all possible allocations for each article given the aggregated safety stock level, the allocations (5; 11) and (5; 15) result in significantly lower total costs than the current situation. The explanation why the heuristic is flawed for this two production unit-model is partly because too few perturbations are investigated, and partly the imbalance between the demand rates and the imbalance between the holding cost and the transshipment cost. However, the heuristic is still kept because when more production units are considered, it is unrealistic to go through all possible allocation perturbations (the number of possible allocation perturbations increases exponentially).

In some cases, it is possible that the model will choose an aggregated safety stock level of which there is no allocation that will result in a lower total cost than the current situation. It should be highlighted that this is rare and only happens to one article in this thesis. The cause is likely that the first part does not consider the transshipment cost which resulted in a lower aggregated safety stock level. Because of the imbalance between the holding cost and the transshipment cost, the third part of the model showed that when the transshipment cost is considered, it is cheaper to have one more in aggregated safety stock to be able to reduce the number of transshipments.

6.2. Moving forward with the safety stock model

RQ1 was to develop a model for determining the safety stock levels, considering lateral transshipment. While the initial purpose of such a model was to be a model to be used at an operative level by spare parts planners in the organization, the contents of both chapter 4 and 5 indicate that such applications of the model might not be feasible. Factors that contribute to that conclusion include the infrastructure for lateral transshipments, data infrastructure within IKEA Industry and the complexity and usability of the model.

6.2.1. Infrastructure for lateral transshipment

In order to successfully implement the new safety stock model, IKEA needs to decide on a number of infrastructure related matters. Firstly, IKEA needs to be aware of that complete pooling is a necessary prerequisite if transshipments should be utilized. This ultimately means that every production unit should share *all* of their stock without hesitation. As it looks today, this capability is not available since the local maintenance managers decide if a part will be transshipped or not. The matter of pooling is closely related to what type of decision-making IKEA utilizes within their organization. Since the model determines the safety stock levels for all affected production units at the same time, centralized decision making is a prerequisite.

The routines for placing lateral transshipment orders are not formally standardized. A production unit simply makes a phone call and sends an email, asking for a spare part to be sent out to them from another production unit. It certainly complicates the consideration of the phenomenon in the model. An alternative could be to investigate how an option for transshipments could be implemented in the ERP. This way, the production units could easily place a transshipment order and all remaining tasks (such as looking up where the part is available, the cost and other attributes) could be handled by the implemented algorithm in the ERP. At the same time, given the low frequency of transshipments, it is hard to recommend such a costly investigation.

Another question IKEA needs to contemplate is what cost-model should be used, and who should pay for a transshipment. The process of issuing the transshipment order, picking and packing the goods generates a cost for the transshipping production unit. The question is who is going to pay this extra cost. A mark-up on the goods value and the related transportation costs is one alternative.

6.2.2. Data infrastructure at IKEA Industry

If IKEA chooses to move towards centralization of decisions, inventory control and other business functions, one vital prerequisite is standardized data among all production units. Throughout this project, data-related assumptions are made which impact the final results. This thesis highlights possible improvement areas regarding data from both an IT- maintenance and finance-perspective.

Regarding IT, one of the identified deficiencies is the fact that access to historical data for demanded spare parts and supply lead-time is limited. The majority of the historical data is stored with the old spare part numbers; no migration of this data has been made. Ultimately, this means that in order to access historical data, a conversion table between harmonized spare parts and local spare parts have to be used. As if that is not enough, the historical data that is easily available with a conversion table only goes back to three years with the older data being archived. This means, that in order to get a sample size as big as possible, assistance is needed from both maintenance- and IT-staff. Not only does that slow improvement projects like this down, but it also distorts data, as multiple people are interpreting it.

As for maintenance, the presentation of data is confusing. In order to determine whether a spare part was requested for planned maintenance or for a breakdown required that maintenance personnel went through the history manually. If inventory decisions are to be centralized, it needs to be easy to identify the type of transaction in the ERP (or QlikView). The fact that the maintenance personnel in fact were able to make the distinction means that the data exists, but it is not easily available.

As mentioned in chapter 6.1.2., the uncertainty of the financial data is too high for the model to be directly applicable. The limitation derives from a flawed infrastructure of financial data. Holding cost percentages are not available at all for indirect material and shortage costs have only been estimated crudely to a limited extent. Most of the financial data that was acquired for this thesis, was not readily available, but obtained from interviews and e-mails.

The analysis in this project focused on spare parts which were *common* between factories, since all data has not been harmonized yet it meant that a lot of spare parts which are common in the cluster were not identified. According to maintenance personnel at both sites, there should be a lot more of common spare parts than the ones identified in this master thesis. The possibility of identifying these spare parts, as well as more common spare parts between other production units, will open up as soon as IKEA has harmonized the remaining spare parts.

6.2.3. Model complexity

Even though the model makes many simplifying assumptions in order to function, it can be difficult to understand exactly how it works at a mathematical level. The optimization problem is inherently complicated since there are so many different scenarios that have to be taken into consideration. The result is a model that is easy to use, but difficult troubleshoot and develop further. In order to be used at a larger scale the model will have to be developed even further to include more production units and to be able to calculate more than one article at a time. These alterations are not as complicated as developing the proof of concept presented in this thesis. However, IKEA Industry has to consider these challenges when deciding on whether mathematical solutions should be used for complex problems. It should be pointed out that the first two parts of the model are substantially simpler than the third part and do not require extensive training to use.

