Division of Production Management
Department of Industrial Management and Logistics
Lunds University
Box 118
221 00 LUND, SWEDEN

Master's thesis in Industrial Management and Logistics

Lund 2013

Printed in Sweden

Preface

This thesis was written during the spring of 2013 as the final part of our Master of Science degree in Industrial Engineering and Management at Lund University, Sweden. This thesis was developed together with BorgWarner TTS Landskrona with the aim to provide a better understanding of the risks in supply chain operations and how they affect the service level towards customers.

It has been an interesting and challenging, but most of all fun, period during which we have learned a lot. The support from the BorgWarner employees both in terms of time invested and keeping our spirits up has been invaluable. We would therefore like to express our outmost gratitude to the employees of BorgWarner and the logistics department in particular. We would like to dedicate a special thanks to our company supervisor Johan Cederfeldt, Logistics manager at BorgWarner, for making this project possible and for providing all the necessary resources.

We would also like to thank our supervisor at the university, Assistant Professor Fredrik Olsson at the department of industrial management and logistics, for raising important questions and giving us valuable comments throughout our thesis.

Finally, as this marks the end of our five-year long journey towards the degree in Industrial Engineering and Management, we would like to thank all of our classmates out of which many have become friends for life.

Lund, June 2013

……………………………………………….	……………………………………………….
Martin Olofsson	Daniel Persson

Abstract

Title: Developing an analysis tool for risk calculation in supply chain operations – A case study at BorgWarner TTS Landskrona

Authors: Martin Olofsson & Daniel Persson

Supervisors: Assistant Professor Dr. Fredrik Olsson, Department of Industrial Management and Logistics, Lund University, Sweden

Logistics Manager Johan Cederfeldt, BorgWarner TTS Landskrona, Sweden

Problem: The case study company, BorgWarner, currently has no quantitative method for evaluating the risks connected to different inventory levels throughout their internal supply chain. Meanwhile there are internal goals for lowering the amount of capital tied in inventory.

Purpose: The purpose of this thesis is to investigate how changes in the component and finished goods inventory levels affect the service level. Currently, the inventory level in each instance of inventory is set manually by the material and production planners and is based on their experience. Consequently, there is no way to evaluate the impact or quantify the risks of stock-outs if there is a decision to lower the inventory levels. The outcome of this thesis is a quantitative tool that shows how changes in inventory will affect the service level towards the customers and the capital tied in inventory.

Delimitations: The scope is limited to only include BorgWarner TTS Landskrona and to only analyze the effect on the customers and products associated with the serial production. Only the immediate suppliers and customers will be included. Spare parts and any return flows are excluded from the scope of this thesis.

Methodology: The thesis work was carried out by a comprehensive value stream mapping of all activities and processes connected to the internal supply chain, such as;

forecasting, product assembly and stock keeping. The value stream map formed the basis for the data analysis from which statistical conclusions could be drawn. Finally, the analysis formed the basis for the quantitative tool.

Result & conclusion: To fulfill the thesis' purpose, a computerized analysis tool has been developed. The tool evaluates the effect a change in inventory level has on the service level and capital tied in inventory. The approach during this thesis has both contributed to the effectiveness of obtaining the results and for the validation of the analysis model.

Keywords: Inventory control, inventory management, simulation, multi-echelon inventory, value stream mapping, BorgWarner

Sammanfattning

Titel: Utveckling av ett riskberäkningsverktyg för interna värdeflödesaktiviteter – En fallstudie på BorgWarner TTS Landskrona

Författare: Martin Olofsson & Daniel Persson

Handledare: Dr. Fredrik Olsson, Assisterande Professor, Institutionen för teknisk ekonomi och logistik, Lunds universitet

Johan Cederfeldt, Logistikchef, BorgWarner TTS Landskrona

Problem: Fallstudieföretaget, BorgWarner, har idag ingen kvantitativ metod för att utvärdera de risker som finns kopplade till olika lagernivåer. Samtidigt finns det en intern målsättning att sänka kapitalbindningen i lager.

Syfte: Syftet med det här examensarbetet är att undersöka hur förändringar i material- och färdigvarulager påverkar servicenivån mot BorgWarners kunder. I dagsläget sätts lagernivåerna för respektive lager manuellet av material- och produktionsplanerare baserat på deras erfarenhet. Följaktligen finns det inget sätt att utvärdera den påverkan eller kvantifiera de risker för brister som finns kopplat till ändringar av lagernivåerna. Resultatet av detta examensarbete är ett kvantitativt verktyg som visar hur ändringar i lagernivåerna påverkar servicenivån mot kunderna samt kapitalet bundet i lagret.

Avgränsningar: Arbetet är avgränsat till att endast omfatta BorgWarner TTS i Landskrona och endast analysera effekten på de produkter och kunder som omfattas av serieproduktion. Endast BorgWarners direkta leverantörer och kunder kommer att omfattas av analysen. Exkluderat från arbetet är flödet av reservdelar och eventuella returflöden.

Metodik: Examensarbetet utförs genom en grundlig värdeflödesanalys av alla aktiviteter i den interna värdeflödeskedjan så som; prognostisering, produktmontering och lagerhållning. Värdeflödesanalysen följs av en dataanalys där data från värdeflödesanalysen anpassas till statistiskt användbar data. Denna data är sedan grunden för utvecklingen av analysverktyget.

Resultat & slutsats: För att uppfylla examensarbetets syfte, har ett datoriserat analysverktyg utvecklats för att utvärdera hur en förändrad lagernivå påverkar leveranssäkerheten och kapitalbindningen i lager. Det valda tillvägagångssättet har under detta examensarbete bidragit till att underlätta framtagandet av resultatet och till att validera analysmodellen.

Nyckelord: lagerstyrning, flernivålagerstyrning, värdeflödesanalys, simulering, BorgWarner

List of acronyms

A list of acronyms used in this thesis is presented in Table 1.1.

Table 1.1. List of acronyms used in this thesis.

Acronym	Expansion	Explanation
BOM	Bill Of Materials	List of sub-components of a product.
BW TTS	BorgWarner TorqTransfer Systems	The focal company of this thesis.
CNC	Computer Numerical Control	Computer system for controlling machine tools.
ERP	Enterprise Resource Planning	Software system used to manage a company.
FGI	Finished Goods Inventory	The inventory where finished products are stored.
FIFO	First In First Out	Inventory policy.
FCA	Free Carrier	INCO-term. Responsibility and ownership is transferred when the goods leave the sender.
Gen4	Generation 4	Product generation at BW TTS.
Gen5	Generation 5	Product generation at BW TTS.
INCO	International Commerce Terms	International organization for trade terms
ISO	International Organization for Standardization	International organization for setting commercial and industrial standards.
MRP	Material Requirements Planning	Production and inventory control system, see Section 3.2.3.
OEM	Original Equipment Manufacturer	In automotive industry; the manufacturer of the vehicle.
OEE	Overall Equipment Efficiency	A metric for measuring the effectiveness of a manufacturing operation.

List of figures

List of tables

Table of contents

1 Introduction

This chapter gives an introduction to this master's thesis and describes the background of the studied field and the case company. The purpose, research questions, scope and delimitations are also presented as well as the structure and the target group of the thesis.

1.1 Background

This master's thesis is conducted as a case study at BorgWarner TorqTransfer Systems in Landskrona in the field of inventory control. In this section the reader is introduced both to the topic and the company.

1.1.1 The inventory's role in business

Today, manufacturing companies operate in a competitive environment and streamlining the company's supply chain is becoming an even more important priority (Christopher, 2005). Reducing capital tied in inventory is a focus in many companies. The ability to finance the business and the company's return on equity is directly affected by the capital tied in inventory (Mattsson, 2003). In the average manufacturing company the capital tied in inventory represents a significant proportion of the total capital. Generally, manufacturing companies tie as much capital in inventory as in plant and equipment assets and more than the capital tied in accounts receivables (Mattsson, 2003). This shows that there is room for improvement, which is recognized by top management in many firms (Axsäter, 2006).

Reducing inventory and planning production have consequently become important means for companies to compete in the market (Voss & Woodruff, 2005). A well-known philosophy in manufacturing companies is the Lean concept, which focuses on reducing waste in the production system. In the Lean perspective inventory is regarded as one of seven defined wastes, since components and goods in inventory does not add any value to the customer (Pepper & Spedding, 2010). The Lean concept is well adopted, especially in manufacturing companies, since efficient production systems are capable of producing goods at a lower total cost. Compared to an investment in a new machine, the inventory level is not only affected by a single decision or position. Improvements are made through better planning processes and control systems (Mattsson, 2003).

Inventory control is a structured and analytical approach to manage inventory and production schedules in organizations. One of the central and original pillars of inventory control is Materials Requirement Planning (MRP), which is the planning of materials requirements, in production, using demand forecasts for future time periods. This facilitates more precise control and links demand with material ordering (Jacobs & Weston Jr, 2007). Before the introduction of MRP systems simple decision rules were used and planning had to be done manually (Axsäter, 2006). Computerized MRP systems emerged in the 1960s as a tool for planning and scheduling of products with complex product structures (Jacobs & Weston Jr, 2007). The development of information technology has enabled more efficient inventory control through more accurate and real-time information flows (Axsäter, 2006).

The field of inventory control has contradictory objectives; minimizing cost and maximizing customer service. The costs are related to ordering, holding inventory, production and transportation. Customer service level concerns meeting customer requirements in terms of delivery capabilities (Axsäter, 2006). The cost and customer service aspects are closely correlated; improving one aspect is likely to have negative impact on the other. For example, by increasing inventory a higher customer service level can often be achieved but will also lead to higher inventory holding cost (Lumsden, 2006). To further increase the complexity, inventory control is influenced by a number of variables which affect the performance of the system (Axsäter, 2006). Consequently, companies need to continuously work with inventory control in order to achieve a cost efficient way to produce their goods.

1.1.2 BorgWarner TorqTransfer Systems

BorgWarner TorqTransfer Systems AB produces all-wheel drive couplings for passenger cars. The company's mission is to develop leading powertrain technologies that improve fuel economy, emissions and performance (BorgWarner Inc., 2011). The patented product features a programmable electronic control unit that can be customized to meet each customer's specific requirements (Cederfeldt, 2013). This type of coupling was first produced in 1998 by the Haldex Traction System division at the plant in Landskrona, Sweden. The development of couplings has progressed over the years and has been driven, mainly, by a cost reduction focus. Currently, a fourth generation coupling is the principal product sold but the company is in a transitional phase where the less expensive generation five coupling is being introduced and will replace the fourth generation (Cederfeldt, 2013).

The Haldex Traction System division was acquired by BorgWarner Inc. in 2011 (BorgWarner Inc., 2011). BorgWarner Inc. is an American based company producing powertrain solutions. BorgWarner Inc. operates in 19 countries, has approximately 19 000 employees and a revenue of USD 7.11 billion in 2011

(BorgWarner Inc., 2011). The company is divided into Engine and Drivetrain solutions, where BorgWarner TTS is a business unit within Drivetrain solutions, see Figure 1.1 (Borg, 2013). BorgWarner TTS Europe has approximately 430 employees where 330 are based at the plant in Landskrona, which is also the headquarter of the business unit, and 100 employees are based at the plant in Szentlorinckáta, Hungary (Borg, 2013).

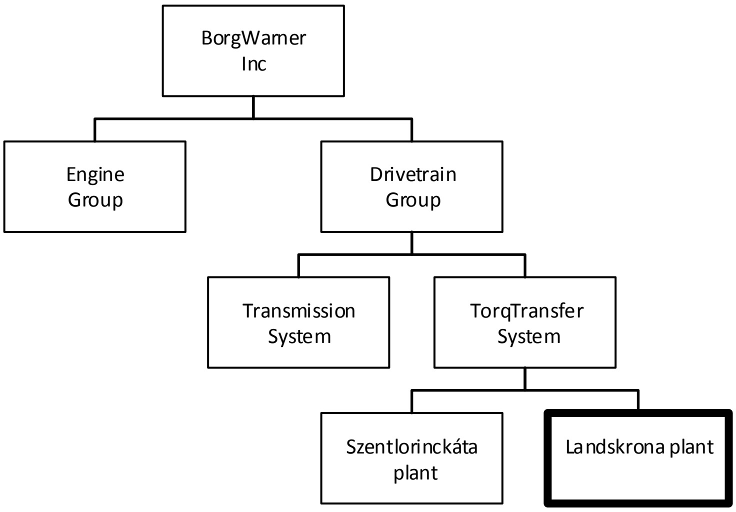


Figure 1.1. Schematic figure of organizational structure (Borg, 2013).

The main value adding activity performed at the Landskrona plant is the assembly of couplings. The product range consists of approximately twenty different couplings (BorgWarner TTS, 2013), which are assembled in four semi-automatic assembly lines with a total yearly output of approximately 900 000 couplings (BorgWarner TTS, 2013). Each coupling consists of 40 to 70 different components depending on generation and variant (BorgWarner TTS, 2013). All, but one, of the components for the couplings are externally sourced from a worldwide supplier base although the majority of the suppliers are based in Europe. The component that is not fully sourced from outside suppliers is the coupling house, which is the base of the coupling (Svensson, et al., 2013). Approximately one third of the coupling houses are processed at the Landskrona plant, which has its own machining department with six CNC lathes and a yearly output of 300 000 coupling houses. The rest of the coupling houses are bought, fully processed, from external suppliers (Svensson, et al., 2013).

An important supporting function at the Landskrona plant is the logistics department, which has the complete responsibility for receiving customer orders, planning the assembly and machining departments and calling off material from suppliers in order to meet production. The logistics department also overlooks the warehousing and shipping department where finished couplings are sent to customers (Cederfeldt, 2013). The customers that the Landskrona plant serves are primarily first tier suppliers to the European automotive industry. The main customers, in terms of sold products, is a drivetrain manufacturer located in Austria and a Swedish manufacturer of driveline solutions (Palm & Sahlé, 2013). The Landskrona plant has a finished goods inventory (FGI) on site and distributes couplings directly to the Swedish customer and spare parts and low volume couplings to smaller customers. The distribution to the Austrian customer is carried out via a consignment stock at the customer's production site in Austria where BorgWarner retains ownership of the couplings until the customer uses them in production (Palm & Sahlé, 2013).

1.2 Purpose and research question

The purpose of this thesis is to investigate how changes in the component and finished goods inventory levels affect the service level. The service level is measured as the total amount of units delivered divided by the total amount requested by the customer. Today BorgWarner has a goal of 100% service level and the actual performance in 2011 was 99.8% (Palm & Sahlé, 2013). At the same time there is a goal to reduce the capital tied in inventory by reducing the number of inventory days. The logistics manager in Landskrona, suspects that optimal inventory levels are not utilized at the Landskrona plant. Currently, the inventory level in each instance of inventory is set manually by the material and production planners and is based on their experience. Consequently, there is no way to evaluate the impact, or quantify the risks, of stock-outs if there is a decision to lower inventory levels. The logistics manager needs a quantitative tool that shows the current and forecasted delivery ability, but also how changes in inventory will affect the performance. In order to build a foundation and to facilitate the development of such a tool the internal processes at BorgWarner needs to be mapped.

This purpose yields the following research questions:

- What are the risks and uncertainties that exist in the value chain?
- How do these risks and uncertainties affect the inventory levels?
- How do changes in the inventory levels of each instance affect the service level?

1.3 Scope and delimitation

The focus of this thesis is the high value products and components in serial production that tie the most capital in the value chain of BorgWarner TTS Landskrona (hereafter called BorgWarner). The thesis is limited to the component buffer, finished goods inventory and processes related to these inventories.

Consequently, the thesis will only consider the suppliers closest upstream in the value chain and the immediate customers downstream of BorgWarner. Internal aspects such as machine breakdowns in assembly and disruptions in the intermediate transports of the value chain will be taken into consideration. See Figure 1.2 for a schematic view of the scope and limitations.

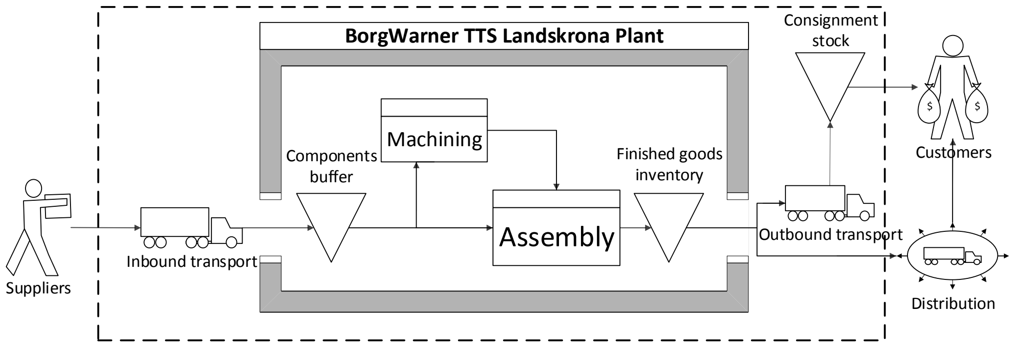


Figure 1.2. The scope and limitations of the master's thesis.

The thesis is limited to the scope described above and does not consider changes in the current process setup. There are also a number of material flows going through the Landskrona production plant that will not be considered, such as spare part production, components not used in high volume serial production and return flows from customers. External, uncontrollable, factors unrelated to the material flow such as fires or earthquakes will not be taken into account.

1.4 Requirements specification for the analysis tool

The goal of this thesis is to deliver an analysis tool to BorgWarner for use in situations related to inventory and service levels. Together with the logistics manager, the following requirement specification for the tool was established:

- Fulfill the purpose outlined above.
- Function independently of any enterprise system.
- Compatible with MS Excel 2010.
- Show current stock value in component buffer and finished goods inventory.
- Show predicted service level per product within the planning horizon.
- Show how manual changes of inventory levels, per product and component, affect the service level.
- Allow flexibility, including scalability, to adjust to future conditions.

1.5 Structure of thesis

In Figure 1.3, a schematic view of the thesis is shown. The introduction and methodology chapters introduce the background to the study, the research questions and the chosen approach. The theoretical framework chapter forms the basis for the analysis together with the empirical data chapter.

The analysis chapter combines the theoretical findings with the empirical findings to form a foundation of analyzed data, which is to be used as input for the tool. Finally, the model and the logic of the model are described in the model chapter and a discussion about the outcome of the thesis is presented in the conclusion chapter.

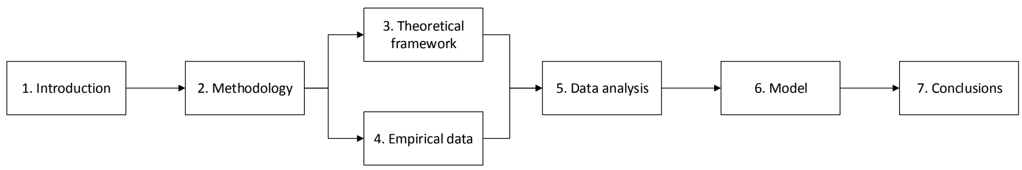


Figure 1.3. Schematic view of the thesis.

1.6 Target group

The target group for this master's thesis is primarily the logistics manager, material planners and production planners of BorgWarner. Additionally, staff at BorgWarner responsible for the material flow at the Landskrona plant and top management may be interested in the results of this thesis. The thesis can also work as a starting point for further improvements at BorgWarner, performed by employees or external sources, or similar initiatives at other companies. The thesis also targets academics in logistics and other people interested in the field of logistics.

2 Methodology

This chapter presents the methodology used in this thesis; the scientific approach is presented followed by research method, strategy, design and data collection plan. The methodology chapter is a roadmap of how the purpose and research questions of the thesis will be answered.

2.1 Scientific approach

When conducting research it is important to approach the problem in a methodological manner in order to give the reader a better understanding of what, previously, has been done within the field but also how future research can be conducted (Gammelgaard, 2004). Traditionally, research within the field of logistics has mostly been carried out in a positivistic approach (Gammelgaard, 2004). Gammelgaard (2004) argues that the positivistic research approach is too one-sided and that the field would benefit from more methodological approaches.

In this thesis the scientific approach adopted is a systems approach. The systems approach is characterized by a holistic view of the problem and that the links between each component of the problem is just as important as the components themselves (Arbnor & Bjerke, 1997). The objective of the researcher is to understand the components, links, goals and feedback mechanisms of a system in order to suggest improvements (Gammelgaard, 2004). This means that the systems approach is contextual and in order to find information it is necessary to analyze and compare cases instead of finding cause-and-effect relations (Gammelgaard, 2004).

The systems approach is also logical in its nature and therefore the outcome of the research conducted is a problem solution that works in practice as opposed to absolute facts (Gammelgaard, 2004). As the aim of this thesis is to understand how inventory levels and uncertainties in BorgWarner's value chain affects the delivery performance, the systems approach is well suited for this thesis.

The systems approach can be compared to the analytical approach presented by Arbnor and Bjerke (1997) where each component should be analyzed individually in order to find an optimal solution for the whole system. This is not appropriate in this thesis or when optimizing multi-echelon inventory levels as the solution provided is likely to be sub-optimized (Axsäter, 2006). The outcome of this thesis also aims to provide a practical analysis tool as opposed to the optimal inventory levels.

Neither the actors approach, presented by Arbnor and Bjerke (1997), is suitable as it heavily focuses on the qualitative aspects of the people involved in the system. This is not sufficient as the main activity analyzed in this thesis concerns the processes at BorgWarner.

The three scientific approaches mentioned above, form the framework presented by Arbnor and Bjerke (1997). The basis of the framework is that the choice of research method should be influenced by the researcher's perspective of reality and not solely on the nature of the research question (Arbnor & Bjerke, 1997). Gammelgaard (2004) argues that this framework is well suited for research in the field of logistics as a complement to the traditional positivistic approach.

2.2 Research method

It is important to select an appropriate research method for the problem in order to achieve the objectives of the study. The research method influences how the research is conducted, from what perspective it originates and how conclusions should be drawn. The research path generally moves between theoretical studies and empirical observations, and the method should be designed as a combination of these to fulfill the research goals (Arbnor & Bjerke, 1997).

For this thesis an abductive research method is used. The abductive method follows a process, which starts with empirical observations, where problems or deviations are identified (Kovács & Spens, 2005). A search for existing theories or frameworks in the field of study is then initiated to match the observations made. This is an iterative process which continues through additional empirical observations and further knowledge gains until an adequate theoretic framework can be established. This, suggested, research method can then have additional applicability in real-life (Kovács & Spens, 2005). An illustrative description of the abductive research method is shown in Figure 2.1.

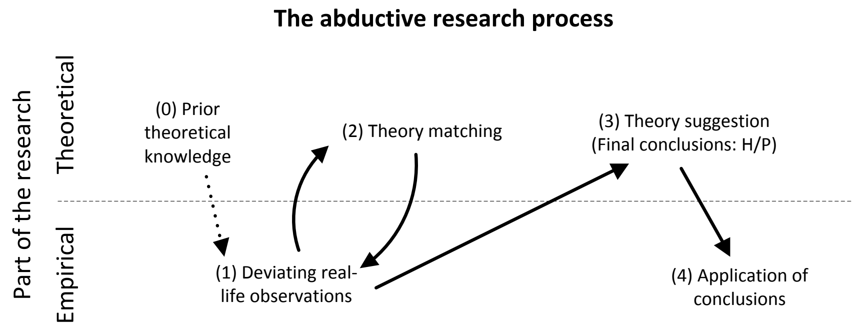


Figure 2.1. Illustration of the abductive research process (Kovács & Spens, 2005)

The abductive method is highly applicable to the purpose of this thesis. The thesis originated from an identification of a problem at BorgWarner and a central pillar of the research process is the task of matching this problem with established theory in the field of inventory control. The aim is to develop a theoretical model that represents BorgWarner's situation, which will be the basis for the analysis tool. Since the thesis starts from an observed problem at the company and the intended finish point is the deployment of an analysis tool, neither a deductive nor inductive approach would be suitable. The deductive method starts in theory, where a hypothesis is formulated and empirical tested and then either confirmed and rejected. Inductive research starts with a real-life observation which is analyzed and theoretical conclusions are drawn (Kovács & Spens, 2005). However, inductive research lacks the iterative process between observations and theory. With this iterative process, the theoretical conclusion is developed through incrementally gained knowledge and understanding of the company's processes, which assures validity of the conclusion and further usability.

2.3 Research strategy

It can easily be concluded that different research strategies should be utilized in different research situations. A number of strategies for approaching research have been identified in academic literature. Yin (2003) describes five frequently used strategies while Höst et al. (2006) mention four similar and related strategies. The strategies described by Yin (2003) are experiment, survey, archival analysis, history and case study. A case study can be defined in the following way:

> *"A case study is an objective, in-depth examination of a contemporary phenomenon where the investigator has little control over events." (McCutcheon & Meredith, 1993, p. 240)*

In the work of Höst, et al. (2006), a variant of case studies is described, called action research. For this thesis, this variant of a case study is deemed appropriate. Action research is described as suitable when a problem should be solved at the same time as it is studied (Höst, et al., 2006). The first phase of action research is to observe and clarify the problem that is set to be solved. With a proper understanding of the issue, a solution is proposed and implemented. The final phase is to evaluate the implemented solution (Höst, et al., 2006).

2.4 Design strategy

The deliverable of this thesis, except this written report, is a computerized support tool for inventory control. To achieve this deliverable, it is fundamental that the tool represents reality in a satisfactory manner. However, the complexity of such a system can be severe and to reduce the risk of misalignment between the tool and reality, incremental development is used (see Figure 2.2). Incremental development is a method commonly used in software development and implementation projects. The strategy is based on a process where the core functions are implemented first to ensure functionality. Subsequent development is in the form of small increments with additional functionality that is implemented stepwise (Jalote, 2008). This strategy enables the focus to be on one defined problem at a time and validations can be performed after each step. Drawbacks are that rework of the implemented parts might be required when features are added, which prolongs the total development time (Jalote, 2008).

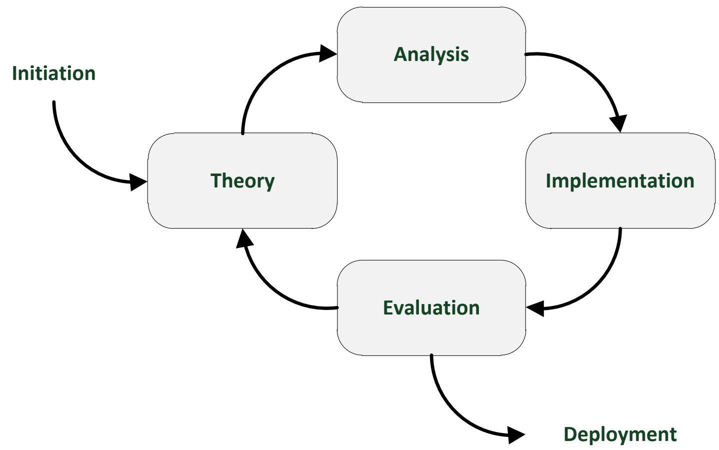


Figure 2.2. Process over the incremental development design

In general terms, the methodology for action research in this case is performed in cycles, and moves between being theoretical and empirical, which fits well with the abductive method.

2.5 Data collection

As the outcome of this thesis is an elaborate analysis tool, comprehensive data gathering is required as a basis for the analysis and development phases. The data collection is necessary in order to understand the physical flows of material and information in the system. Furthermore, in order to understand the dynamics of inventory management and control, a comprehensive study of literature in this field is to be conducted.

In order to approach this problem in a structured manner a short pre-study of the BorgWarner's production and distribution system is conducted through exploratory interviews. The pre-study is followed by a literature review of the field to establish a theoretical framework. The theoretical framework serves as a basis for the extensive mapping of BorgWarner's processes and activities within the scope of this thesis. As the thesis follows the abductive research methodology the last part of the data collection phase will be interspersed with the analysis phase. The research procedure is illustrated in Figure 2.3.

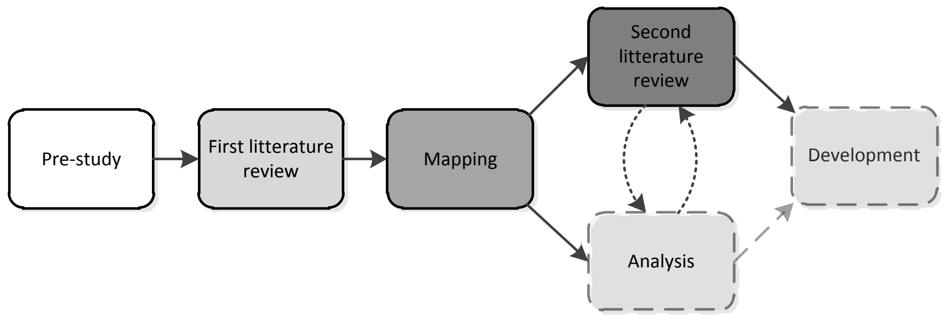


Figure 2.3. The different stages of research procedure in this thesis.

2.5.1 Quantitative and qualitative data

Data collection can be conducted in two distinctive forms, quantitative, and qualitative. The different collection forms should be used in different research situations. Quantitative data is data that can be counted and classified such as numbers, proportions and colors (Höst, et al., 2006). Quantitative data can be analyzed with statistical methods whereas qualitative data is in the form of words or descriptions and requires analysis methods, based on categorization and sorting, to understand and draw conclusion from (Höst, et al., 2006).

2.5.2 Primary and secondary data

There are two sorts of data types, primary and secondary data. Primary data is data that has been collected first-hand by the researcher for the specific project while secondary data is data that has been produced and collected for another purpose or study (Björklund & Paulsson, 2003). While primary data often can be collected and interpreted as the researcher desires, secondary data that has already been analyzed can, possibly, be biased (Höst, et al., 2006).

2.5.3 Exploratory interview

In order to approach the problem correctly and to understand the overall structure of the processes and activities, at BorgWarner, exploratory interviews are held with the personnel of the logistics department. The interviews are conducted in a semi-structured way, meaning that the interviews follow a predefined structure with some fixed questions and some questions being adapted to the answers of the interviewees (Höst, et al., 2006). The content of each interview is summarized and the interviewees are given the chance to make corrections or clarify any misinterpretations. The sum of the digested information from the interviews serves as guidance for the continued study.

2.5.4 First literature review

The purpose of the first literature review is to establish a theoretical framework based on the findings of the pre-study. The focus of this literature review is mapping techniques for processes and material flows in manufacturing industries.

The review will be based on literature recommended by the university supervisor as well as suitable literature found by the authors of this thesis. In order to find reliable literature searches are to be conducted in university and scientific catalogues. Relevant literature can then be used as the base for finding additional literature by using the “snowball” approach (Jalote, 2008). The snowball approach starts with a credible source and then expands by using its references to continue the review followed by a new set of references. By using this approach specific knowledge can be found by going deeper into specific literature. To increase the validity, of literature found in these catalogues, sources with high citation ranks will be prioritized.

2.5.5 Mapping - Observations, ERP data extraction and interviews

When the theoretical framework has been laid down the mapping phase commences. The mapping process encompasses both quantitative as well as qualitative data and is divided into three categories;

- Empirical observations
- Data extraction from BorgWarner's ERP system
- Interviews

Empirical observation is a type of primary data collection where the researcher observes a certain event or behavior. The observation point for the researcher can range from just observing to taking an active part in the event itself (Höst, et al., 2006). In this study the empirical observations will be conducted by, passively, observing processes at the Landskrona plant and performing time measurements in order to determine e.g. specific process times. The purpose of the empirical observations is to gather quantitative, primary, data that is not available through other channels.

One of the principal sources of quantitative data for this thesis will be the ERP system of BorgWarner. Operational data on e.g. quantities, bill of materials (BOM) and historical sales will be collected in order to comprehend the scale of operations and to form the data basis for the analysis.

Finally, qualitative data about decisions in the value chain are to be gathered through interviews and by "walk-alongs". The interviews at this stage will be conducted as the open question type interviews, where the subject of the interview will be presented and the interviewee can then speak freely within the frame of the subject (Höst, et al., 2006). The walk-alongs will be conducted, by the authors, by following key personnel through a typical day of their work. This aims to build a better understanding for the decision making in the value chain.

2.5.6 Second literature review

The last part of the data collection phase is closely linked to the analysis phase as they will be carried out simultaneously. In accordance with the abductive research methodology theory and analysis will be combined as the study progresses. The focus of the second literature review will be on specific analysis methods and approaches applicable to the findings of the mapping phase. The findings in this phase will also form the basis for the subsequent development phase. Again, literature recommended by the university supervisor as well as literature found by the "snowball" approach will be used, but with a narrower focus. By the end of this phase the scope of the thesis will be finalized, see Figure 2.4.

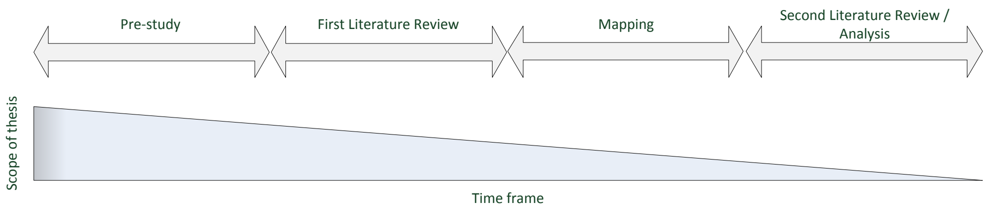


Figure 2.4. As the thesis progresses, the scope of the thesis gets more specific.

2.6 Validity and reliability

As briefly stated in the previous section, it is of high importance that the analysis tool developed is representative of reality. For this reason the data collection methods, analysis methods and the results have to be validated and the reliability checked.

In this thesis different approaches are used for different phases. During the theory building phase there is a strong emphasis on ensuring the validity of the information. In this thesis there has been a focus to collect information from highly credible sources. To ensure correct theoretical understanding, the authors primarily collect information from academic journals and books, where the number of citations and replication of theory have been used to evaluate the credibility.

The aim of the empirical data collection is to collect data from primary sources when possible. The data can be in the form of both first-hand observations and interviews. To validate that the data is understood correctly it is verified by the interviewee or, for observations, confirmed by appropriate personnel.

The analysis and calculation will be built on the theoretical knowledge and empirical data. It is important to have a high validity in the analysis phase to produce valid results. Much of the analysis and calculations have underlying assumptions, which are based on theory and empirical data. To improve the validity, the authors discuss the assumptions in terms of how reasonable and realistic they are and the effect they have on the results if the assumptions do not hold.

3 Theoretical framework

In this chapter the theoretical framework used in this thesis is presented. The chapter contains theory on the value stream mapping technique used during the data collection phase as well as the theories linked to the analysis and modeling phases.

3.1 Value stream mapping

In order to introduce the value stream mapping tool, the value stream concept should first be clarified. The value stream of a company involves all activities and actions necessary to bring a product from raw material to finished goods in the hands of the customer (Rother & Shook, 1992). The value stream perspective gives a holistic view instead of focusing on individual processes. This is very useful when improvement measures are to be implemented, as a holistic view will prevent sub-optimization (Rother & Shook, 1992). The actual value in the value stream consists of all the activities that add value in order to meet the need of a customer. Value adding activities can be; machining, assembly, drilling, etcetera. (Manos, 2006). Activities that are not adding value are, most likely, waste such as waiting time, overproduction and unnecessary transports (Hines & Rich, 1997).

The value stream mapping tool is a simple, yet effective, way to map the processes, both value adding and non-value adding, of a value stream in a company (Rother & Shook, 1992). The idea is simply to follow a product's production path from the supplier to the customer while making visual representations of every activity and step of the way (Rother & Shook, 1992). In addition to the physical flows in the production path the information flows must also be mapped. This makes the value stream mapping tool unique as it is the only tool that shows the link between information and material flow (Rother & Shook, 1992).

3.1.1 Process family matrix

As many companies offer several products and many products have different BOMs and go through different processes it is important to narrow the scope of the value stream map (Rother & Shook, 1992). One way of finding a balance between mapping each product separately, which would be inefficient and time consuming, and mapping all products at once, which would result in a chaotic and incomprehensible map, is to map according to process families (Rother & Shook, 1992). Process families are groups of products that share or go through similar process steps (Manos, 2006). In order to determine the process families a process family matrix can be used. The process family matrix consists of two axis, one axis for all the products and the other axis for all production steps and equipment. Every intersection where a product passes through a product step should be marked with an 'X'. By plotting all the products in this manner the product families should be determinable (Manos, 2006).

3.1.2 Creating the current state map

The current state map is a representation of the current state, showing both the material and the information flow as well as the performance (Suciu, et al., 2011) (Manos, 2006). The current state map normally starts with a single plant focus, showing an overview of the flow from receiving goods through production to shipping. With a clear picture, the focus can later be changed to involve either additional plants and companies or to focus on single process steps (Rother & Shook, 1992).

As mentioned earlier, value stream mapping is a very practical tool. However, in academic literature there exist a few guidelines for how a current state map should be created. One key aspect, is that the people creating the current state map should walk the material and the information flows themselves, interviewing the people performing the tasks (Rother & Shook, 1992) (Manos, 2006). The argument for 'walking the flow' is that a better picture of the entire process is developed and misconceptions of how tasks are performed are minimized (Manos, 2006). To obtain the overview of the flow in the plant, the walk should first be conducted from receiving to shipping. However, when starting to draw the map, the walk should be done by following the material flow upstream, starting from the shipping dock and finishing at the receiving. With this methodology the processes closest to the customer will be drawn first, which should guide the processes upstream (Rother & Shook, 1992). When gathering data and process times, the collector should avoid using default data and times when possible, and instead measure the data personally (Rother & Shook, 1992). In the literature it is also suggested to draw the draft of current state on paper simultaneously while walking the flow (Rother & Shook, 1992) (Manos, 2006).

The current state map is more than an illustrative representation of the material and information flow, it shows key data of the processes. Normally, the represented data include time in each process step and inventory, machine availability and rejection rates (Rother & Shook, 1992). The last step in the creation of the current state map is to add a timeline indicating when value is added and when there is waste (Rother & Shook, 1992).

3.2 General inventory control

Inventory control is a sub-field of operations research and this section will describe the theory of the relevant topics connected to this master's thesis. The underlying cause that drives the need of inventory is often the uncertainties that exist in an inventory system (Axsäter, 2006). This section will begin with a description of the uncertainties and common inventory control terms used and end with describing different theories concerning ordering policies.