6.2.4. Safety stock model recommendation

This thesis shows that IKEA lacks many aspects of the necessary prerequisites of clean data in order to implement a sophisticated method of any kind, regardless of if the purpose is to lower safety stocks or something else. This is especially true if the aim is to use the model at an operative level. The model should first and foremost be seen as an incentive for the continuation of cleaning up data and facilitating the use of it. With the correct data, the model can be a powerful tool for making stocking decisions that result in significant cost savings over time. With this in mind, the recommendations can be divided into immediate and long term actions. These are explained below and summarized in Figure 6-1.

Immediate actions

Immediate actions are not necessarily actions that take a short amount of time but are actions which IKEA could take today. Such actions includes the continuation of the harmonization project to ensure the visibility of the common articles in the ERP. The harmonization project has taken two years to reach its current state and is estimated by Master Data to take an additional four years to complete. This will show how many of the articles that are common between the production units.

In order to address the issues of lacking demand data and supply lead-time data IKEA should migrate all historical data, assign it to the harmonized article part numbers and make it easily accessible for different uses. This will be add more data points to analyze which can be used for both more accurate parameter estimation and allow for statistical verification of demand- and lead-time distributions.

Spare parts where it is not enough to only replace the broken spare part during a breakdown (see chapter 4.4.2.) have to be excluded. The maintenance personnel were able to make such distinctions in the selection process. If additional spare parts are to be tested with the model, product groups with that limitation have to be identified and excluded with the help of maintenance staff.

Regarding financial data, there should be more clearly defined estimations of all the three cost parameters used in the model. There is an official percentage used for the holding cost of direct material and there should be one for indirect material as well. Shortage costs should be investigated for more production units than Lubawa, and to a greater detail than just having the entire production standing still. Both an accurate holding cost and shortage cost have useful applications outside the scope of this thesis (e.g. batch sizes and production-related measurements). Since the cluster of production unit considered uses a freight forwarder (TNT) contractually for lateral transshipments, it should be possible to get more accurate figures for the transshipment cost that is sensitive to what type of article is being transshipped. Requests for these figures were made to Goleniow and PL West but no response was received.

Long term action 1: validate model and use full functionality

With issues regarding the data are resolved the model including all of its parts can be used in the long term to make stocking decisions. For that to be viable, the model should ideally be validated with some form of simulation model that uses the same assumptions. If the model performs to a satisfactory degree, the decision of safety stock levels would have to be centralized, while the purchasing function can remain the same as today (this thesis has not investigated whether or not purchasing should be completely centralized). The model would initially be applied to the cluster of production units defined in this thesis but other clusters could be identified as well. The time horizon for this is difficult to state now since a completely different project with the purpose of building a simulation model would have to be undertaken.

Long term action 2: use a simplified version of the model

If IKEA Industry decides that the third part of the model is too complex to maintain, it could be excluded. The model is very quick and easy to use and does not require extensive programming knowledge. The limiting factor is that the model can only determine an aggregate safety stock level and allocate it proportionally to the demand rates in the affected production units. The cost of the transshipments would not be considered in this case. It would probably not be appropriate to solely rely on an allocation based on the demand rate proportions. The most appropriate usage of a model like this would be use the first part of the model to guide the maintenance staff what the aggregated safety stock level should be. The maintenance staff would then have to jointly determine the allocation of the safety stock based on experience.

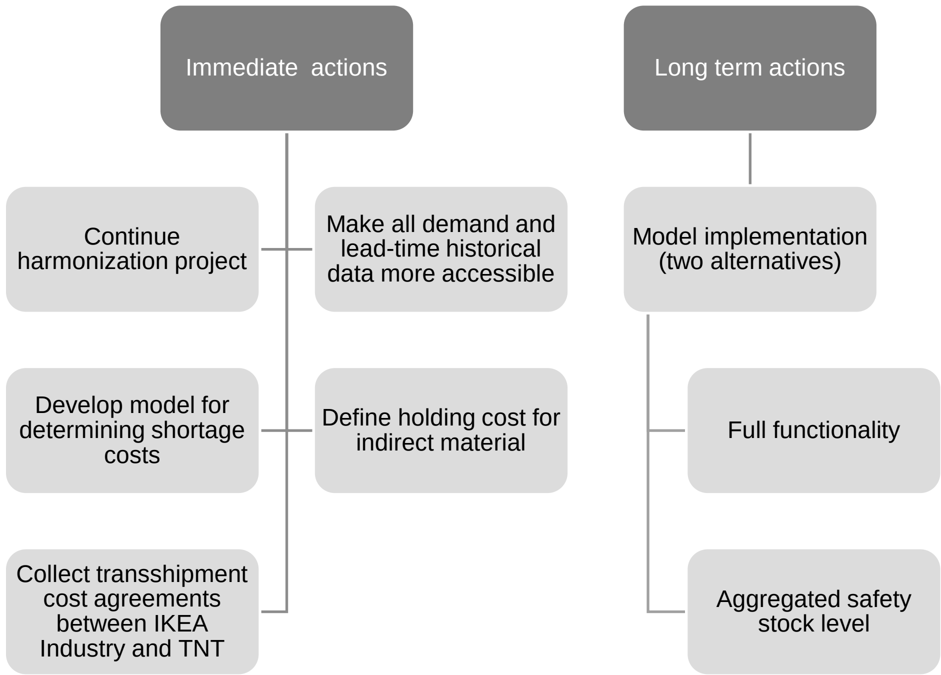

Figure 6-1: Immediate and long term actions for the safety stock model.

6.3. Interpreting performance measurement findings

This master thesis has showed that the current way of measuring performance for spare parts at IKEA is somewhat lacking. The main focus IKEA keeps within performance measurement is for the performance of maintenance, not the spare parts inventory itself, as shown in Table 5-4. IKEA utilizes OEE which is not connected to the spare parts directly, and further mapping of performance measurement outside of the spare part flow was not in the scope of this thesis. The literature review conducted showed that there are ways of measuring spare parts inventory performance and that there are several benefits to be gained. The analysis has showed that there is an opportunity for IKEA to implement a framework which divides spare parts into categories based on a number of attributes. However, the results also show that the data in its current form is not sufficient to be utilized in any sophisticated method for performance measurement. The data is there to be found, but it is not easily accessible and interpretable. For this reason, IKEA needs to work more with standardizing and cleaning data before it can be used in a performance measurement framework, reaping all the benefits presented in this report. This conclusion is similar to the conclusion drawn in 6.2.2. for RQ1, showing that the data for demand and lead time is not sufficient to be used in a sophisticated model or framework.

The impact that the implementation of a spare parts performance measurement framework would have on the manufacturing operation is not fully investigated. The reason for this is that this master thesis focuses on spare parts, and not directly on manufacturing. The main motivators for implementing the framework are presented in 5.2.3. IKEA should, if the framework is chosen to be implemented, monitor *all* KPIs used within maintenance and manufacturing (and departments which are believed to be affected) to see what areas are impacted by the implementation. This master thesis should only act as a primary investigation, showing what potential benefits could be reaped and what benefits have been gained in the case study by Jouni *et al* (2011).

Another limitation is connected to the spare part categorization part of the framework. To utilize the framework, a thorough categorization needs to be done. Because some spare parts are unique for one or a small number of production units, it will be difficult to draw any conclusions regarding the performance of those specific spare parts. These spare parts may be excluded from the framework, if their occurrence is small enough to be negligible.

6.4. Moving forward with performance measurement

Following the findings in this project, IKEA is advised to follow three main recommendations connected to RQ2 and spare part performance measurement. The recommendations are listed in Figure 6-1 with estimated time horizons and explained below. The second recommendation is complemented by an implementation plan presented in figure 6-2.

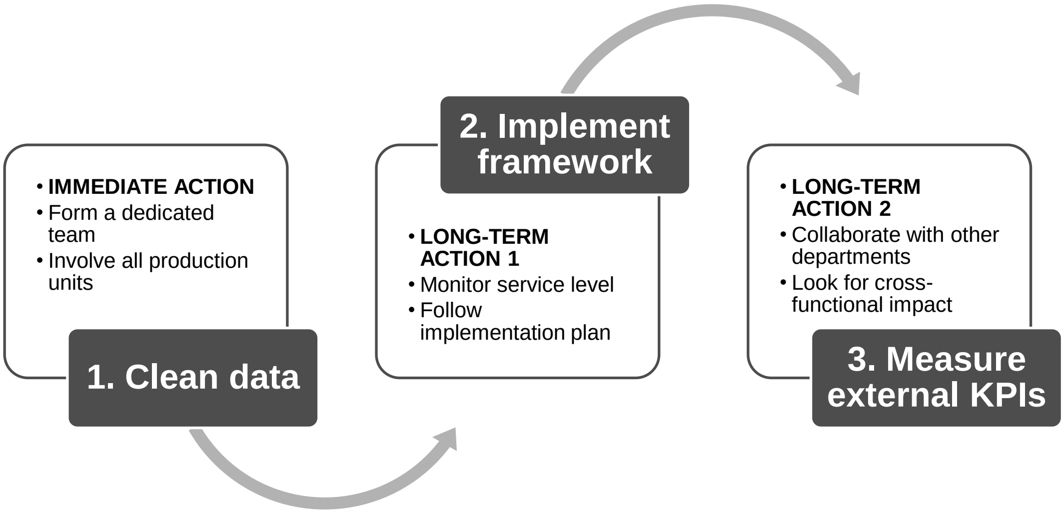

Figure 6-2: Recommendations for RQ2.

Immediate actions

IKEA should make it one of their main priorities to clean their spare parts data. In order to succeed with this, a dedicated project team should be formed to deal exclusively with the data cleaning and standardization. This way, regular maintenance employees will be able to keep focus on their current daily tasks and projects, and only act as a source of knowledge and information to the project team. Clean data is mainly considered to include the demand for the spare parts, the lead time and the material price, which is the data needed for the framework. This is a time-consuming phase since it requires companywide collaboration between production units, but at the same time it will establish the required prerequisites for a future framework implementation.

Long-term action 1: implement the spare parts performance measurement framework

Since IKEA is not currently using any structured method to monitor their spare parts inventory, and there are several benefits to gain from doing it, IKEA is recommended to implement the framework developed by Jouni *et al* (2011). By implementing the framework, IKEA will gain benefits in the form of higher performance levels and the ability to pursue other improvement initiatives made possible by an initial spare part categorization effort. The global performance measurement will also enable central management to identify issues which are common for several production units and in that way be able to focus their efforts more efficiently. Local maintenance managers will also draw benefits from the framework by being able to identify underperforming spare part categories and making efforts to mitigate or resolve them.