3.2.1 Uncertainties and forecasts

The uncertainties can often be grouped in three different groups; customers, internal processes and suppliers (Axsäter, 2006).

Customers

The major uncertainty from customers is demand uncertainty, both in regard to the quantity and at what time the demand will occur. This uncertainty is a problem because there is a lead-time between starting a process and the point at which the goods can be delivered to the customer. Additionally, it is often necessary to order or process goods in batches (Axsäter, 2006). When starting a process the actual need at the point of delivery to the customer is normally unknown. To estimate the demand in advance, several forecasting techniques can be used. The most widely used technique is to base the forecast on historical demand data (Mattsson & Jonsson, 2003). For articles that are solely a component of a final product, the forecast is usually made for the final product and with such forecast a production plan can be determined. The forecasted demand for the component is then derived from the production plan (Axsäter, 2006). Forecasts can also be based on, or adjusted for, other factors, e.g. sales campaigns.

Apart from predicting the demand, it is also important to know how uncertain the forecast is or how much the actual demand varies from the forecast. The deviation is important to know in order to size the safety stock correctly. The deviation is usually measured with the standard deviation. If X is a stochastic variable and m is the mean, the standard deviation σ is defined as (3.1).

$$\sigma = \sqrt{E(X - m)^2} \qquad (3.1)$$

It is common to assume that the forecast errors are normally distributed (Axsäter, 2006).

Internal process

There are several measures used to monitor internal production processes. Dal et al. (2000) describes one measure known as *Overall equipment efficiency (OEE),* which was developed by Nakajima in 1988. How BorgWarner measure its internal production process is described in Section 4.3.1 and later included in the simulation model, Section 6.4.3. OEE is considered to combine two related areas, *operations and maintenance,* and *management of manufacturing equipment and resources*. The measure is built up by quantifying six different losses in the process(Dal, et al., 2000), see Table 3.1.

Table 3.1. The OEE losses.

OEE losses
Equipment failure/breakdown
Setup and adjustment
Idling and minor stoppage
Reduced speed
Reduced yield
Quality defects

The first two losses are categorized as downtime losses which reduces the availability of the production process. The availability measure is concerned with the total unscheduled stoppages, setup time and changeovers, and is calculated as (3.2) by dividing (3.3) with (3.4).

$$Availability = \frac{Actual\ operating\ time}{Planned\ operating\ time} \tag{3.2}$$

where,

$$\begin{aligned} &Actual\ operating\ time \\ &\quad = Planned\ operating\ time \\ &\quad - Unplanned\ maintenance \\ &\quad - Minor\ stoppages \\ &\quad - Setup\ \&\ changeover \end{aligned} \tag{3.3}$$

and

$$\begin{aligned} &Planned\ operating\ time \\ &\quad = Total\ shift\ time \\ &\quad - Planned\ maintenance \end{aligned} \tag{3.4}$$

The third and fourth losses are regarded as speed losses and measure the performance efficiency, i.e. the ideal speed compared to the actual speed of the process. See (3.5), and its subcomponents, (3.6) and (3.7).

$$Performance\ efficiency = Net\ operating\ rate * Operating\ speed\ rate \tag{3.5}$$

where,

$$Net\ operating\ rate = \frac{Number\ produced * Actual\ cycle\ time}{Operation\ time} \tag{3.6}$$

and

$$Operating\ speed\ rate = \frac{Theoretical\ cycle\ time}{Actual\ cycle\ time} \tag{3.7}$$

The remaining two losses are categorized as quality, which is a measure to quantify the number of defects in relation to the total production volume, see (3.8).

$$Quality\ rate = \frac{Total\ number\ produced - Number\ scrapped}{Total\ number\ produced} \tag{3.8}$$

The OEE measure is then calculated by multiplying the three main elements (3.2), (3.5) and (3.8). This gives the OEE, see (3.9).

$$OEE = Availability * Performance\ efficiency * Quality\ rate \tag{3.9}$$

Many of the uncertainties in a production environment are connected to these different measures; availability, efficiency and quality. For example, the availability measure takes all unplanned stoppages into account, the performance efficiency considers the actual output and the quality rate includes possible quality problems. Using the OEE measure makes it possible to track the total performance and variations of the internal production process.

Suppliers

The supply process, naturally, has some uncertainties because it is out of the control of the company. In the same way, as with demand uncertainty, the uncertainty lies in what quantity and at what time a delivery will actually take place. The lead-time uncertainty is one of the uncertainties in the supply process. The lead-time is defined as the time between placing an order and the delivery of that order (Mattsson & Jonsson, 2003). There are two types of stochastic lead-times; sequential deliveries, and independent lead-times. Sequential deliveries cannot cross in time, which means that an order placed after another cannot be delivered before the first order (Axsäter, 2006). This is reasonable to assume if the orders are handled on a first-come, first-served (FIFO) policy. However, there are situations when the orders are handled according to some prioritization that will allow an order that was placed later to pass an earlier placed order. Also if the orders are treated by different servers, they can cross each other.

It is more difficult to model lead-times when orders cannot cross each other, because the lead-time depends on the queue at the supplier, which in turn results from previous orders (Axsäter, 2006). To be able to model this situation, information about the inventory and the queues need to be included. Further on, Axsäter (2006) argues that in reality it is more difficult to evaluate lead-time variation than demand variation, and if the lead-time variation is small enough it can be replaced by its mean value.

3.2.2 Definitions

The following subchapter describe definitions related to inventory control.

Cost

The cost factors are not included in the simulation model of this thesis. However, it is important to understand the costs that are related to inventory control in order to understand the effect of different inventory levels, which is highly relevant in this thesis.

One essential difference in terms used, is the difference between inventory position and inventory level. Inventory level is the physical on-hand inventory minus possible backorders, i.e. orders that have been demanded but not yet delivered to the customer, see (3.10). The inventory position also includes outstanding orders, i.e. placed orders that have not yet been delivered, see Definition (3.11) (Axsäter, 2006).

$$Inventory\ level = Stock\ on\ hand - Backorders \tag{3.10}$$

$$Inventory\ position = Stock\ on\ hand + Outstanding\ orders - Backorders \quad (3.11)$$

Holding cost is the cost of keeping inventory. The cost is associated with the return of capital that could be given from alternative investments, but also other factors of keeping inventory should be included, for example material handling, obsolescence, insurance and taxes (Mattsson & Jonsson, 2003). All variable costs associated with the inventory level should be included in the holding cost and the holding cost is measured per unit and time. The holding cost exists only for positive inventory levels (Axsäter, 2006).

If the inventory level is negative, i.e. backorders exist, the corresponding cost is called shortage cost (Axsäter, 2006). The cost depends on what happens if the requested demand cannot be delivered. If the customer chooses another supplier, the shortage cost is the cost of lost sales, both current and future. If the customer accepts to wait while the order is backlogged different costs occur, for example extra administration or price discounts. Another example is when material can be bought immediately from another source, at a higher price, and the shortage cost is then the additional cost for buying the material (Axsäter, 2006).

A third cost generally included in theory of inventory control is ordering cost. In the case of ordering goods, ordering cost is the cost of placing a replenishment order. In terms of production, ordering cost is the cost of setting up the production (Axsäter, 2006).

Safety stock and safety time

As described in section 3.2.1 several uncertainties exist within an inventory system. Safety stock is a part of the inventory that is used to compensate for these uncertainties (Lumsden, 2006). Determining the safety stock is related to determining the ordering point (Axsäter, 2006). The reorder point *R* is equal to the expected demand during the lead-time $\hat{x}_L$ and the safety stock *SS,* see (3.12).

$$R = \hat{x}_L + SS \quad (3.12)$$

The safety stock is not always a quantity unit, it can also be measured in time units (Axsäter, 2006). When the safety stock is time based, an order should be delivered at least one safety period before it is needed. It is common to use safety times when using Material Requirements Planning (MRP) (Axsäter, 2006).

Service levels

Service levels are used to determine a suitable reorder point and order quantity for the system or to evaluate the current ordering policy. This thesis mainly focuses on evaluating the service level of the current inventory system. Axsäter (2006) uses three different measures of service level.

- S_1 = $SERV_1$ = probability of no stockout per order cycle
- S_2 = $SERV_2$ = fraction of demand that can be satisfied immediately from stock on hand, called fill rate
- S_3 = $SERV_3$ = fraction of time with positive stock on hand, called ready rate

S_1 is not recommended to use in practice for inventory control because it has some critical disadvantages (Axsäter, 2006). It measures the probability of no shortage during an order cycle. It does not take into account the size of the batch, only what happens after an order is triggered until it is delivered. Fill rate and ready rate represent the true service level better since they also consider the order quantity (Axsäter, 2006). If the demand is either continuous or Poisson distributed, fill rate and ready rate are equivalent. However, if the demand is modeled as a Compound Poisson distribution, where several units may be ordered at the same time, the ready rate can be high if there are only a few units in stock but the fill rate can be low because the stock cannot cover the orders (Axsäter, 2006).

There are more ways to represent the customer service than the use of the three measurements previously presented. It can also be measured in terms of how long waiting time a customer experience or through the usage of shortage costs (Axsäter, 2006). The use of shortage costs can, in a similar way as service level measures, be used to determine a suitable reorder point. Instead of defining the required service level the cost of having backorders is determined. In the empirical chapter (Section 4.9) it is described how BorgWarner has defined their service level and in the model chapter (Section 6.4.3) it is discussed how the service level in the tool should be interpreted.

In practice the pre-determined service level should be based on the actual customer expectations, or if shortage costs are used it should reflect the true costs that occur with backorders (Axsäter, 2006). It is also of importance that the service level used is well defined throughout the company (Axsäter, 2006).

Consignment stock

Manufacturing companies often purchase ingoing material ahead of the actual point of use, in order to be able to counteract delivery disturbances or supplier problems. The stock is often kept physically close to the manufacturing facility and all warehousing operations are carried out by the manufacturing company. The setup of keeping a material stock can vary between companies but traditionally a company purchases the stock from a supplier as previously described. An alternative approach is the use of consignment stock, which means that the goods are physically transported to the buyer but the ownership is retained by the supplier until the buyer calls off the material for production. Through this approach the manufacturing company can reduce the risks associated with late deliveries while minimizing the capital tied in inventory (Voss & Woodruff, 2005).

3.2.3 Ordering policies

An inventory control system has a twofold purpose, both to determine when and how much to order. The decision is taken in regard to the current stock situation, anticipated demand and other factors (Axsäter, 2006). The purpose of this section is to give the reader a better understanding of ordering policies to be able to understand the processes at BorgWarner.

Continuous or periodic review

Continuous or periodic review concern how the inventory level and position is monitored. With continuous review the inventory is monitored continuously, which means that as soon as the inventory position gets below a predefined level an order is triggered (Mattsson & Jonsson, 2003). If a periodic review system is used, the inventory position is only checked at predefined intervals. If the inventory position is below the set ordering level, an order is triggered and if the position is above, one waits until the next interval to check whether the position has dropped below (Mattsson & Jonsson, 2003). With the use of periodic review the inventory position can drop below the ordering level if the demand during the last interval has been high. With a periodic review system the inventory position must safeguard against demand variation both over the review interval and the lead-time. Such a system has advantages when the ordering of several products needs to be coordinated. Such systems also result in a lower total operating cost (Axsäter, 2006).

(R, Q) policy

An (*R, Q*) policy is an ordering policy that orders a predefined batch quantity *Q* when the inventory position is at the level *R* or below, see Figure 3.1. If the inventory position is at a level where ordering only *Q* units will not get the inventory position above *R*, a multiple of *Q* will be ordered. Therefore an (*R, Q*) policy might be called an (*R, nQ*) policy (Axsäter, 2006).

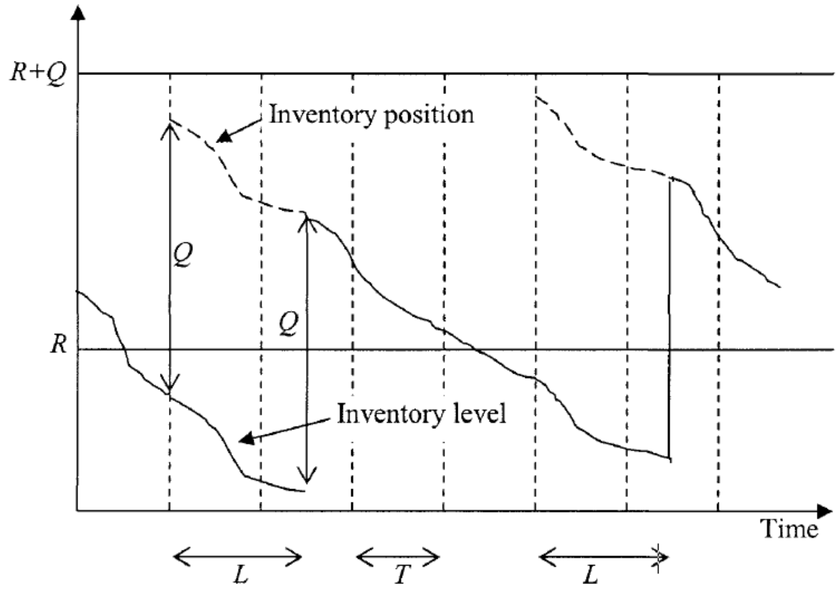


Figure 3.1. (R, Q) policy with periodic review and continuous demand (Axsäter, 2006).

An ordering policy that is closely related to an (R, Q) policy is a KANBAN policy (Axsäter, 2006). A KANBAN system contains a number (*N*) of containers each of which has a KANBAN card associated with them. When a container becomes empty, the card is used to trigger the replenishment of *Q* units (Axsäter, 2006). At all times there are *N-1* containers that are either full or have a triggered order associated with them. This corresponds to an (R,Q) policy, $R = (N-1)Q$, where the order quantity is *Q*. KANBAN systems are only suited for repetitive manufacturing (Hopp & Spearman, 2000).

(s, S) policy

Another ordering policy is the (s, S) policy. This policy has many similarities with an (R, Q) policy, but also a few significant differences. The reorder point at level *s* is interpreted in the same way as the reorder point *R* for an (R, Q) policy. The difference is that an (s, S) policy does not order the same quantity, or a multiple of it, each time. Instead a quantity, *S*, that increases the inventory position to the fixed level *s* is ordered, see Figure 3.2 (Axsäter, 2006).

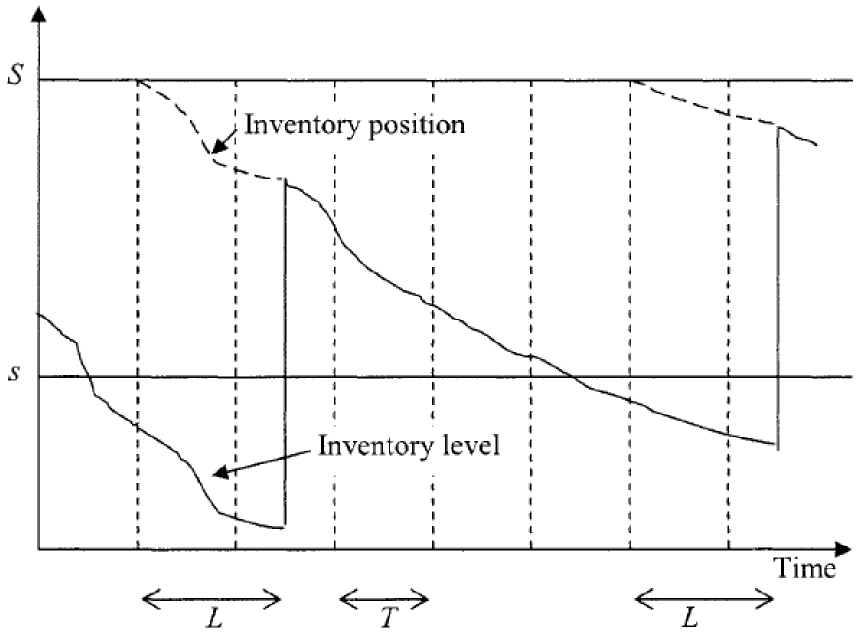


Figure 3.2. (s, S) policy with periodic review and continuous demand (Axsäter, 2006).

Material requirements planning

Both the (R, Q) and the (s, S) policies are based on a static reorder point and the creators of MRP found that this ordering approach was better suited for final products than components (Hopp & Spearman, 2000). Final products have a demand that is triggered outside the company's system, while components' demand is dependent of the production of the final products. For this reason the two types should be treated differently (Hopp & Spearman, 2000).

MRP is used to determine when and how much to order of components to satisfy the production and external demand of the final products (Hopp & Spearman, 2000). MRP usually has a periodic review and a rolling planning horizon. The planning procedure is based on the following data and assumptions (Axsäter, 2006).

- A production plan for final products.
- Demand for components that do not originate from the production plan, for example spare parts.
- A BOM for all items specifying all of its immediate components and the quantity needed per parent item.
- Inventory status for all items.
- Constant lead-time for all items.

- Rules for safety stocks and/or safety times and batch quantities.

The planning starts with determining the demand for final products, which then results in a master production schedule (Hopp & Spearman, 2000). The master production schedule is used to determine the requirements for the immediate components and the respective order date with respect to delivery lead-time and potential safety time. This procedure can then continue for further immediate components, using the production plan of the subsequent component. The result of the procedure is an ordering plan with regard to when the material is required.

Freeze time

A common problem when using MRP is the instability that can occur due to changes in the plans for single products (Axsäter, 2006). Small changes for a few high level items in the BOM can create large changes for many lower level items. To avoid the instability one can freeze the production or orders within a certain time frame. By freezing the plan, no changes can be made within that time frame. Freezing the MRP is a cost effective way to reduce the instability (Sridharan & LaForge, 1994). With a longer freeze time, the need of a larger safety stock is often required because it reduces the company's ability to respond and adapt to changing market needs. However, under some circumstances increasing the freeze time does not reduce the service level or increase the need for safety stock (Sridharan & LaForge, 1994).

3.3 Statistics theory in connection with inventory control

This section presents relevant theory within the field of inventory control and the scope of this thesis. This statistics theory is valuable for the data analysis in Chapter 5.

3.3.1 Distributions

In statistics theory there are several standard distributions that can be used to represent empirical data or observations. These standard distributions represent many natural processes in a satisfactory manner. Some of the most known and used distributions are the exponential distribution, the uniform distribution and the normal distribution (Blom, et al., 2005).

The exponential distribution and the Poisson distribution are closely related. The exponential distribution describes the time between events in a Poisson process, which is a process where events happen independently and continuously at a constant average rate. An example would be to model the number of calls to a customer service center during a set time period.

In a uniform distribution the probability of obtaining a specific outcome is equal for all values within a set range (Blom, et al., 2005). The waiting time on the platform for a train or the outcome of rolling a fair dice can be modeled as having a uniform distribution.

The normal distribution has a widespread use in modeling and statistics and is often used to describe the variation for different events (Blom, et al., 2005). One reason for the widespread use, is that the mean of a sample drawn for almost any distribution can be modeled as having a normal distribution, using the central limit theorem (Blom, et al., 2005). Even though few examples are exactly normal distributed, many are assumed or approximated to be normal distributed.

3.3.2 Goodness of fit test

To determine if a set of data fits a statistical model one can analyze the goodness of fit. A goodness of fit test compares the discrepancy between the observed values and the values expected from the statistical model. Several different goodness of fit tests exist today, but in this section one of the most common tests will be described; Pearson's chi-squared goodness of fit test (Franke, et al., 2012).

The null hypothesis that is tested in Pearson's chi-square test is that the observations or data follow a specified distribution. The alternative hypothesis is that the data does not follow the specified distribution (Franke, et al., 2012). The calculation of the chi-square value χ^2 is presented in (3.13).

$$\chi^2 = \sum_{i=1}^{m} \frac{(O_i - E_i)^2}{E_i} \tag{3.13}$$

where *m* is the number of bins used, O_i is the observed value and E_i is the expected value. χ^2 is compared with the chi-square distribution for *d* degrees of freedom and rejected if the observations differ significantly from the specified distribution at a significance level α (Franke, et al., 2012), i.e. according to (3.14).

$$\chi^2 > \chi^2_\alpha(d) \tag{3.14}$$

The chi-square test should not be used if the sample size is less than 20 (Laguna & Marklund, 2005). Before calculating the χ^2, appropriate bins need to be chosen and expected value E_i calculated, see (3.15).

$$E_i = n * p_i = n * (F_0(a_i) - F_0(a_{i-1})) \tag{3.15}$$

where n is the number of observations, p_i is the probability for bin i and F_0 is the cumulative distribution function of the hypothesized distribution. To improve the accuracy of the test, it is advisable to use a bin width which results in all bins having the same probability (Laguna & Marklund, 2005). There are no explicit rule of how many bins to use, but a rule of thumb is that at each bin should have an expected value of at least five (Laguna & Marklund, 2005). If the same probability is used for each bin, the expected value can be as low as one (Blom, et al., 2005).

3.4 Modeling

When analyzing a system it is of interest to study how a system behaves under different conditions. This thesis is about analyzing the effect that a change in inventory level has on the service level and other parameters. A system is defined as a limited collection of entities, which interact with each other to achieve a desired goal (Law & Kelton, 2000). There are several ways to study a system, where simulation is one. Law and Kelton (2000) describe different alternatives, as shown in Figure 3.3. These alternatives are discussed in Section 6.1.1, when choosing the appropriate way to fulfill the purpose of this thesis.

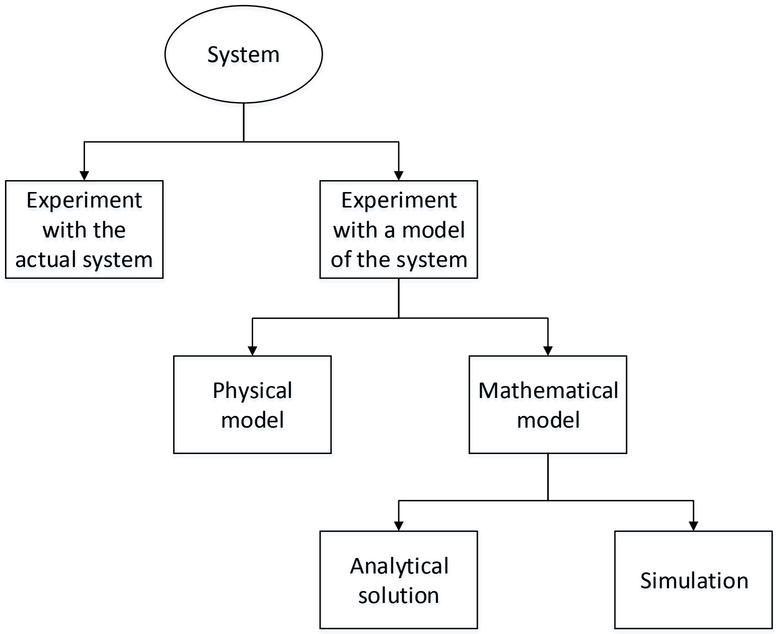


Figure 3.3. Different ways to analyze a system (Law & Kelton, 2000)

3.4.1 Experiment with the actual system vs. experiment with a model of the system

If possible, it is often advantageous to make alterations to the actual system and then study the system under the new conditions. However, it is rarely possible or cost effective to change a system, and it might cause unacceptable disruptions to the system. For the purpose of this thesis such an experiment would be to increase or decrease the inventory level and analyze the effect on the service level. The alternative is to construct a model that represents the system. A potential limitation when using a model is how well the model represents reality.

3.4.2 Physical model vs. mathematical model

Physical models are e.g. flight simulators or clay cars in wind tunnels. Physical models have also been built and used within other fields, such as miniature representations of material handling systems. A mathematical model is a logical model that describes the logical and quantitative relationships between entities. By altering these relationships the effect can be studied and conclusions can be drawn for the real system if the logical relationships are representative.

3.4.3 Actual solution vs. simulation

When choosing a mathematical model, it can be studied either by an analytical approach or through simulation. If the model representing the system is simple, it might be possible to study the relationships and quantities to get an exact analytical solution. If the relationships can be studied analytically, it is often desirable to do so. However, many times the model is too complex to analyze analytically and therefore must be studied through simulations. The drawback of simulation is that the method does not give an exact outcome of the model.

3.5 Simulation

Some key issues to consider when constructing a simulation model are making adequate approximations and assumptions, gathering data and information, setting the logical and quantitative relationships and ensuring the realistic representation of the model. The assumptions and the logical relationships are further described in Chapter 6 and data gathering are described in Chapter 4. In this section relevant theory is presented for ensuring correct representation of the simulation model.

When discussing the realistic representation of a simulation model, three definitions need to be clarified; validation, verification and credibility. First, verification means that the conceptual simulation model is implemented correctly in the computer program (Sargent, 2010). Validation is that the computerized model represents the system satisfactorily within the model’s intended purpose

(Sargent, 2010). Closely related to validation is output analysis, which is the estimation of the simulation model's representation of the true performance (Law & Kelton, 2000). Sargent (2010) describes several different methods to ensure verification and validation, and the relevant test methods for this thesis are presented in Table 3.2.

Table 3.2. Different tests for validation and verification (Sargent, 2010).

Test method	Description
Degenerate test	Test the degeneracy of the model's behavior by selecting appropriate input and output parameters.
Extreme condition tests	The outputs for any extreme combination of factors should be plausible.
Face validity	Knowledgeable individuals are asked about the behavior and performance of the model .
Historical data validation	The performance is checked against historic data.
Internal validity	Several replications are made to determine the variability in the model and if the variability is high it might cause the results to be questionable.
Predictive validation	The model predicts the behavior and is compared to the system's real behavior.
Traces	The behavior of entities are followed through the simulation to determine that the logic and accuracy are correct.
Turing tests	Knowledgeable individuals are asked if they can discriminate between the real outcome and the model outcome.

However, the validation of a simulation model can usually be increased by increasing the cost and time of developing the model. To determine that a model is absolutely valid is often too costly. The developers of such a model need to find a good balance between assuring the validation of the model and the cost associated with it.

4 Empirical data

This chapter presents the findings of the value stream mapping phase of this thesis. The chapter is divided into subchapters describing each part of the internal supply chain at BorgWarner; products, assembly lines, the machining department, customers and forecasting, supplier situation, planning procedures, inventory, service level and quality issues.

4.1 Purpose of value stream mapping

The value stream mapping phase was carried out with the approach described in Chapter 3.1. The purpose of the value stream mapping was to create a current state map for the products within the delimitations of this master's thesis, i.e. the high volume serial produced couplings. No effort was made to establish the value adding times of each activity as the purpose of this thesis is not to identify possible areas of improvement.

In order to narrow the scope of the value stream map the products were classified according to a process family matrix, see Section 3.1.1. In the process family matrix the key activities were identified and then matched against each product, the result can be seen in Appendix A. From the process family matrix two main conclusions could be drawn; production is similar for all products in generation 4, except for product 1, and generation 5 production is substantially different. The conclusions resulted in a decision to make separate value stream maps for the different product generations. The result of the value stream mappings is presented in the subsequent subchapters and a graphical representation is shown in Appendix B.

4.2 Products

The products manufactured at the production facility in Landskrona are couplings for all-wheel drive passenger cars. BorgWarner's customers are first tier suppliers for the major car manufacturers in Europe and North America. The majority of the couplings produced are conventional couplings which are separated into product families by generations. In the spring of 2013, two generations, Gen4 and Gen5, are serial produced in high volume while spare parts are produced in low quantities for the older generations, see Figure 4.1. In this thesis only the high volume serial produced couplings will be considered.

Figure 4.1. A Gen4 (left) and Gen5 (right) coupling. (BorgWarner Inc., 2013)

The Gen5 coupling is the latest conventional coupling and is a development of the Gen4 coupling. The development of the couplings is mostly cost driven, which has resulted in a simpler design of the Gen5 coupling. The simpler design is mainly lowering the cost through fewer components and, consequently, a simpler product structure. The Gen5 couplings cost approximately ten percent less than the Gen4 couplings. The Gen5 product family, currently, only consists of two product variants, while more are under development. The Gen4 product family consists of about ten different product variants. Each variant has a unique BOM and while the product structure of some variants is very similar, each variant has its own unique article number and each article is sold to one customer only.

During the development of this thesis (spring 2013) the majority of the products sold are still Gen4 couplings, but it is expected that the demand will shift towards the Gen5 couplings during the second half of 2013. To the largest customer, see 4.5, only the Gen4 coupling is sold.

4.3 Assembly lines

The couplings that are relevant for this thesis are assembled in three semi-automatic assembly lines at the Landskrona plant. Two assembly lines, called A and B, produce the Gen4 coupling while a third, called C, produces the Gen5 coupling. Since the physical product structures of the two product generations are different it is not possible to produce the Gen4 couplings in assembly line C or vice versa. In the Gen4 product family there are some variants that have product structures that differ enough to require a changeover of tools when switching between the variants. All of these variants are produced in assembly line B and the changeover time is relatively short compared to the takt of the assembly line. A changeover is also necessary when switching between the Gen5 variants in assembly line C. The changeover time for line C is longer, especially compared to the takt of the assembly line.

All three assembly lines feature sequential layouts and successively the couplings are assembled one component at a time in batches. The assembly lines are semi-automated which means that some steps are carried out automatically by automated processes where robots or tools assemble the parts and some steps are carried out by a human operator. Steps that are carried out automatically are typically simple steps or operations where force needs to be used, e.g. tightening a bolt. The steps carried out by operators typically require a slightly higher level of coordination, e.g. fitting a cable while bending it. At different stages in the assembly process the couplings are also, automatically, tested in order to ensure a high product quality.

The assembly process is one of the most important processes at BorgWarner and to ensure high validation of the model, correct representation of the this process is crucial, see Section 6.4.3.

4.3.1 Efficiency

The output of the assembly lines depends on the weekly capacity and takt of each line. The takt is set according to the type of variants that are going to be produced as there are some minor differences, which require extra time, in the assembly process.

The workforce manning the assembly lines also directly affect the output of the shifts. It is possible to operate the assembly lines with reduced staffing. The planned output is based on the planned, available workforce, but if there are unexpected sick leaves this will affect the output negatively. The output is also affected if the operators work slower than planned or if they make more mistakes than what is acceptable, e.g. what might be expected for new staff. The performance of the staff is measured in the performance efficiency component of the OEE, see (3.9). If the assembly lines are run with full workforces the limiting factors of the assembly lines are the automated steps and procedures, hence it is not possible to run the assembly lines faster than the takt set with full workforce. Table 4.1 shows the key parameters for each assembly line.

Table 4.1. Parameters for each assembly line.

Line/parameter	A	B	C
Takt[1] (units/h)	75	77/75	70/58
Max Capacity[1] (weekly)	9100	9300/9100	4600/3800
Max batch size[2]	486	486	270/180
Variants	6	6	2
Changeover time (min)	-	6	18
Full workforce	7	7	4

There are also non-value adding activities that reduce the output such as changeover time and scheduled maintenance. These non-value adding activities are considered by the production planners, when the master planning is carried out, and are not considered to be production losses.

However, there are more serious disruptions that reduce the output capacity of the assembly lines. These disruptions include machine breakdowns, worker inefficiency, material shortage and material quality issues. All of these unplanned disruptions are recorded in a central management system. From the central management system the OEEs of the assembly lines can be derived.

For the purpose of this thesis the OEE data, per shift, for the three assembly lines was collected from the beginning of January 2012 to mid-march 2013. This is presented in Figure 4.2, Figure 4.3 and Figure 4.4. The OEE data is further analyzed in Section 5.2.1 to obtain a statistical representation of the data in the model.

[1] When run with full workforce. Also depends on the variants assembled.

[2] Batch size depends on the variant of coupling.

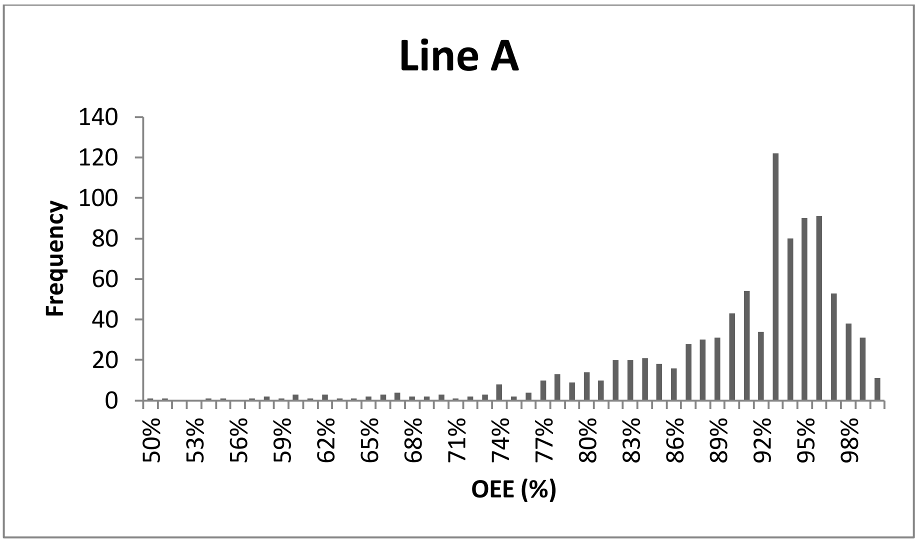


Figure 4.2. Histogram of the OEE output of assembly line A.

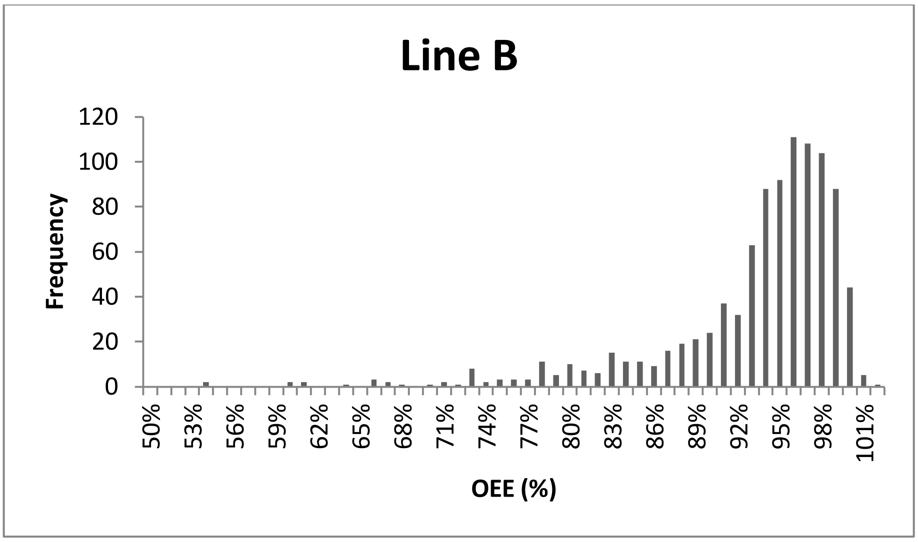


Figure 4.3. Histogram of the OEE output of assembly line B.

For assembly line A and B the OEE output is relatively stable and the majority of the outcomes are in the range of 85% to 100%. This is typically due to minor production incidents, such as sporadic quality issues or reduced workforce. The stable output is also a sign of a balanced takt in the assembly lines.

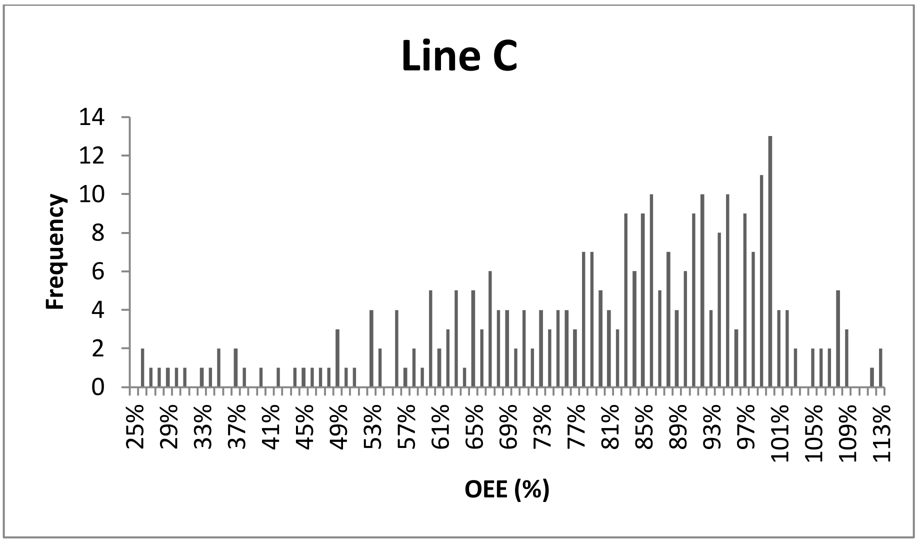


Figure 4.4. Histogram of the OEE output of assembly line C.

For assembly line C the OEE data is a lot more scattered and the center of gravity of the OEE outcome is just barely noticeable in the upper range above 70 %. This is mainly due to start-up and fine tuning issues. It is also worth noting that the number of observations for assembly line C is significantly lower than for the other two assembly lines. This is mainly due to the fact that production in assembly line C started during the spring of 2012, and that during the time period of the data collection the number of shifts in assembly line C was significantly lower than the other two.

Closer analysis of the OEE data shows that there is no significant nor systematic seasonality for output of the assembly lines and that the deviations are, relatively, similar for each month. See Appendix C for detailed monthly data.

4.3.2 Scheduled production and overtime production

Generally, line A and B run 24 hours per day, in three shifts, on weekdays until Friday. On the afternoon of Friday the weekend shifts begin which are slightly longer – nine hours on Friday afternoon and Saturday morning and twelve hours on Sunday. Line C is generally operated on the morning and afternoon shifts of each weekday and not operated at all during the weekends. The current operating hours of the assembly lines can be seen in Appendix D.

Overtime production

When there are disruptions in production there are certain routines for handling such events. Usually, a meeting is held between the production planners, material planners and production managers. The trigger for these meetings is generally that the output of a single assembly line falls 100 units behind the set goal of the week. One possible measure to reverse the production loss is to issue overtime production.