To implement the framework by Jouni *et al* (2011), IKEA needs to categorize the spare parts, they need a KPI to monitor and they need to implement the system in all production units. To be able to do this, IKEA could follow the four-phase implementation plan presented in Figure 6-3:

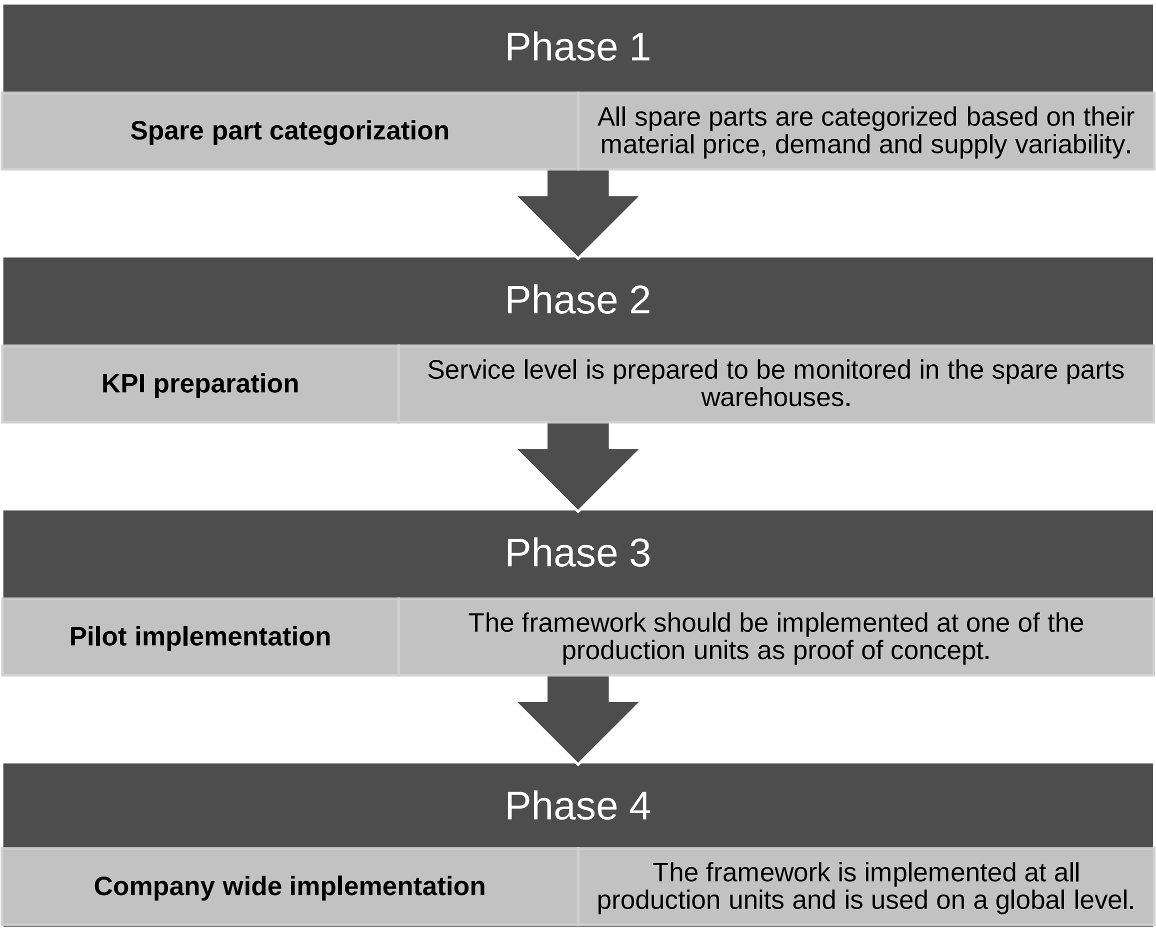

Figure 6-3: Four-phase implementation plan for performance measurement.

In the first phase, all spare parts should be categorized according to their demand, material price and availability risk. Note that the demand for the same spare part between two different production units may differ since the production units are not a hundred percent similar in their configuration. The quality of the categorization will be vital for ensuring accurate values of the performance indicators in the framework.

In the second phase, IKEA should prepare to monitor the service level for spare parts, which also is what the case company studied by Jouni *et al* (2011) did. Note that any KPI can be chosen, but since RQ2 particularly asks for availability and cost of handling it is fitting to choose a KPI connected to either one. For looking at the cost of handling, total cost could be used as KPI, and for looking at availability $SERV_2$ could be used. Since $SERV_2$ is easily connected to the safety stock model it is recommended to be the KPI used for the pilot implementation of the framework. The service level is defined as the fraction of time in which a demand can be satisfied directly from stock on hand, (see $SERV_2$ in chapter 3.4.1.). This service level refers to when a technician requests a spare part from the local spare parts inventory. If the spare part is not in stock, it will have a negative impact on the service level. Identical to Jouni *et al* (2011), the service level could be calculated per work order line. If a work order for maintenance requested a spare part and it could not be given, that particular order line is considered as unmet demand. In this way, IKEA would get a quick overview of which spare part groups require most attention, see Figure 3-11. IKEA should develop a report in QlikView which retrieves work orders from M3 and checks what spare part order lines are late. The data will then build up what service level each product category has and present it in the framework by Jouni *et al* (2011). No specific target is recommended for the service level since the purpose of the framework is to show what product categories are underperforming compared to other categories. IKEA could, if preferred, set target levels for each determined product category.