Overtime production can be issued for a whole extra shift or for just a few extra hours. The limit is that there must be an empty subsequent shift. For line A and B the normal overtime shift is the night before Saturday and if that is not sufficient there is also the possibility to issue overtime on the night before Sunday. Overtime for line C is normally issued on the Saturday weekend shift.

4.4 Machining department

Beside the assembly process at BorgWarner there is also a machining department that does surface treatment of blanks (untreated coupling houses). The machining department consists of six automatic CNC lathes. The theoretical cycle time for one batch in one lathe is around 30 minutes, while the changeover time for switching tools in the lathes is around 30-40 minutes. Therefore it is important to minimize the number of changeovers. Normally, three lathes are setup to process Gen4 blanks and one or two lathes are set to process Gen5 blanks. The remaining lathes are used for processing blanks for older generations. Apart from the lathes the machining department also consists of a deburring machine, two washing machines and six leak test machines. The bottleneck in the treatment process is the lathes which have a lower total takt than the rest of the machines, see Appendix E.

The treatment process for the different generations of blanks is not identical. Blanks of both generations start in the lathes for treatment, after which the Gen5 coupling houses go straight to washing and then to the leak test. After processing in the lathes the Gen4 coupling houses go to the deburring machine for extra processing. After the deburring, the coupling houses are sent to an external contractor for sealing. This extra step typically takes two full days, including shipping. When the Gen4 coupling houses return from sealing they are also washed and leak tested. A summary of the parameters for each activity is presented in Appendix E.

The entire machining department is KANBAN controlled and consists of two KANBAN loops. For both generations of coupling houses the first loop consists of the leak test and the washing machines. For the Gen4 the second loop consists of the external sealing, deburring and the lathes. For Gen5 coupling houses the second loop only consists of the lathes.

The first KANBAN loop is initiated when a pallet of finished coupling houses is collected, by the material handlers of the assembly lines, from a pallet rack with finished goods. This sends a KANBAN production order to the washing and leak test to start production. This in turn, sends a KANBAN production order to the second KANBAN loop to start production. The representation of the KANBAN loop in the model is described in Section 6.5.3.

4.5 Customers and forecasting

BorgWarner has two major customers, in terms of turnover and number of couplings sold. The largest customer is a first tier supplier for the automotive industry located in Austria. BorgWarner currently holds a consignment stock on-site for this customer. For the other customer the goods are sold with the INCO-term FCA. The FCA INCO-term means that the ownership and responsibility for the goods is transferred from the consignor to the consignee when the goods are loaded onto the mode of transport, e.g. a trailer.

As BorgWarner retains the ownership of the couplings in the consignment stock at the largest customer, that customer keeps no inventory or safety stock of finished couplings itself. The other customer owns its own inventory and its own safety stock. For the sake of this thesis the second largest customer is hereafter referred to as customer X while the largest customer is referred to as customer Y.

Shipping

Since customer Y is located in central Europe the physical distance implies a delay in transporting the goods to the consignment stock. The transport lead-time to the consignment stock is two days and goods are shipped every weekday and received, by the customer, every weekday. Goods to customer X are sent every Monday to Thursday. For the other customers goods can be shipped on any weekday, although less frequently.

Forecasting and freeze time

BorgWarner has no independent forecasting routines, but instead relies on the forecasted demand provided by the customers. The origin of the customers' forecasts is in turn based on the OEMs in the automotive industry. Forecasts are sent to BorgWarner once a week from the customers and typically span the coming ten to twenty weeks. The forecasts are then the basis for planning at BorgWarner. The forecasts are further analyzed in Section 5.2.4.

The forecasts can be changed by the customers from week to week but in the agreements between BorgWarner and their customers there is a theoretical freeze time. The freeze time is typically the weeks closest in time from the date of the forecast. During the freeze time there are certain limitations of how much, often specified in percentage, the forecasted quantities can be changed by the customer. For example there can be a two week zero percent flexibility followed by a two week fifteen percent flexibility. In practice, these freeze times against the customers are not utilized and the production planners and material planners try to meet the fluctuating demand of the customers as good as possible. The argument for providing this extra flexibility is to gain goodwill from the customers, i.e. if BorgWarner helps their customer in times of need, the customer will be more forgiving if there are problems at BorgWarner.

There are no set regulations or specifications of this flexibility in the freeze time. This leads to a problem when it comes to defining the delivery precision. According to the agreements BorgWarner should have 100 percent delivery precision. The definition of what 100 percent delivery precision means is very vague. There are, currently, no implied fees for late or missed shipments, instead any incident that incurs a production loss at the customer will result in a penalty equivalent to the cost of the production loss.

4.6 Suppliers and supply planning

Apart from the coupling house, all the components for the couplings are bought from external suppliers. There is a plethora of suppliers supplying everything from O-rings to electronic control units. The ordering of components follows a MRP system and is today carried out by four material planners at BorgWarner.

Receiving goods is possible on every weekday but the frequency of deliveries depend on a number of different factors, such as demanded quantity, value of the component and the lead time from the supplier. For all components in serial production there is a minimum safety time of two days production, i.e. the inventory on hand should be sufficient to cover the planned production for the coming two days without restocking. This safety time is not evaluated on a regular basis and could be subject to change in order to optimize the component inventory. A longer safety time would likely result in a higher service level towards the customers, while a shortened safety time could result in problems with material shortage to a larger extent than today. Some of the components that are ordered less frequently have a safety time that is longer in order to cover the gap between deliveries.

The delivery precision of the suppliers is also measured and reported into a central management system. An on-time delivery is defined as a shipment delivered to BorgWarner on the same day as planned. A late delivery is defined as any shipment that arrives at least one day later, than agreed upon and an early shipment is measured correspondingly. No consideration is taken to how many days late or early a shipment is. The delivery precision for the most important, in terms of critical components, suppliers during 2012 can be seen in Appendix F and an analysis of the data can be seen in Section 5.2.3.

In contrast to the agreements with the customers, there are freeze times that are actually used against the suppliers. The freeze times range from one week up to four weeks depending on supplier. The flexibility within the freeze time is followed rigorously and only in case of emergency requests are made to the suppliers to get extra deliveries outside of the planned, and agreed upon, quantities. The representation of the freeze time towards suppliers is discussed in Section 6.5.3.

Plans to the suppliers are sent once a week and include a call off plan for the upcoming weeks, a short-term forecast based on the planned production orders and a long-term forecast for the coming year outside of the planned quantities.

4.7 Planning and master planning

The fixed production plan at BorgWarner typically covers a four week period. Within this period all production orders for all assembly lines are released and pending in a production queue. It is often possible to make minor quantity adjustments to the released orders or to change the order of them in the queue, provided that the change does not cause a material shortage. Outside of this time period the forecasted demand from the customers serve as basis for planned production orders, which are not yet released.

The master planning is performed once a week by the two production planners in cooperation with the material planners. Before the master planning is carried out the latest forecasts and call offs from the customers are updated. Adjustments are then made to the existing production plan, if possible, and production orders are released for another week. When the master production plan is updated the material planners update their material plans and send new plans with the updated quantities to the suppliers.

4.8 Inventory levels and movement

4.8.1 Finished goods inventory

The value of the historical inventory held at BorgWarner can be seen in Figure 4.5. The value shown is the total value of all finished couplings and components used in serial production. It can be observed that the component buffer follows the inventory of the finished goods with a slight negative offset. This is due to the fact that components are called-off ahead of production.

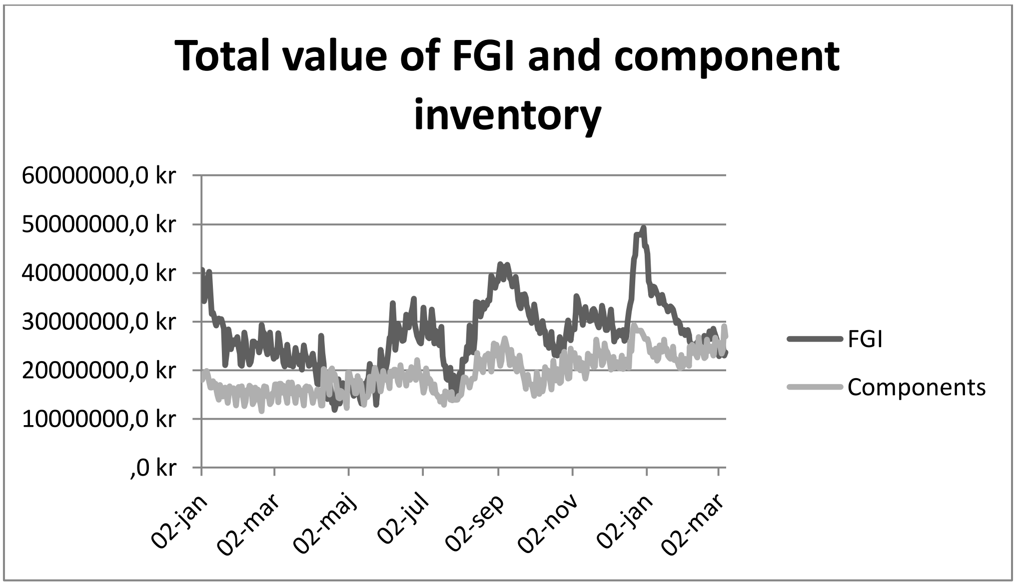


Figure 4.5. Total value of the FGI and component inventory from January 2012 to March 2013.

The past aggregated inventory level for all finished Gen4 and Gen5 products can be seen in Figure 4.6. In Figure 4.7 the inventory levels of customer Y can be seen. Recall, that only the Gen4 couplings are sold to customer Y. By comparing Figure 4.6 and Figure 4.7 it is evident that most of the inventory held is in couplings for customer Y and that the majority is located at the consignment stock. This is a deliberate strategy, to keep high inventory levels at customer Y, in order to provide flexibility. The inventory in the consignment stock works as a buffer against customer Y in case there are any changes in demand for customer X. In this way the assembly lines can focus on producing couplings for customer X, while the consignment stock supplies customer Y. The strategy provides a lot of flexibility in terms of focusing production in the assembly lines on the different customers.

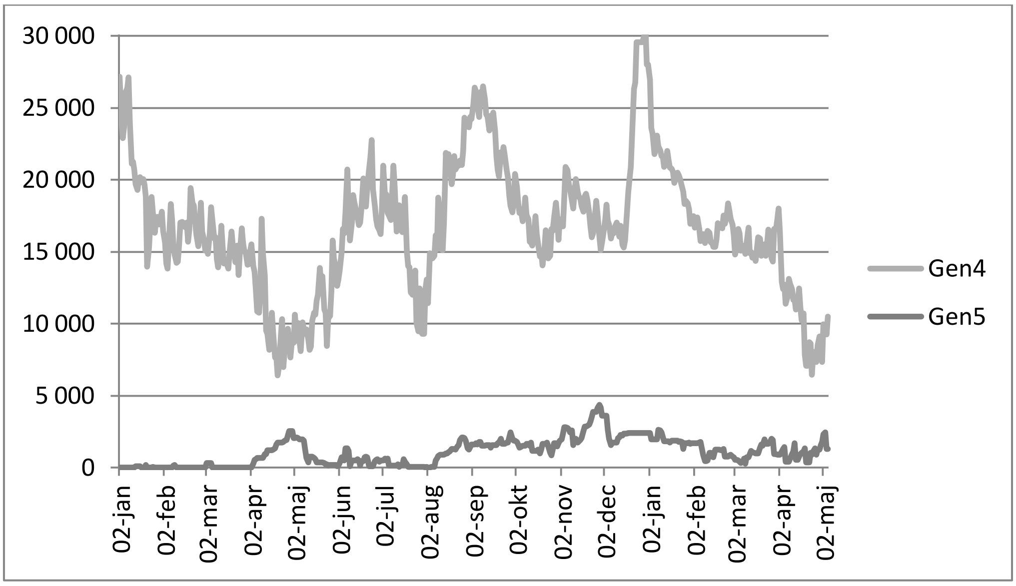


Figure 4.6. Total inventory levels (units) per generation from January 2012 to May 2013.

However, since the couplings in the consignment stock are different variants the strategy does not offer much flexibility if demand shifts between variants. The remote location of the consignment stock also presents problems if there are quality issues that had not been discovered before the couplings left the Landskrona plant. In some cases the Landskrona plant has had to send personnel to the consignment stock for quality checks and sorting. The main problem of a consignment stock of this size is the capital tied in inventory.

The Gen4 inventory level, seen in Figure 4.6, consists of both the consignment stock at customer Y as well as the FGI of all the Gen4 couplings. The introduction of the Gen5 coupling can be seen in the spring of 2012. Two major inventory increases can be seen in August and around Christmas in 2012. In both cases the customers made major reductions in their call offs within the set freeze time, which resulted in the build-ups. In April of 2012 and in late spring of 2013 there are reductions of inventory levels. These are not intentional, nor seasonal, but are the results of material quality problems.

Since the value of each coupling within a generation is approximately the same, the capital tied in finished goods inventory is directly proportional to the values displayed in Figure 4.6. It should be noted that the value per coupling is lower for Gen5 than Gen4, because of the simpler product structure.

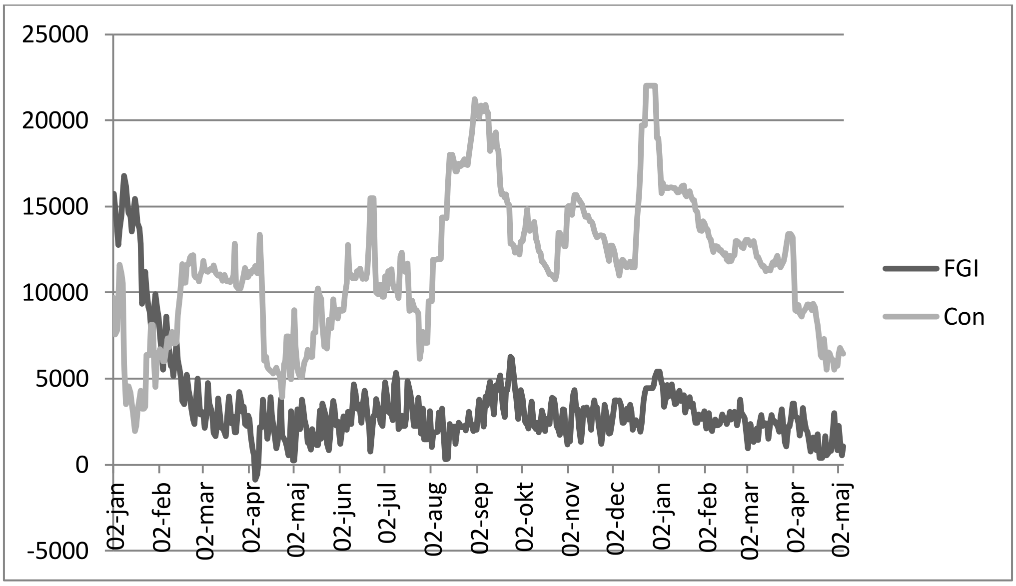


Figure 4.7. Inventory levels at the consignment stock and the FGI for customer Y from January 2012 to May 2013.

Figure 4.8 and Figure 4.9 show the average inventory per day for customer X and customer Y. The FGI inventory for customer Y and the FGI for customer X follow the same trend. The inventory is depleted during the week, due to deliveries being carried out on weekdays, followed by a buildup during the weekend. Since customer Y has production during the weekends, there is a slight build-up in the middle of the week. This is due to the fact that shipments that were sent during the preceding week arrive, which is then followed by a slight inventory reduction in the weekend when no deliveries are made.

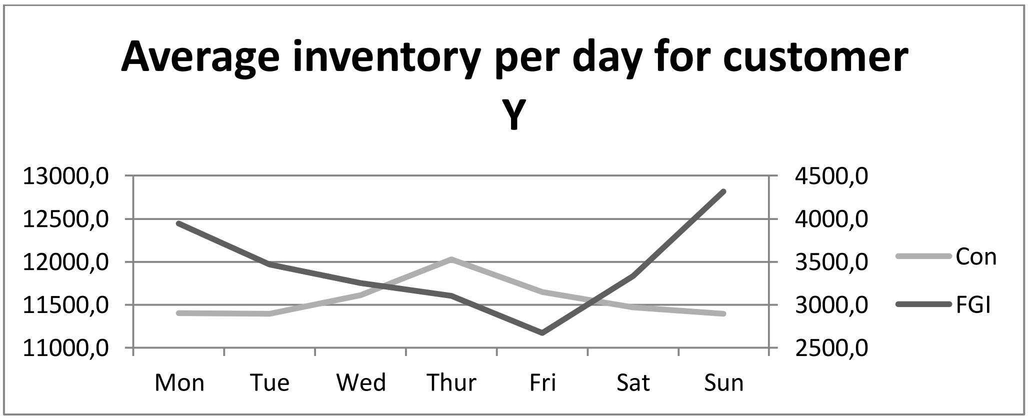


Figure 4.8. Average inventory per day at the consignment stock and the FGI for couplings for customer Y from January 2012 to May 2013.

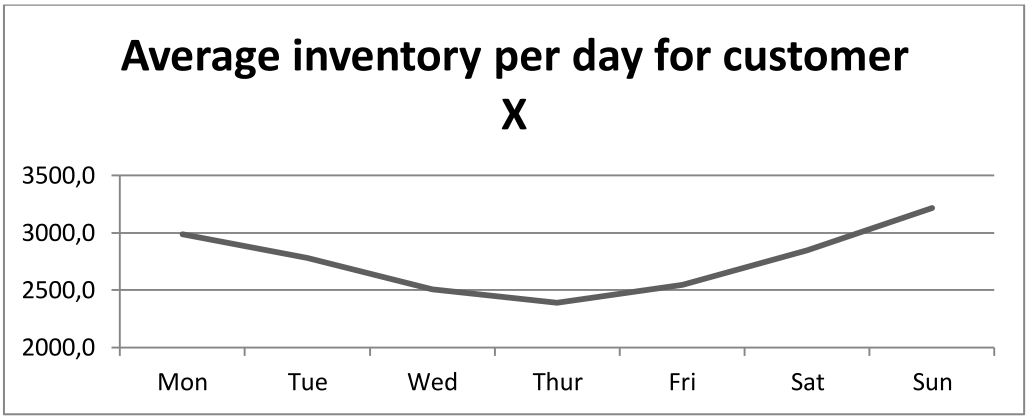


Figure 4.9. Average inventory (units) per day for couplings for customer X from January 2012 to May 2013.

Safety stock for the FGI

There is no explicit safety stock policy for the finished goods as there is for the components buffer.

4.8.2 Component buffer

The component buffer is comprised by all the components for the production of couplings. Typically, the components arrive at the goods receiving and are either put under incoming goods inspection or transferred directly to the components buffer. The components buffer then supplies the assembly lines with the required material. A special case is the coupling house, which is a component both when it arrives, as a blank, and when it is fully processed in the machining department. The processed coupling houses are not physically transferred back to the components storage area, but retained at the finished coupling houses pallet rack in the machining department.

The inventory levels in the component buffer depend on the value of the components, as well as the lead time from the supplier. Typically, low value components such as bolts, washers and O-rings are purchased in high quantities with infrequent deliveries, while high value components such as electronic control units are purchased in lower quantities and delivered more frequently. This incurs a higher average inventory level for the low value components.

The value of the past component inventory levels can be seen in Figure 4.10.

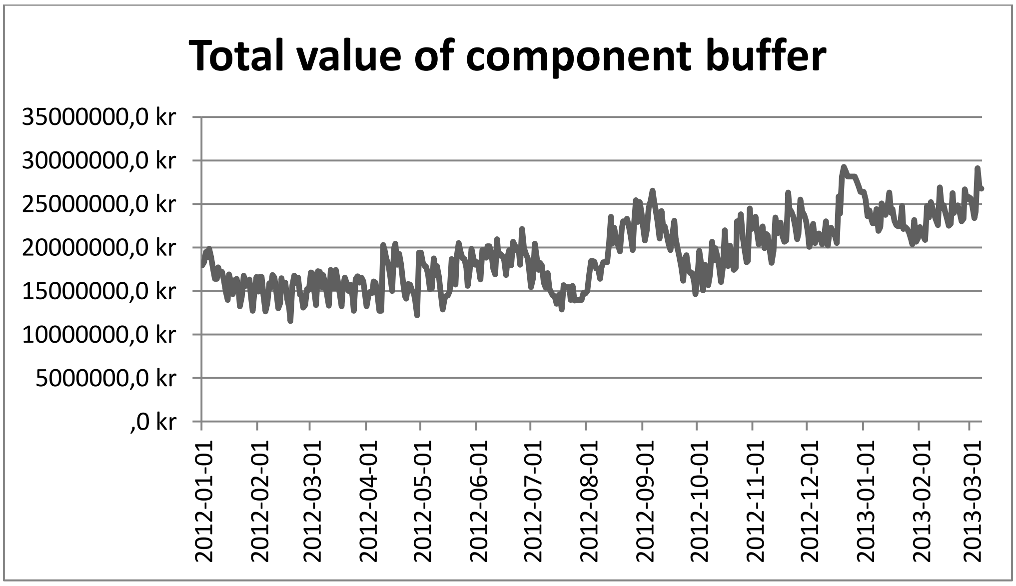


Figure 4.10. Total value of components buffer January 2012 to March 2013.

Safety stock for components

As stated earlier there is a safety time for the components buffer. The safety time is not a fixed quantity but a floating quantity that depends on the production plan for the following days.

4.9 Service level

BorgWarner has a goal of having 100% service level towards its customers. The definition of service level, used within the company, is the number of couplings delivered to the customer divided by the number of couplings promised on a monthly basis. This measurement only considers the absolute number of couplings. No consideration is taken to if BorgWarner delivers the correct variant of the couplings, hence under-delivery of one variant can be compensated by over delivery of another variant. The data for this measurement is aggregated each month, and therefore under delivery one day can also be compensated by over delivery another day without affecting the service level.

4.10 Quality issues

Since no process is perfect, there is a risk of defects in processing and assembly as well as a risk of defects in the incoming material. However, there are routines for dealing with these types of problems at BorgWarner. There are rigorous routines for detecting defects and errors throughout the assembly process, from when the components arrive at the component buffer until finished couplings leave the production plant. There are also routines for dealing with quality issues downstream in the supply chain at the customers and the OEMs, but this is outside of the scope of this thesis.

At the end of the machining process, as well as during the assembly process, there are a number of tests to ensure that the couplings meet the quality requirements and that every component is functioning properly. If a defect is discovered in one of the tests, the coupling is rejected from the assembly line and moved to a quality check area where the defect is analyzed. Each rejection is treated and analyzed independently and the outcome of the analysis is the basis for what action will be taken.

If the rejection is due to a process error the process will be reviewed and adjusted. If the rejection is due to a material defect, and there are numerous defects of the same type and the problem is severe enough, a material suspension will be issued. During a material suspension all material in the component buffer will be checked for further defects in order to ensure that no faulty material enters the assembly lines. Usually, a material suspension also implies an incoming goods inspection for that component.

Goods that are put under incoming goods inspection will be checked for defects before being transferred to the component buffer. Normally, components that are put under incoming goods inspection need to pass three consecutive deliveries without any defects in order to be removed from the list.

5 Data analysis

The purpose of this chapter is to explain the purpose and strategy of transforming the empirical data to input data for the simulation model.

5.1 Purpose and strategy of data analysis

In order to use the empirical data in the tool, the data needs to be analyzed and fit to statistical distributions that can represent the behavior of the different processes. The goal of the distribution fitting is to use distributions, that are as general and intuitive as possible, in order to keep the tool scalable and easier to expand with e.g. new products or assembly lines in the future.

With the outlined strategy the first-hand priority, in this thesis, has been to fit normal distributions to the observed data, as the necessary parameters, mean value and standard deviation, can easily be derived from input data, see Section 3.3.1.

5.2 Fitting statistical distributions to the data

In the following section the data fitting of the internal processes, as well as the forecasting and shipment events, will be presented.

5.2.1 OEE output of assembly lines

The OEE output of the assembly lines, in terms of probability, is described in Section 4.3.1. A first look at the data would suggest that assembly line A and B follow a log-normal or a Weibull distribution with a negative skew. For assembly line C no standard distribution can be intuitively chosen, but the shape also resembles a negatively skewed log-normal or Weibull distribution although the data is more scattered. The major drawback of the Weibull distribution is that its parameters are complicated and cannot easily be fitted to represent the data in a satisfactory manner.

In line with the data analysis strategy a normal distribution is tested to represent the data. The normal distribution is not optimal as its characteristic bell-shape will not represent the outlying observations in the “tail” of the data. Therefore, caution should be advised when using the normal distribution, as it is not restricted to positive numbers and could result in negative values.

Unfortunately, using normal distributions with the given means and standard deviations of the assembly lines’ OEE does not fit the observed data of the assembly lines very well, see Figure 5.1.

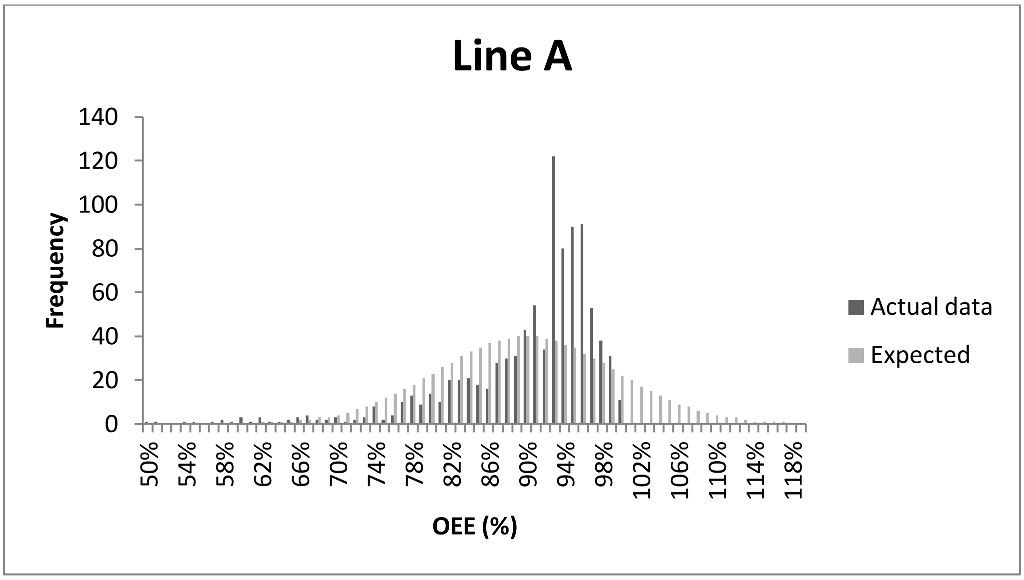


Figure 5.1. Normal distribution with mean value and standard deviation to represent the data.

The fitting is also evaluated with a Pearson's chi-square test, see Section 3.3.2. The result of the chi-square test is presented in Table 5.1. The obvious problem is that the statistical distribution generates outcomes that are higher than the actual data, e.g. for assembly line A, 15% of the generated outcomes are above 100% OEE, while in the actual data there are no observations above 100%. This problem can be solved by setting an upper bound for the distribution data. However, this will in turn result in an altered version of the general normal distribution and might not be intuitive for future updates. Another problem is that in the actual data the high spikes, which can be seen especially for line A and B, are not represented very well by the normal distribution. For example, for assembly line A approximately 13% of the observations yield an OEE of 93%, while the corresponding percentage for the normal distribution is approximately 4%.

Table 5.1. Outcome of chi-square test on the OEE of the assembly lines.

	A	B	C
Mean	0,893443589	0,920663528	0,771749077
Standard deviation	0,093986373	0,105279662	0,23930268
Number of observations	948	991	312
Number of bins suggested	31 to 190	31 to 198	18 to 62
Number of bins used (r)	37	38	37
Number of estimated parameters	2	2	2
χ^2-test score	657,28	1080,82	133,14
$\alpha=\chi^2$-significance [χ^2(r-k-1)]	0,000	0,000	0,000

In conclusion, it is not advisable to use a general normal distribution to represent the actual data of the OEE for the assembly lines. However, since the number of observations is relatively high, especially for assembly line A and B, the actual data can be used as input data for the simulation tool. The tool can base the simulated OEE on the historical data, by randomly picking an outcome from one of the shifts in the actual data. As there are no seasonal deviations or discrepancies in the actual data this can be seen as a fair approximation. Future updates of the input OEE data for the tool can also be made with relative ease as the OEE data is readily accessible.

Regardless of approach, the actual observations of the OEE are generally not independent, i.e. if there is an unresolved quality issue in one shift, it is likely that it will also affect the subsequent shift. Neither a normal distribution, nor the chosen approach, considers this. However, the chosen approach is still deemed valid as the mean outcome will conform to the observed mean while generating valid data for each outcome.

5.2.2 Output of the machining department

The machining department is a special case since it is both an internal customer of blanks and an internal supplier of processed coupling houses. As a complicating factor, the machining department is KANBAN controlled. As a result there is no production plan and subsequently no record of deviations from a production plan. However, the OEE of the lathes is measured based on the uptime of the machines. Unfortunately, this is not sufficient to estimate the output of the machining department, as the process also depends on incoming blanks arriving on time and being available. The analysis of the incoming blanks is presented in Section 5.2.3. As described in Chapter 4.4, there are also two different flows within the machining department, one for Gen4 and one for Gen5, which differ significantly. In order to represent the data from the machining department in the tool, a qualitative interview with the responsible material planner at BorgWarner was combined with the OEE data from the machining department.

The OEE data of the lathes has a pattern similar to the pattern of the OEE data in the assembly lines, with a long “tail” on the low numbers and with “peaks” not corresponding with the mean value of the data. For this reason, it is not well represented by a normal distribution. Using the large amount of data available, the historic data is better to use as input for the simulation tool, in the same way as for the representation of the assembly lines.

The lathes are the bottleneck for the machining process and therefore the performance of the washing and the leak test can be neglected (Svensson, et al., 2013). For Gen4 coupling houses there is an additional risk of having delays or disruptions in the process, when the houses are sent to an external contractor for sealing. No data exists on the performance and reliability of the contractor. According to the interviewed material planner, the reliability of the interaction with the contractor is substantially higher than the internal laches. The performance of the external contractor can therefore be neglected when predicting the outcome.

5.2.3 Deviation of supplier deliveries

The performance of BorgWarner’s suppliers is measured from the proportion of early deliveries, on-time deliveries and late deliveries. The definition of on-time deliveries is deliveries arriving on the same day as planned. The measure only considers if the order arrives early or late and not the magnitude of the deviation. Data for on-time deliveries for the twelve most critical suppliers is presented in Appendix F.

Because BorgWarner lacks data on the magnitude of the deviation, it is difficult to fit a representative distribution to the data. Since deviations from a plan often follow a normal distribution (Axsäter, 2006), this is assumed for the deviation of supplier deliveries as well. The normal distribution can then be estimated by comparing the actual on-time deliveries with the expected on-time deliveries from the distribution, with an unknown standard deviation. An on-time delivery of the distribution is decided to be from a half day earlier to a half day later than expected. Estimating the standard deviation, σ, could be done using (5.1) and numerical approximation, where the mean of the normal distribution is set to zero.

$$X_{obs} = N * \int_{-0,5}^{0,5} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}} dx \qquad (5.1)$$

where,

$$X_{obs} = number\ of\ observed\ deliveries\ on\ time$$

$$N = number\ of\ total\ observations$$

It is assumed that the mean of the deviation for supplier deliveries is zero. It is not completely accurate, but because the lack of data it is impossible to get a true estimation of the mean.

5.2.4 Forecast deviations

The forecast deviations for customer X can be seen in Figure 5.2 together with the fitted normal distribution. For customer X the deviations follow a normal distribution with a 12,1% significance according to the Pearson's chi-square test presented in Table 5.2. Since the data is based on 33 weeks of forecasts, and there are very few extreme deviations, this result is deemed sufficient at the given significance level.

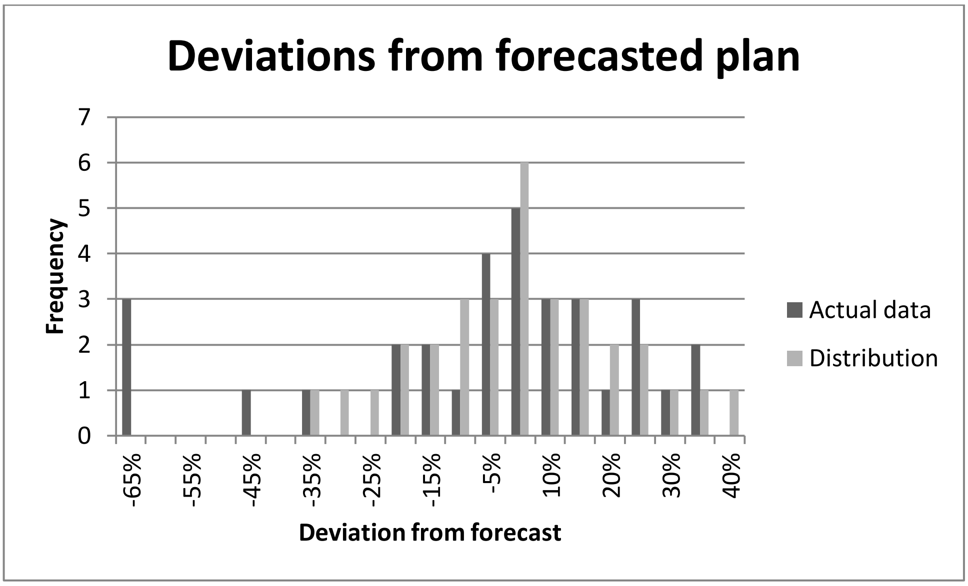


Figure 5.2. Deviations from forecasted plan for customer X.

Table 5.2. Chi-square test for the normal distribution fitted to the observed forecast deviations of customer X.

	Customer X
Mean	0,002196
Standard deviation	0,200604
Number of observations	33
Number of bins suggested	5 to 10
Number of bins used (r)	10
Number of estimated parameters (k)	2
χ^2-test score	5,49
$\alpha=\chi^2$-significance [χ^2(r-k-1)]	0,121

For customer Y the deviations are not as easily interpreted as for customer X. There are significantly larger deviations and there are also more extremes. A chi-square test shows that the deviations for customer Y are not normal distributed with the mean and standard deviation given from the data. The chi-square test result can be seen in Table 5.3. However, there is much ‘noise’ in this data because of the method that is used when collecting the data. The data measures the difference between the forecasted plan, which is sent from the customer, and what the actual call off from the customer was during the specified time period. In the real-life process, the production planners always make sure that as much as possible of the local finished goods inventory is sent to the consignment stock. This in turn means that if there is a deficit of one article, another article will be sent in its place in order to fill up the trailer. The result of these actions is that every time there is negative deviation there will be a positive deviation as well. This affects both the mean and standard deviations since the missing articles are replaced with available articles and might not always be replaced one for one. For example, if there is a deficit of 1000 units for product 1 it might be replaced by 300 units of product 2, 500 of product 3 and 200 of product 4.

Table 5.3. Deviations from forecasted plan for customer Y.

	Customer Y
Mean	0,124196
Standard deviation	0,565290
Number of observations	81
Number of bins suggested	14 to 40
Number of bins used (r)	40
Number of estimated parameters (k)	2
χ^2-test score	164,8175
$\alpha=\chi^2$-significance [χ^2(r-k-1)]	0,000

As there is no other data available, and the time frame and scope of this thesis limit the possibilities to perform an independent study, the actual deviations for customer Y will be assumed to be normal distributed with the given mean and standard deviation.

5.2.5 Delays during shipping

Deviations and delayed shipments of finished articles, sent to the customers or to the consignment stock, are not analyzed in this thesis. The reason for this is two-fold; firstly, there is no data available and, secondly, shipments that are sent directly to the customers are sent with the FCA delivery agreement, which states that ownership of the goods is transferred from the consignor to the consignee when the goods leave the consignor. The shipments that are sent to the consignment stock are subjects to deviations, but according to the production planners at BorgWarner this is negligible as it is very uncommon.

5.3 Static data

In addition to the statistical data, the simulation model will also consider the current plan for the assembly lines, as well as the actual demand forecasts that are sent from the customers and the planned demand that is sent to the suppliers. This data will not be analyzed in this thesis, as it is checked and confirmed by the production planners and material planners respectively in their daily work. The production planners and material planners will be responsible for providing this data when needed for a simulation.

6 Model

The outcome of this master's thesis is a tool to support the analysis of delivery capabilities connected to current plans and inventory levels. This chapter describes both the overall structure of the model and the detailed functionality of the incorporated components.

The model calculates the quantity per product that can be delivered to the customer over a given time interval when knowing the component ordering and production plan as well as the expected customer demand. The tool also takes into consideration the internal processes that affect the delivery capability from the point when BorgWarner places an order to the suppliers to the point when a finished coupling is ready for delivery to the customer. This process contains stochastic elements and is also affected by human decisions. For example, the delivery capability is affected by late arrivals of components from suppliers and machine break-downs, see Chapter 5. With the occurrence of these events the planners will change the plans to minimize the negative effect of these unpredictable events.

All of these factors are included in the model in order to estimate the quantity that can be delivered to the customers and compare this to the true demand.

6.1 Model approach

This section describes the approach the authors of this thesis have used when developing the tool. A discussion about the validity of the approach, and how the authors have been working to increase the validity and verification is also included.

6.1.1 Type of approach

Several different methods can be used to fulfill the purpose of this thesis, with regard to its scope and delimitations. These methods are described in Chapter 3.4, Theoretical framework. The authors have chosen a simulation approach because it was deemed to fit the conditions of the system of study best. Carrying out a real-life experiment by changing the inventory level at BorgWarner was considered difficult and not appropriate for this thesis. First, the authors lack the authority to change the inventory levels at BorgWarner. Secondly, lowering the inventory levels will also induce the unknown risks that this thesis aims to investigate and will consequently affect the service level to BorgWarner's customers negatively.