In the third phase, IKEA should choose one production unit which should be the first to utilize the performance measurement framework. This initial implementation of the framework should act as a proof of concept, showing what kind of impact can be made. The selected production unit should document all effects of the implementation of the framework, monitoring both cost reductions and differences in performance with regards to OEE. The finishing of phase three leads IKEA into phase four, implementing the framework on a global level for all production units. This phase should be less time consuming than the first two, because once the data is ready and the framework is developed, the last step is to make the necessary implementation for each product group at each production unit and include it in a global framework. The complexity, and thus time needed, for the global implementation will depend on how well the data was prepared and how well the framework in QlikView was developed.

Long-term action 2: continuous performance measurement

Another long-term action is an iterative and continuous procedure. Once the framework is being used by all production units, and the global performance is monitored, an effort should be made to document what benefits have been gained after the implementation. IKEA could choose to monitor if any significant cost reductions occur within maintenance, or if machine availability rises due to better spare part availability. In general, OEE could be compared before and after the implementation to show what impact the project had. There could also be collaborations between different departments to see if any positive impact was made on e.g. production planning, procurement etc. The main idea is that the introduction of a spare part performance measurement framework will enable IKEA to identify issues and resolve them, ultimately leading to performance increases in other departments beside maintenance. These performance increases can only be recognized if they are monitored, and this is why IKEA is recommended to do so. The last phase is going to be constantly ongoing since KPIs should be measured and compared continuously, making it a long-term recommendation.

6.5. Concluding remarks

The initiation of this project alone confirms the initial statement of the thesis that inventory control has received increased attention. The findings at IKEA Industry has confirmed that the previous view on spare parts inventory control has been that it is just a necessary cost. However, the demonstrated interest in a more sophisticated and coordinated approach to spare part stocking decisions, by both IKEA Industry and academia shows that this is changing.

A reflection made during the thesis is that the model and the results it outputs is only as accurate as the input data. If the input data for demand, lead times and costs are inaccurate, the safety stock levels will consequently be invalid. This is something that IKEA Industry needs to keep in mind if choosing to proceed with implementing the model. As stated in chapter 1.1., IT is an enabler of these kinds of models. While the required IT-systems at IKEA Industry are in place and contain some of the necessary information, there are still strides to be made to make it readily available.

Another reflection is the fact that indirect material at IKEA Industry has been treated differently than direct material. It seems as if it has not gotten as much attention in terms of inventory control and performance measurement. Some interviews suggests that there is no consensus among the maintenance personnel that there is anything significant to gain from keeping a closer eye on the spare parts inventory. Attention from employees within maintenance is almost exclusively focused on the machines and KPIs revolving them, and not the spare part inventory.

One of the reasons for lack of standardized data and procedures seems to be that a lot of employees are busy with other projects and individual, position related duties. IKEA Industry should consider prioritizing standardization projects to make sure that the required effort is applied and that the projects are finished within a limited time period. Such projects would facilitate other improvement projects.

The research area of stocking decisions for lateral transshipment has been explored thoroughly prior to this thesis. The chosen overall approach has uses elements that have spanned across inventory models for decades going back all the way to the METRIC model from 1968. This thesis mainly contributes, the same way other research has done before: by adapting the situation the specific context, IKEA Industry in this case. Indeed, the components of the model in this thesis have been utilized in literature before, but using them all at the same time has not been done extensively. This combination includes the network configuration (single-echelon) method for determining the transshipment quantities (M/M/∞ queue), the sourcing rule (random), the type of replenishments (supplier-pool) and the way of determining a network supply lead-time (weighted average).

6.6. Suggestions for future studies

During this project, a number of potential areas to improve were recognized. Most of them are included in the immediate actions since they are needed for the implementation (e.g. developing a model for determining shortage costs). Interesting areas to develop further would be to design a simulation model with the same assumptions to validate the analytical model. It would also be interesting to expand the model to include more production units and more clusters of production units. Intuitively, a spare part that is used in a high number of production units would benefit more from transshipments than a spare part that is used in fewer production units. In order to someday use the model at a larger scale, the model should be adapted to calculate the safety stock for multiple spare parts at a time, perhaps through some Excel script or a QlikView-application.

While the results from the model do not support that the stock levels are too high from a cost perspective, the fact that many production units have non-rotating items in stock for several years would support lowering of some stock levels anyway. It would therefore be interesting to map the rotations of many articles to see just how widespread this phenomenon is. Conclusions from such studies could complement the results from the model to get a more balanced perspective. Depending on the outcome of the categorization project at the Orla unit, the categories can be used for setting stock levels for slow- and non-moving items while the model could assist in setting the safety stock levels for faster-moving items with stochastic demand as there currently is no method for that.

Another study which should be made is regarding the current KPIs used within maintenance at the different production units. The work with performance measurement in this thesis has showed that the different production units and their corresponding maintenance departments are using different KPIs. This makes it harder when trying to compare the performance of different production sites, especially their spare parts inventories. For this reason, a thorough mapping should be done to establish what KPIs are currently used, what they measure and if they are needed at all. This should be done before implementing the presented spare parts performance measurement framework by Jouni *et al* (2011). This also apply to the fact that several production units are using OEE, but not all are following the official instructions on how to do it. An initiative should be taken to train personnel and make sure that all production units are using the KPIs in the right way.

An idea which has surfaced several times during discussions with maintenance personnel and key figures within IKEA Industry is the possibility of a central spare parts warehouse. This may lower total holding costs significantly, as well as purchasing costs due to the possibility of centralizing the purchasing function and thus entering agreements with suppliers for larger quantities at lower prices. A downside of this solution is the increased lead time for spare parts, especially during breakdowns. The idea should be investigated to determine whether the solution is feasible or not and what benefits or disadvantages it includes.

IKEA Industry has been closing production units recently, and several production units cover large areas in e.g. Lubawa and Poland West. It could be interesting to investigate to what degree production can be centralized, increasing production capacity at some production units and closing down others. This is a long-term project at its extreme and is only presented for IKEA Industry to include in their plans for the future of the company.

From an academic point of view, more research should be pointed towards models handling large sets of articles that not only have different input parameters, but also circumstances that normally would influence the model design. Items may have a different number of bases, different cost structures, different demand distributions, different lead-times at different bases and so on. Some limitations can be attributed to the single-item approach which reinforces the findings from the literature review that the multi-item spare part inventory research needs more attention.

Most literature only consider two alternatives when facing a shortage; either replenishment (sometimes from a supplier, sometimes through a repair facility) or transshipment. In reality, there can be wide range of alternatives that all theoretically could be considered in a model. Such a range could include: supplier replenishment, emergency shipment from supplier at extra cost, buying from competitor, repairing the item and lateral transshipments. Using priority rules a model could be designed to calculate the probability of each alternatives and estimating the total cost. The supplier dimension could also be explored (it was outside of the scope in this thesis). Some companies may have close relationships with their suppliers for complex and highly customized items. It may be interesting to see

Scientific articles that have been studied in the literature review suggest that many models are too complicated to be implemented in a company, and this thesis supports that reasoning. The articles from the literature review in this thesis did not discuss if companies would be able to implement the suggested model, instead the model is just presented and explained. It could be interesting to further investigate this matter in academia by determining what prerequisites are needed in a company for it to be able to implement the model, and to include these in the articles describing the model. This could help to know beforehand what type of company will be able to reap the benefits of a complex model, or at least what prerequisites the company needs. In the case of inventory control, and this master thesis in particular, that kind of prerequisite would be the preparation and standardization of data before a complex model is implemented.

It can also be noted that is not only IKEA Industry that is lacking when it comes to tracking the performance of spare parts inventory. Research of maintenance performance has been heavily focused on the direct effect on productivity within production and not spare parts. A majority of the literature reviewed presents models for measuring e.g. the availability of production equipment, production plan adherence and other manufacturing related KPIs. There were few models which considered performance of the spare parts inventory and how it impacts other parts of the supply chain. For this reason, academia should try to cover this subject better by developing more models and investigating how they impact other parts in a company.

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APPENDIX A

Table A-1: List of interviews conducted.

Date	Interviewee(s)	Topic	Interview type	Documentation	Duration
2020-01-22	Ulrika Garbe – Process Leader, Maintain	Introduction to IKEA Industry, the thesis, supply chain and maintenance	Unstructured	Notes	1 h
2020-02-18	Pawel Konopko – Spare parts and planning specialist, Orla Michal Tratwal – Spare parts and planning specialist, Poland West Matus Majera – Purchasing Jozef Lesko – Maintenance solution owner	Spare parts flow mapping, Setting of stock levels at the Poland West site and Orla Site	Semi-structured	Notes	3 h
2020-02-18	Pavla Lengalova – Process leader, master data	Introduction to the Navigation Portal system	Semi-structured	Notes	1 h
2020-03-09	Jaroslaw Godlewski	Tour of the Lubawa production unit	Unstructured	-	2 h
2020-03-09/10	Marcin Kalbarczyk – Maintenance Manager, Lubawa Jaroslaw Godlewski Łukasz Zapora	Spare Parts flow, Lubawa production unit	Semi-structured	Notes	4 h
2020-03-11	Krzysztof Jaros	Financial aspects, Lubawa production unit	Semi-structured	Notes	1 h
2020-03-11	Andrzej Domanski, Maintenance manager, Wielbark	Spare Parts flow, Wielbark production unit	Semi-structured	Notes	1 h
2020-03-17	Jakub Wróblewski - Technical department, Goleniow Sławomir Przybylski – Maintenance, Goleniow	Spare Parts flow, Goleniow production unit	Semi-structured	Notes	1 h
2020-03-18	Michal Tratwal – Spare parts and planning specialist, Poland West Krzysztof Buda – Spare parts department, Poland West	Spare Parts flow, Poland West production unit	Semi-structured	Notes	30 m

APPENDIX B

Table B-1: List of interview questions.

RQ	Category	Questions	Recipients of questions
RQ1	Planning procedures	- Brief explanation of the supply chain. What are the steps the spare parts go through? - How is safety stock defined? - Do you have a separate safety stock beside regular stock, or is it the same, i.e. is safety stock a separate stock that is dedicated solely to unplanned maintenance stops? - Are spare parts for planned maintenance taken from the stock or ordered separately in advance? - Usage of safety time? - How do you determine safety stock levels for spare parts today? - What is the current order policy? - What is the current reviewing policy? - Are articles segmented in some way and if so, how? - How are lateral transshipments currently conducted? - How are transshipments order placed (e.g. ERP, e-mail or phone)? - Are there records specifying whether articles are shipped normally or laterally? - Is it possible to issue emergency orders to suppliers? - What are the criteria for deciding whether an order should be emergency ordered from a supplier or transshipped from another unit? - Would all production units be willing to share all of their spare part stock? - Who decides whether a request for lateral transshipment is accepted or not? - How does the return flow work? - Are spare parts repaired and if so, how?	Pawel Konopko – Spare parts and planning specialist, Orla Michal Tratwal – Spare parts and planning specialist, Poland West Krzysztof Buda – Spare parts department, Poland West Jaroslaw Godlewski – Miantenance, Lubawa Łukasz Zapor – Maintenance, Lubawa Marcin Kalbarczyk – Maintenance Manager, Lubawa Andrzej Domanski – Maintenance manager, Wielbark Jakub Wróblewski - Technical department, Goleniow Sławomir Przybylski – Maintenance, Goleniow
RQ1	Financial questions	- How are holding costs calculated? - How is the stock valued? - What are the ordering costs? - What are the transportation costs for regular orders? - What are the costs for transshipments? - How long must an article not be used to be considered a non-rotating item?	Matus Majera – Purchasing Krzysztof Jaros – Finance, Lubawa
RQ2	Performance measurement	- How is maintenance measured? - What are the KPIs? - Is there any desired service level to be achieved? - What are the desired availability levels? - How is availability defined? - Is the number of breakdowns due to lack of spare parts tracked?	Jaroslaw Godlewski – Miantenance, Lubawa Marcin Kalbarczyk – Maintenance Manager, Lubawa Andrzej Domanski – Maintenance manager, Wielbark