For the scope of this thesis and the studied system, it is better to build a mathematical model than a physical model. The purpose of the model is to analyze the logical relationship between inventory level, service level and the processes related to these. A mathematical model could be used for this purpose. As mentioned in Section 3.4.3 an analytical solution is often preferred over a solution obtained through simulation. The studied system is a multi-echelon inventory and production system, from which it is difficult and complex to obtain an analytical solution, especially within the time frame of this thesis. One approach to reduce the complexity could have been to decouple the different processes and inventories, and perform the calculation independently of each other. However, this would have reduced the validity of the results since the components, to a high extent, are connected in reality.

Developing a simulation model is a time effective and, probably, a less difficult approach to produce the results for this thesis. Since simulation has the drawback of not producing an exact result and a risk of not representing reality properly, there has to be much focus on these issues to give credibility to the solution.

6.1.2 Validation and verification of the model

Many of the tests for validation mentioned in Table 3.2 have been used during and after the development of the simulation model. Even though all development has been carried out by the authors of this thesis, all assumptions and logical relationships in the model have been discussed with the most knowledgeable employees at BorgWarner, using the *face validity test*. Each assumption and relationship was discussed both during the pre-study phase and during the development phase. In order to verify that the computerized model behaves as expected, key parameters have been traced during simulations, the approach *traces*. When the development phase was finished, the outcome of the modules in the model has been discussed with the same knowledgeable employees, to ensure that the outcome is reasonable.

Other tests to compare the simulated outcome with expected real outcome have also been performed. For example, an *extreme condition test* was conducted when the inventory level was set to be higher than the demand, and demand was set to have close to no deviation. The expected outcome of the real system is then to have 100% service level during the time period, which was also the outcome in the model. Setting the demand higher than the possible production volume, as in the *degenerate test*, showed a decrease in the inventory level over time. A third possible test of the models validity is to compare the model outcome with historic data. Analyzing the correlation between historic inventory levels and historic service levels is difficult since it depends on many unknown factors. However, by comparing the result to the output from the model, it can be concluded whether or not the result is within a reasonable magnitude. Finally, the users of the model at BorgWarner have the possibility to compare the simulated forecasted outcome with actual outcome if they keep track of all factors that affect the outcome during the run.

6.2 Overall structure

To simplify the development, the model is divided in two separate modules which interact with each other in their interface. The two modules and their respective scope of the actual system are shown in Figure 6.1.

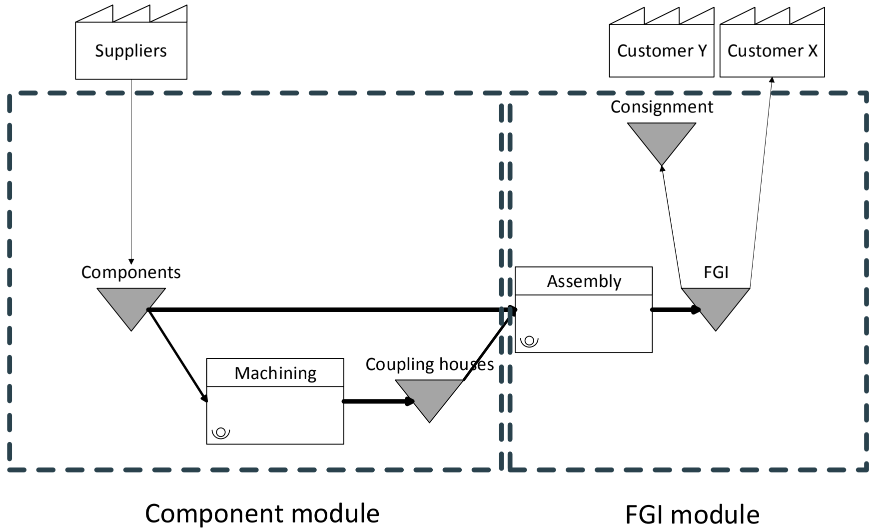


Figure 6.1. The two modules in the model.

The scope of the component module is from placing an order to the delivery of components to the assembly line. The component module takes into account the delivery reliability of the suppliers, the machining process and the inventory level of both components and coupling houses. The component module uses the component ordering plan and the production plan as input data and the output is the quantity of each product that can be produced, which is the internal service level measure. This module also changes the ordering plan over time similar to how the material planners change the plan in reality, which is described in Chapter 4.6.

The FGI module, on the other hand, models the processes from receiving the demand forecasts from the customers to the delivery of the products. This module includes the performance of the assembly lines, the inventory level at the FGI and consignment stock and the accuracy of the forecasts that are received from customers. A central part of the module is the production plan and how it is affected by the performance of the assembly lines as well as how the actual demand changes over time. Input data for this module is the demand forecasts and the production plan, at the day when simulation starts, as well as product specific characteristics. The result represents the quantity of products that can be delivered to the customers i.e. the external fill rate. The model also uses the possibility to issue over-time in production to produce the products required according to actual demand, which is described in Section 4.3.2.

The interaction between the two modules is performed through revised production plans and shown in Figure 6.2. The model starts with the FGI module generating an updated production plan based on the stochastic outcome of the subcomponents. This production plan, which includes possible over-time, is sent to the component module which is then run with this input. Finally, the output from the component module is sent back to the FGI module to calculate the fill rate to the external customers and actual inventory level.

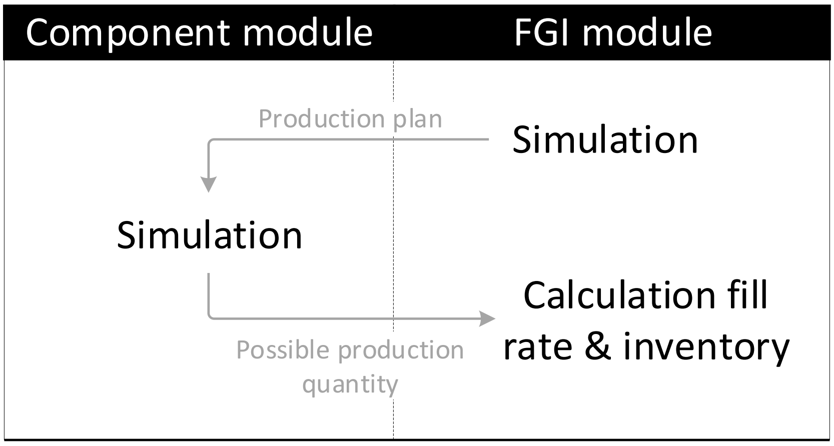


Figure 6.2. Interaction between the two modules.

In order to generate a statistically valid result from the model, each module performs multiple simulations. The number of simulations is user-defined and when the model is run with more than one iteration, the output is presented with the median, the quartiles closest to the median, the maximum and the minimum value of all iterations. By presenting the outcome in terms of median, quartiles, maximum and minimum it is easier for the user to evaluate the likely effect of a reduction in inventory. The median shows the expected median of the outcome while the quartiles can be seen as a measure of deviation of the outcome. The maximum and minimum values show the extreme outcome from all iterations. For a graphical representation of the outcome see Figure 6.3.

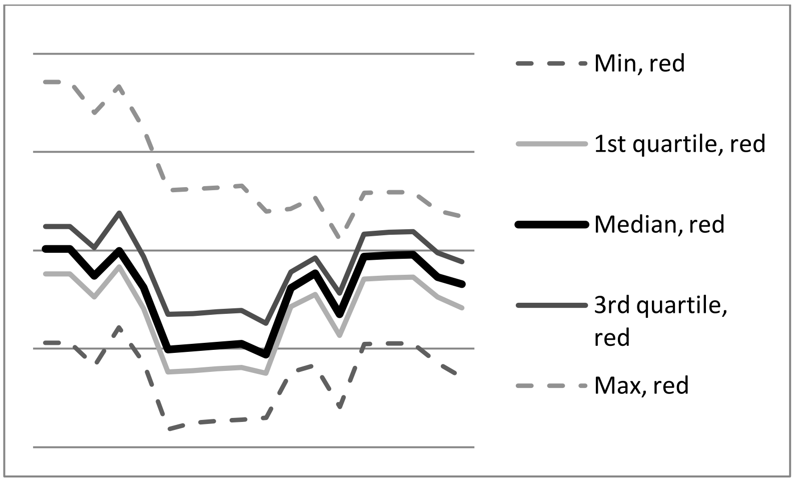


Figure 6.3. Graphical representation of arbitrary output.

6.3 Assumptions

Several assumptions about reality have been made in order to be able to construct a model within the given time frame of this thesis. Some of the assumptions are assumptions concerning the activities performed at BorgWarner and affects only parts of the model. These assumptions are described and discussed in each module desciption below, where the model is described in detail. A few assumptions affect the overall model and are discussed in this section.

6.3.1 Periodic review

The model is based on BorgWarner using a periodic review system with a period of one day. In reality the planners track and plan orders with a finer resolution in some instances of the work flow. This can have the effect that the model produces inaccurate results, e.g. there can be a material shortage in the morning but material is delivered in the afternoon, which covers the shortage. The model will in this case not register the shortage that may occur in the morning. However, it would be difficult and time consuming to develop the model with better resolution and the increased accuracy would not be significant.

When using periodic review, assumptions regarding when things occur within the period are also needed. In this model it is assumed that every event happens at the start of a period, e.g. that the entire quantity is produced at the beginning of the day. Furthermore, it is assumed that the quantity produced during one day is ready for shipping at the same day.

6.3.2 Changeover times

In the model, the changeover times of the assembly lines and the machining lathes are excluded. This is deemed reasonable as the model performs calculations with a daily resolution and the changeover times constitute a relatively small loss for the assembly lines and a very infrequent loss for the lathes in the machining department. The changeover times are further described in Chapter 4.

6.3.3 Rescheduling

The model assumes that no manual changes are made with regard to the plans or the parameters during the time period of the simulation. However, in reality major changes are made once a week during the master planning, and minor rescheduling is made within the week. The model performs some updates or changes automatically, for example adding over-time production when necessary, in order to get realistic results that the user can interpret. The assumption that no other rescheduling is made is obviously a simplification, but the events leading to rescheduling are many and difficult to interpret. Modeling these events automatically is consequently very difficult. If major changes are made in reality, the model can be restarted with these changes.

6.3.4 Inventory for customer Y

In order to reduce the multi-echelon complexity for customer Y it is assumed in the model that all couplings assembled for customer Y are sent with the next available shipment to the consignment stock of customer Y. This is a fair approximation as most of the inventory for customer Y is held at the consignment stock, see Subchapter 4.8. The assumption has no impact on the output of the model in terms of capital tied or inventory level for the products of customer Y, as it is still the same amount of couplings.

6.4 Finished goods inventory module

The simulation performed in the FGI module is based on the planned production and demand from the production planners, as well as individual production characteristics for each product. In this section the components of the FGI module and the performed calculations are described.

6.4.1 Input data

The product specific production characteristics are represented in the tool by input parameters. These parameters describe each product from the viewpoint of when the simulation starts, e.g. the expected forecasting error, starting inventory level, etc. and can be seen in Table 6.1. The parameters are based on historical data and observations, see the data analysis in Chapter 5. Consequently, none of the parameters are constant over time and will need to be updated periodically. How often the tool should be updated is a trade-off for the user of the model as it requires extensive data gathering while updated parameters will generate a more accurate result.

Product characteristics

Table 6.1 presents the parameters that need to be entered for each product that is to be included in the simulation. The transit inventory levels and the weekend production are initial values that only need to be considered when a consignment stock is used. The production characteristics are the result of the empirical research in Chapter 4 and the data analysis in Chapter 5.

Table 6.1. Product specific input parameters.

Product characteristic	Description
Forecast error	The mean and standard deviations of the forecasts for the product.
Starting inventory level	The inventory level of the product when the simulation starts.
Produced in assembly line	Specifies which assembly line the product is assembled in.
Number of shifts per week	The number of shifts, per week, in the specified assembly line.
Available extra capacity per week	The total extra capacity, in number of couplings, for the product.
Delivery via consignment stock	Specification if the product is to be delivered directly to the customer or via a consignment stock (lead-time delay).
Transit inventory level, from Thursday	The quantity of couplings en route to the consignment stock, from the previous Thursday, when the simulation
Transit inventory level, from Friday	The quantity of couplings en route to the consignment stock, from the previous Friday, when the simulation
Produced during weekend	The quantity of couplings produced during the weekend, to be sent to the consignment stock, when the simulation starts.
Value of product	The specified economic value of the product.

OEE and plans

The tool also uses the historical OEE for each assembly line in order to estimate the future efficiency output, see Section 4.3.1 for the historical OEE data.

Apart from the product specific characteristics and the OEE data, the tool is also based on the current production planning by the production planners at BorgWarner as well as the current, forecasted, demand from the customers, see Subchapters 4.5 and 4.7.

6.4.2 Module overview

As previously mentioned, the tool performs calculations with a daily resolution, i.e. the results of each product will be displayed on a daily basis. The tool always considers the inventory level of the product in order to account for potential backlogs. The result consists of daily outcomes of:

- Fill rate
- Ingoing inventory level for each day
- Capital tied in inventory each day
- Utilization of over-time production on Saturdays

Figure 6.4 shows a schematic description of the calculations performed by the FGI module. The module is initiated with the input data described in 6.4.1. In the first calculation step the input plans are processed with stochastic operations, see 6.4.3, in order to generate a simulated outcome from the planned production and the planned demand. During the first step over-time production can also be issued in order to be able to meet the demand.

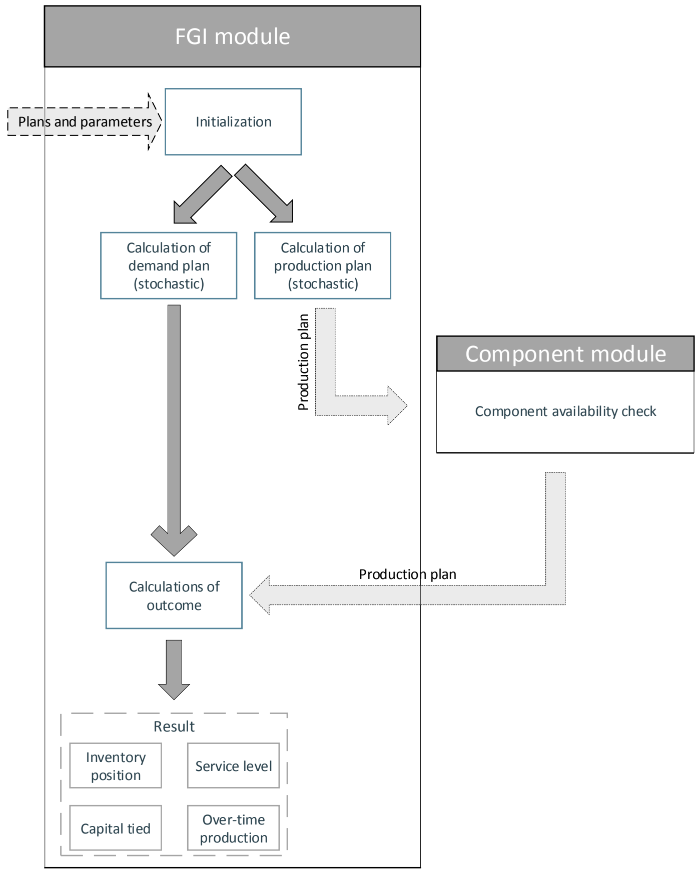


Figure 6.4. Description of the calculations steps in the FGI module.

The result of the initial calculation is a revised production plan that describes what *should* be produced in order to meet the outcome of the demand, with regard to the stochastic deviations. The updated production plan is then sent to the component module which checks the availability of components, see Subchapter 6.5. The component module returns an updated plan of what *is* possible to produce.

From the updated production plan and the previously generated stochastic demand plan static calculations are made to obtain the final inventory level, service level, capital tied and the over-time production utilized.

6.4.3 Calculations

In order to make the input data usable, there needs to be some data processing in order to adjust the input data for the tool, i.e. on a daily resolution. In the following section the components of the FGI analysis module are described for a universal product, *k*, over the different days, *m*.

Forecast deviations

In order to generate a stochastic demand, $Demand\ outcome_{k,m}$, the demand plan from the input data needs to be processed for each day. A relative forecast deviation factor, $(1-\delta)$, is generated from a normal distribution with the mean and standard deviation of the forecast deviation for each product, see data analysis Section 5.2.4. The $Demand\ outcome_{k,m}$ is then calculated by multiplying the deviation factor with the input demand, $Input\ forecast_{k,m}$, of each day according to (6.1).

$$Demand\ outcome_{k,m} = \begin{cases} (1-\delta) * Input\ forecast_{k,m}, & \delta \leq 1 \\ 0, & \delta > 1 \end{cases} \qquad (6.1)$$

where,

$$\delta \in N(\mu_{forecast,k}, \sigma_{forecast,k})$$

This, stochastic, demand outcome is then used as the demand in all subsequent calculations.

Assembly lines

Firstly, it is necessary to understand how the modeled assembly process differs from the real-life assembly process. In the real life process each product is assembled in a work center (assembly line) and each work center assembles one batch of products at a time. Consequently, the real life production plan results in a queue for each work center. If there is an event that reduces the OEE of the work center the current batch will be paused and each subsequent batch will be delayed in time. In order to offset this delay in production, over-time can be issued to catch up on the production plan.

In the modeled assembly lines the products are not produced one at the time in work centers, but parallel at the same time. When the model generates a reduced OEE, this results in a loss of quantity for the single product rather than a delay in production for all products. There is no direct connection between the production losses for products produced in the same assembly line, but all events occur independently for each product. The production loss in the model can be offset by issuing over-time production, where the lost production can be made up for by producing more couplings. For a graphical comparison of how the systems behave with a reduced OEE event, see Figure 6.5.

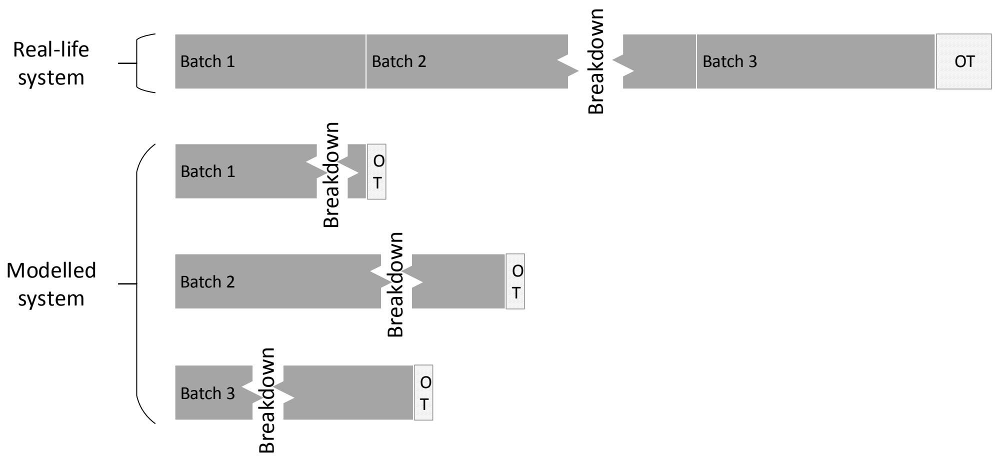


Figure 6.5. The difference between the real-life assembly system and the model.

The net outcome of the two systems in Figure 6.5 is equivalent, but it is important to understand the difference in reduced OEE and over-time production on the real-life production loss (time) and the modeled production loss (quantity).