APPENDIX C

Table C-1: List of selected articles.

Article	Production unit	Lead time [Days]	Supply rate per day	Demand rate per day	Current safety stock	Average purchase price [EUR]	Holding cost (20 %) [EUR]	Shortage cost/day [EUR]	Trans-shipment cost [EUR]
C9000227	Goleniow	7	0.0399	0,0059	3	344.45	69.89	3381	554
	PL West	70		0.0237	2				
C9003863	Goleniow	7	0.0312	0,0082	2	42.06	8.41	3381	554
	PL West	70		0,0548	6				
C9004448	Goleniow	7	0.0644	0,0047	4	17.66	3.53	3381	554
	PL West	21		0,0219	2				
C9004716	Goleniow	7	0.0294	0.0118	4	2.53	0.51	3381	554
	PL West	70		0.0885	10				
C9005031	Goleniow	7	0.0198	0.0047	15	4.81	0.96	3381	554
	PL West	70		0.1041	20				
C9005508	Goleniow	7	0.0553	0.0094	2	1.70	0.34	3381	554
	PL West	70		0.0201	2				
C9005526	Goleniow	7	0.0240	0.0082	2	30.23	6.05	3381	554
	PL West	70		0.1005	3				
C9005840	Goleniow	7	0.0646	0.0094	2	18.31	3.66	3381	554
	PL West	70		0.0146	4				
C9005854	Goleniow	7	0.0406	0.0047	2	308.07	61.61	3381	554
	PL West	70		0.0183	3				
C9009116	Goleniow	7	0.0904	0.0106	2	41.37	8.27	3381	554
	PL West	70		0.0073	2				
C9010878	Goleniow	7	0.0650	0.0047	2	167.47	33.49	3381	554
	PL West	21		0.0210	2				
C9010938	Goleniow	7	0.0642	0.0071	3	86.96	17.39	3381	554
	PL West	21		0.0338	2				
C9011564	Goleniow	7	0.0835	0.0106	3	33.24	6.65	3381	554
	PL West	70		0.0091	2				
C9016039	Goleniow	7	0.0653	0.0071	2	42.13	8.43	3381	554
	PL West	21		0.0311	3				
C9016800	Goleniow	7	0.0563	0.0012	5	25.18	5.04	3381	554
	PL West	21		0.0119	4				

APPENDIX D

In Excel, the model consists of modules in which code is written. These modules are either *subroutines* or *functions*. The *subroutines* contain the code for the overall algorithms used to solve the problem. The *functions* are used to solve small parts of the problem. It is, for example, convenient to define more complicated individual equations that have to be solved as functions. Equations like (Eq. 5-4) and (Eq. 5-14) are defined as functions. These functions can then be called upon in the subroutines whenever they are needed which makes the code in the subroutine easier to read than it would have been if the equations were not defined as functions.

The interface of the model is divided into three sections (also see Figure D-1):

- User input to the model. This includes article number, supply lead-time, demand rates at the production units, holding cost, shortage cost and transshipment cost.
- Model output. This includes the aggregated order-up-to level, the allocated order-up-to-levels, the service level ($SERV_2$), the expected stock on hand per production unit, the expected down-time (due to spare part stockouts) per production unit and year as well as the expected number of lateral transshipment per production unit and year.
- Costs. This includes the total holding cost, total shortage cost, total transshipment cost and the total cost.

There are three buttons in the model. Each button is connected to its own subroutine. One subroutine is developed for each of the three parts the modeling technique was divided into. This means that when the user input data is put in, pressing the first button will calculate the optimal aggregated order-up-to level and its corresponding service level. If button number 2 is pressed, then the aggregated demand is allocated to the different production units proportionally to the demand. Pressing button number three first generates the perturbations that will be investigated and then goes through each of them to find the expected stock on hand, the expected down-time and the expected number of transshipments and calculates the total cost. The allocation that results in the lowest total cost is then chosen and is the one that is displayed in the worksheet.

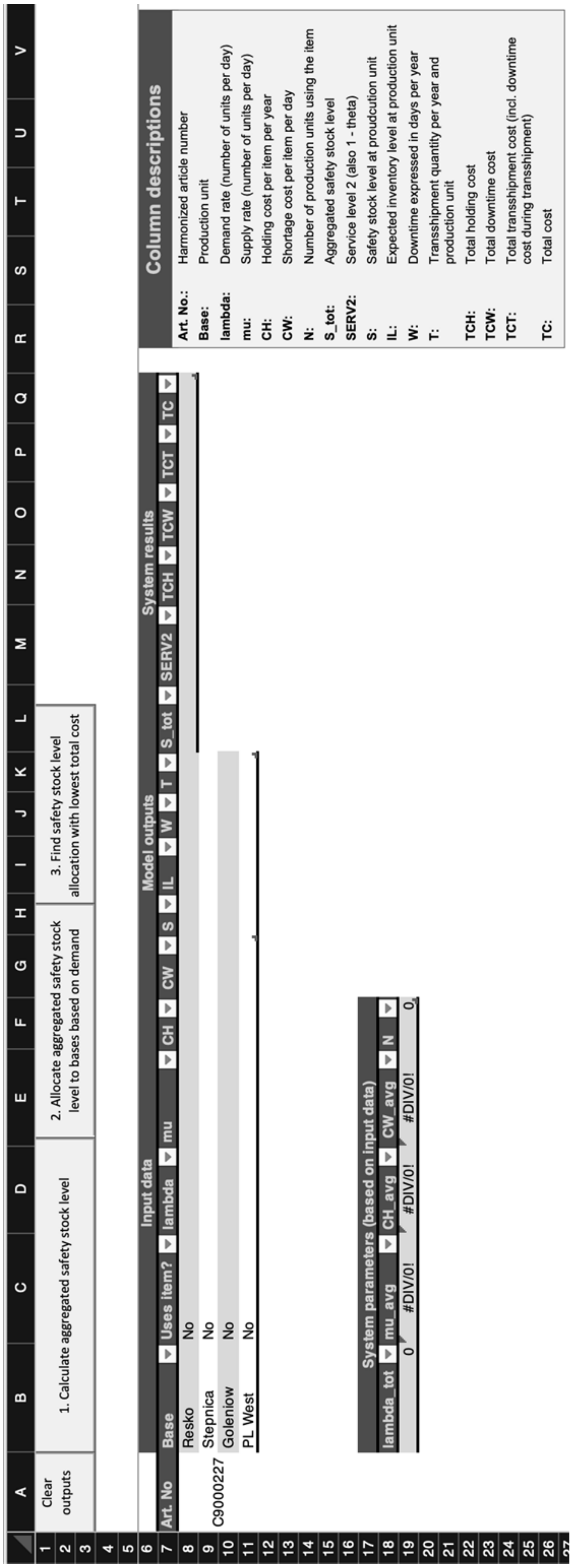

Figure D-1: Model user interface in Excel.

APPENDIX E

Table E-1: Results for the selected articles.

Article	Production unit	Supply rate per day	Demand rate per day	S^0	$SERV_2$	S_i	IL_i^+	W_i	T_i	TC
C9000227	Goleniow	0.0399	0.0059	6	99.99%	2	1.8510	0.0010	0.0205	399.44
	PL West		0.0237			4	3.4052	0.0041	0.0060	
C9003863	Goleniow	0.0312	0.0082	11	100.00%	2	1.7382	0.0001	0.0805	122.45
	PL West		0.0548			9	7.2263	0.0006	0.0002	
C9004448	Goleniow	0.0644	0.0047	6	100.00%	2	1.9270	0.0000	0.0042	22.82
	PL West		0.0219			4	3.6600	0.0001	0.0007	
C9004716	Goleniow	0.0294	0.0118	16	100.00%	3	2.5996	0.0000	0.0311	23.86
	PL West		0.0885			13	9.9881	0.0001	0.0001	
C9005031	Goleniow	0.0198	0.0047	20	100.00%	2	1.7650	0.0000	0.0381	35.61
	PL West		0.1041			18	12.7477	0.0002	0.0000	
C9005508	Goleniow	0.0553	0.0094	7	100.00%	3	2.8297	0.0000	0.0024	4.61
	PL West		0.0201			4	3.6362	0.0000	0.0017	
C9005526	Goleniow	0.0240	0.0082	17	100.00%	2	1.6636	0.0001	0.1250	146.94
	PL West		0.1005			15	10.7956	0.0006	0.0001	
C9005840	Goleniow	0.0646	0.0094	5	100.00%	2	1.8547	0.0004	0.0314	40.65
	PL West		0.0146			3	2.7729	0.0006	0.0052	
C9005854	Goleniow	0.0406	0.0047	5	99.97%	2	1.8800	0.0023	0.0105	325.94
	PL West		0.0183			3	2.5494	0.0090	0.0164	
C9009116	Goleniow	0.0904	0.0106	4	99.99%	2	1.8828	0.0005	0.0235	53.66
	PL West		0.0073			2	1.9186	0.0003	0.0116	
C9010878	Goleniow	0.0650	0.0047	5	99.99%	2	1.9265	0.0003	0.0042	165.27
	PL West		0.0210			3	2.6773	0.0012	0.0069	
C9010938	Goleniow	0.0642	0.0071	6	99.99%	2	1.8885	0.0003	0.0143	110.36
	PL West		0.0338			4	3.4727	0.0016	0.0048	
C9011564	Goleniow	0.0835	0.0106	4	99.99%	2	1.8727	0.0010	0.0273	57.99
	PL West		0.0091			2	1.8903	0.0009	0.0206	
C9016039	Goleniow	0.0653	0.0071	6	100.00%	2	1.8909	0.0002	0.0138	58.87
	PL West		0.0311			4	3.5235	0.0009	0.0034	
C9016800	Goleniow	0.0563	0.0012	5	100.00%	2	1.9784	0.0000	0.0001	24.62
	PL West		0.0119			3	2.7889	0.0001	0.0006	