The OEE is based on which assembly line the product is assembled in. The OEE output, per shift, is picked randomly from the historical OEE data. This is deemed a fair approximation as the OEE data is relatively constant over time and the chance of picking a low OEE output would simulate a major production breakdown for that shift, see section 4.3.1 for more information.

Since the tool calculates results on a daily basis there needs to be a transformation of the output per shift to a mean output of each assembly line each day. This is achieved by calculating the mean OEE of the number of shifts during a day. For example, if an assembly line is run 14 shifts during a week the tool will generate two OEE outcomes for each day and calculate the mean for each day. The mean value is then the OEE output for that product and day, $OEE\ output_{k,m}$.

The $OEE\ output_{k,m}$ is then multiplied with the input production plan, $Input\ production_{k,m}$, for each day and product, which yields the stochastic production outcome according to (6.2).

$$\begin{aligned} Production\ outcome_{k,m} \\ &= OEE\ output_{k,m} \\ &* Input\ production_{k,m} \end{aligned} \quad (6.2)$$

Over-time production for the assembly lines is simulated by producing more couplings rather than adding actual production time, see the *Assembly lines* section. Over-time shifts are typically utilized on Saturdays, but single overtime hours can also be issued on other days, depending on the production schedule, see Section 4.3.2.

In order to simulate over-time production, as realistically as possible, the tool can issue extra production on the Saturday of each week. This is done by the tool by checking the planned production ($Input\ production_{k,m}$) against the simulated production ($Production\ outcome_{k,m}$) of the days leading up to the Saturday of each week. If the total, stochastic, production during the week is less than the planned production, over-time will be issued to make up for the lost production.

The tool also takes deviations in demand into consideration. If the outcome of the stochastic demand ($Demand\ outcome_{k,m}$) is higher than the planned demand, and this results in a negative inventory level, over-time production will be issued. The priority of the tool is to make up for the production losses first and then try to meet the deviations in demand. The over-time production, like the normal production, is subject to OEE deviations and is limited, per product, to the extra capacity specified in the production parameters.

The tool also includes a backlog for the over-time production, e.g. if the production loss is greater than the available extra capacity per week the excess backlog will be produced during the next week. The tool first deals with any backlog and thereafter uses any additional capacity to adjust the current week.

Transport lead-time delay to the consignment stock

For customer Y the tool also needs to consider the transport to the consignment stock, which means that there will be a delay between when the products are produced at BorgWarner and when they are available for the customer. In order to simulate this, a simplification had to be made. The simplification is that BorgWarner holds no FGI inventory for customer Y's products, instead products are shipped directly to the consignment stock upon completion, see 6.3.4. The inventory level and the capital tied in inventory are calculated from the stock on hand at the consignment stock and do, consequently, not consider the inventory in transit.

BorgWarner produces the couplings for customer Y seven days a week but shipping is only carried out on weekdays and the customer only receives products on weekdays. As the lead time of the transport is two days the transport delay is simulated according to Table 6.2.

Table 6.2. Relationship between production day and arrival day

Production day	Arrival day
Monday	Wednesday
Tuesday	Thursday
Wednesday	Friday
Thursday	Monday
Friday	Tuesday
Saturday	Wednesday
Sunday	Wednesday

Note that the weekend production is shipped with the Monday production and arrives on Wednesday. This is a simplification as goods produced on weekends are typically sent both on Mondays and Tuesdays. Nevertheless, the simplification matches the real inventory movement quite well. For the real-life situation, see Subchapter 4.8.

Inventory level

The inventory level, $Inventory\ level_{k,m}$, for each day is calculated by adding the ingoing inventory level of the previous day with the production of the previous day and subtracting the demand from the previous day according to (6.3).

$$Inventory\ level_{k,m} = Inventory\ level_{k,m-1} + Production\ outcome_{k,m-1} - Demand\ outcome_{k,m-1} \quad (6.3)$$

The new inventory level is then stored and used as the ingoing inventory level for the next day.

Calculation of results

When the updated production plan is returned from the components module the results are calculated. The number of products actually delivered to each customer depends on how much of the stochastic demand that can be satisfied from the ingoing inventory level and the returned production plan. The fraction of products delivered on time is calculated according to (6.4).

$$Delivered\ products_{k,m} = \begin{cases} min(X,Y)\ if\ Y \geq 0 \\ 0\ if\ Y < 0 \end{cases} \qquad (6.4)$$

where,

$$X = Demand\ outcome_{k,m}$$
$$Y = Production\ outcome_{k,m} + Inventory\ position_{k,m}$$

The daily fill rate, $Fill\ rate_{k,m}$, for each product is calculated by dividing the amount of delivered with the demand for the product, see (6.5). The fill rate, or service level, measure is included in the model twice using different definitions. The first definition is that the fill rate only measure the quantity of products delivered to cover the demand of the day, i.e. products delivered to cover up a backlog are not included in $Delivered\ products_{k,m}$. The second definition includes the total quantity of delivered products on a given day, i.e. backorder shipments are included and therefore the fill rate can be greater than 100%. The second definition is closer to BorgWarner's definition of service level, see Subchapter 4.9. However, the first definition gives a better understanding of when there is a problem of meeting demand.

$$Fill\ rate_{k,m} = \frac{Delivered\ products_{k,m}}{Demand\ outcome_{k,m}} \qquad (6.5)$$

The module also calculates the daily capital tied, $Capital\ tied_{k,m}$, in inventory by multiplying the value, $Value_m$, of each product with the inventory level of that product, see *(6.6)*.

$$Capital\ tied_{k,m} = Inventory\ level_{k,m} * Value_m \qquad (6.6)$$

6.4.4 Reduction of inventory

One of the central features of the tool is the ability to reduce the inventory level of each product according to user-defined reduction factors. This is done by creating an alternative production plan, where the production plan is reduced in order to meet a target inventory level that corresponds to the user-defined reduction. The target inventory level is calculated according to (6.7).

$$Target\ inventory\ level_{k,m} = Inventory\ level_{k,m} * (1 - Reduction\ factor) \quad (6.7)$$

The new production plan, $New\ production_{k,m}$, for each day and product is then calculated by reducing the $Input\ production_{k,m}$ with the difference between the theoretical, static, inventory level and the target inventory level, see (6.8).

$$New\ production_{k,m} = \ max\ (Z, 0) \quad (6.8)$$

where,

$$Z = \ Input\ production_{k,m} - \left(Theoretical\ inventory\ level_{k,m} - Target\ inventory\ level_{k,m}\right)$$

The $Theoretical\ inventory\ level_{k,m}$ is calculated by the module by calculating the inventory level based on the input production plan and demand plan with no stochastic variation. For an arbitrary day the $Theoretical\ inventory\ level_{k,m}$ is calculated according to (6.9).

$$Theoretical\ inventory\ level_{k,m} = \ Inventory\ level_{k,m-1} + Input\ production_{k,m-1} - Demand\ outcome_{k,m-1} \quad (6.9)$$

Production is the only control variable available to reduce inventory, i.e. it is possible to reduce the planned production but it is not possible to manipulate the demand. The tool uses the new planned production, $New\ production_{k,m}$, as means for inventory reduction (or increase). This in turn means that no inventory reduction (change) can be achieved if the planned production is already zero. For products that have a very high inventory level in relation to the inventory turnover and production the reduction will be slow.

6.5 Component module

This section describes the detailed functionality and logic of the component module and the required input data. The following data and procedures are described in the same order as they are performed in the model.

6.5.1 Input data

The input data to the component module needed is mainly divided into four areas:

- Ordering plan of components from suppliers.
- Production plan of products at BorgWarner.
- BOM structure.
- Relevant parameters to adjust the model.

The ordering plan is finalized by the material planners and consists of the expected quantity of each component to be delivered at the plant each day. The ordering plan is derived from the production plan, because the demand of components comes from the call off at the assembly line. The production plan shows the quantity of each product to be produced each day during the predefined time period. As a link between the components and the products is the BOM-structure. The BOM-structure shows which components that are required to assemble a product and in what quantity. One component can exist in several products and required in different quantities.

The parameters are both used to set a correct starting value on variables in the simulation and used to describe the processes included in the model. The parameters used for components and the ordering process are described in Table 6.3 and the parameters for the coupling houses and machining process are described in Table 6.4.

Table 6.3. Component specific parameters

Parameter	Description
Freeze time	The time before delivering, when the order cannot be changed.
Starting inventory level	The quantity of components in inventory when the simulation starts.
Delivery reliability, supplier	The standard deviation of the delivery precision from suppliers, i.e. if deliveries come when
Delayed quantity	The quantity that should have been delivered to BorgWarner but have not yet arrived.

The outcome deviation of the machining process is an important input parameter for the module as well as the historic data of the OEE of the machining department.

In addition to the input data and input parameters, the prioritization order among the products needs to be specified. When there is a component shortage the prioritization list is used to prioritize to which products the remaining components should be allocated.

Table 6.4. Coupling house specific parameters

Parameter	Description
Blank	The article number of the blank corresponding to the coupling house
Capacity machining	The machining capacity per day
Lead-time machining	The lead-time in the machining process, from a blank to a finished coupling house.
Current processing quantity	The quantity currently in the machining process
Starting inventory level	The quantity of finished coupling houses in inventory when the simulation starts.

6.5.2 Module overview

The component module consists of several steps with the aim to represent the processes at BorgWarner, from the point of ordering components to the internal delivery to the assembly lines. This section describes the steps in the same order as they occur in the module and simulation, shown in Figure 6.6.

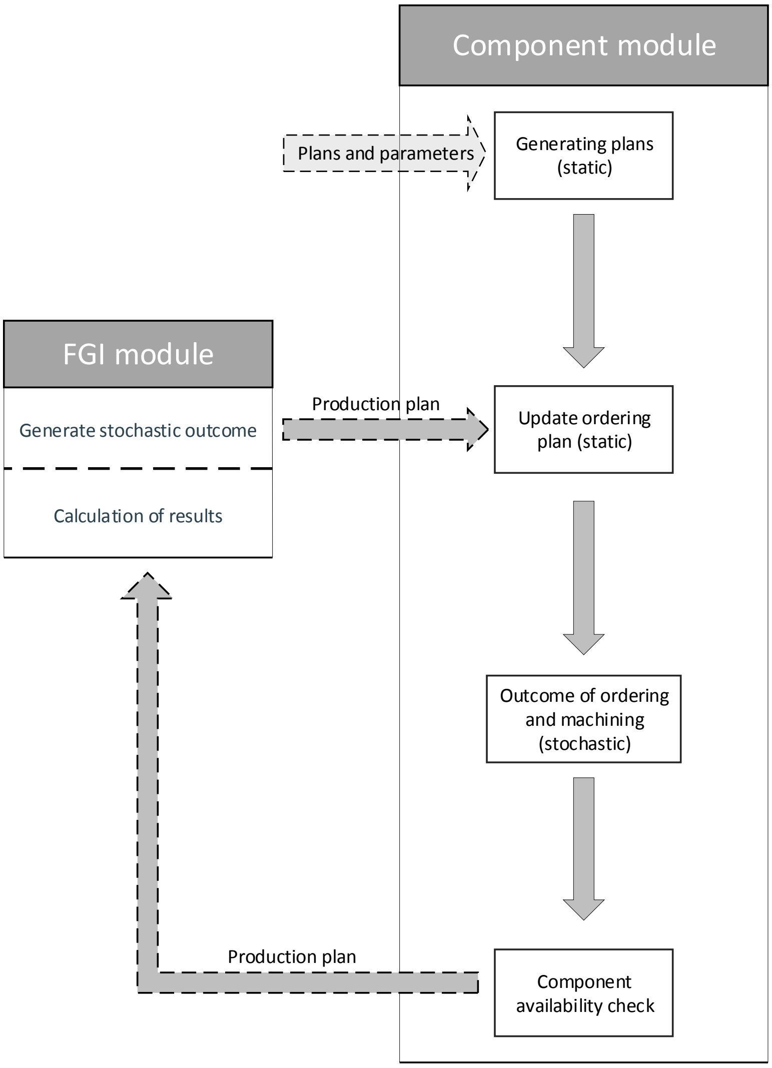


Figure 6.6. Description of the calculations steps in the component module.

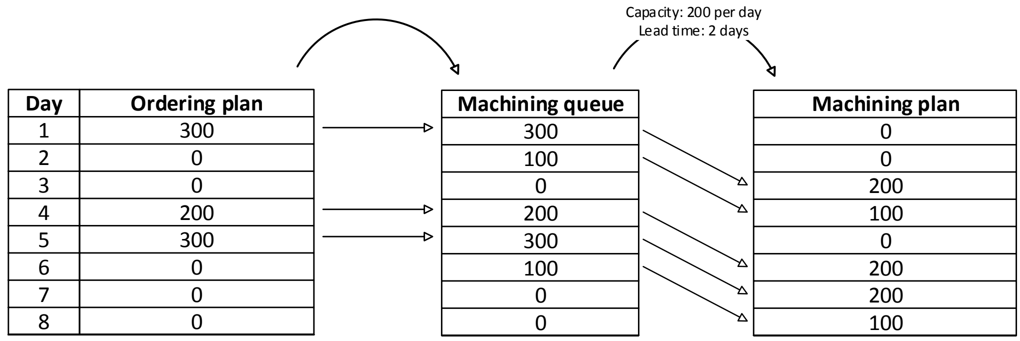
6.5.3 Calculations

To obtain relevant and realistic results, the input data needs to be processed in a similar way to how the data is used in the real-life processes at BorgWarner. The following sections describe, in detail, how the model functions.

Perform deterministic calculations and creation of plans

The component demand comes from the demand of the overlying products, which is stated in the production plan. The component demand is calculated by adding the demand for all products where the component is required, using the BOM-structure.

As described in Subchapter 4.4 the machining process is not controlled by a machining plan, but through KANBAN cards. This is difficult to model in the developed tool since KANBAN is a pull system and therefore additional internal demand data is needed, which is currently not available at BorgWarner. Instead a machining plan is created in the model to represent the process, based on a push system. First, the ingoing blank is placed in a machining queue and machined as soon as possible according to the capacity of the process, see Figure 6.7. The machining process stops when the queue of blanks is empty and restarts with a new delivery of blanks.



Day	Ordering plan	Machining queue	Machining plan
1	300	300	0
2	0	100	0
3	0	0	200
4	200	200	100
5	300	300	0
6	0	100	200
7	0	0	200
8	0	0	100

Figure 6.7. Schematic description of model for machining process.

The subsequent step is to calculate the expected inventory level by comparing the ordering plan and the component demand each day. For coupling houses and blanks, the machining plan also needs to be taken into consideration. This expected inventory level is then the level on which the reduced inventory is based on. The ability to show the effect that a reduced inventory level has on the service level is of great importance to BorgWarner and the purpose of this thesis. The ordering plan is adjusted in the same way as the production plan described in the FGI module, see section 6.4.4.

Update ordering plan

As the customer demand is a stochastic variable that affects the production plan, the ordering plan needs to be updated accordingly in order to meet the new production plan with the changed demand of components. However, there is a freeze time for orders to BorgWarner's suppliers, see Subchapter 4.5. Consequently, the ordering quantity will be adjusted on the first available order after the freeze time.

An example is shown in Figure 6.8 of how the ordering to suppliers is updated. In the example the freeze time for the component is three days. For the first day, the demand for the component is not changed and therefore no action needs to be taken. Reaching the second day, production has an increased demand of 100 units compared to the original plan, but because the orders towards suppliers cannot be changed within the following three days, the order on day 5 is the first order outside the freeze time and hence the additional quantity is added there. For day 3, there is a decreased demand of 50 units and this quantity can be adjusted earliest on day 6. Because there is no order arriving on day 6, the quantity is adjusted on the first following order, which in the example is day 7.

Freeze time: 3 days

Day	Current Ordering plan	Demand old Prod plan	Demand new Prod plan	Updated Ordering plan
1	300	300	±0	Freeze time
2	150	100	+100	Freeze time
3	0	50	-50	Freeze time
4	200	0	±0	±0
5	700	800	+100	+100
6	0	50	+50	No order
7	300	50	+50	-50
8	200	150	-50	+100

Figure 6.8. Example of how the ordering is updated.

Stochastic outcome in ordering plan

The ordering plan laid by the material planners is an expected plan, which is sent to the suppliers. However, the actual deliveries do not always follow the plan because of delays that arise in the supplier's process or in the transportation. To model the actual delivery date, the deviation from the plan is estimated to follow a normal distribution. A normal distribution is assumed realistic since deviations often follow such distribution, which is previously mentioned in Section 3.3.1. The assumed distribution has a mean of zero, i.e. follows the plan, and a standard deviation based on historic performance from the supplier of the component, see Section 5.2.3.

In the model, a random sample is drawn from the distribution. If the sample is negative it means that the order arrives earlier than the plan. In the model early deliveries are bounded and moved to the planned delivery date, according to the plan. The argument for removing the possibility of early deliveries in the model, even though they occur in reality, is that an early delivery could cover up for material shortage, even though early deliveries in most cases are unwanted. The model also allows partial deliveries, i.e. half the order is delivered according to plan and half is delivered late. If an order arrives late, the material planners are usually informed by the suppliers about the late delivery. If BorgWarner is likely to face a material shortage of the component, the late quantity is shipped with an express delivery, and otherwise it is shipped with the next ordinary delivery. Because the module simulates the risk of having material shortage, all late deliveries are assumed to be shipped with express deliveries in order to reduce the negative effect. A consequent drawback is that the tool will present a slightly higher inventory level when there is a late arrival of a critical order.

To simplify the tool, it is assumed that orders have a stochastic independent lead time, i.e. orders can pass each other. In reality this is not the case, but the assumption has little impact on the results. The orders are unlikely to pass each other, since deliveries normally occur a few times a week and the delivery precision has generally small deviation.

At a given time, when the simulation is run, there is a possibility that there are outstanding orders that are delayed and not yet delivered. The quantity of these deliveries is entered into the tool and the new expected delivery date is the first day after the simulation is done. However, the delivery is not assumed to be memoryless. The implication is that if the delivery delay is simulated to be one day, it will still arrive on the new expected date since that means originally one day delay.

With an updated ordering plan that represents a simulated outcome, the outcome of the machining process can be created using the same logic as when creating the machining plan, but the stochastic ordering plan is used instead of the static ordering plan. The actual outcome of the machining process is based on historic OEE data of the bottleneck operation, i.e. the laches. The argument of using historic data for the machining processes is discussed in Section 5.2.2.

Check component availability

With all stochastic variables included in the model it is possible to check how and if the production is affected by any potential component shortage. The BOM-structure is necessary to translate the component availability to the number of products that can be produced. An algorithm that maximizes the number of products assembled given the components available has been created and is described in the following section.

The algorithm first checks whether a component can fulfill the demand from all products, if not the quantities for the least prioritized products are reduced. When this check is carried out for all components the algorithm identifies the component per product that limits the quantity that can be produced. The excessive quantity of the other components will then be made available to other products. With more available components, the algorithm loops through all products to check if more products can be produced, and allocates the components if possible. An example using the algorithm is shown in Figure 6.9. After the completion of the algorithm the ingoing inventory level for the next day is calculated based on the outcome.

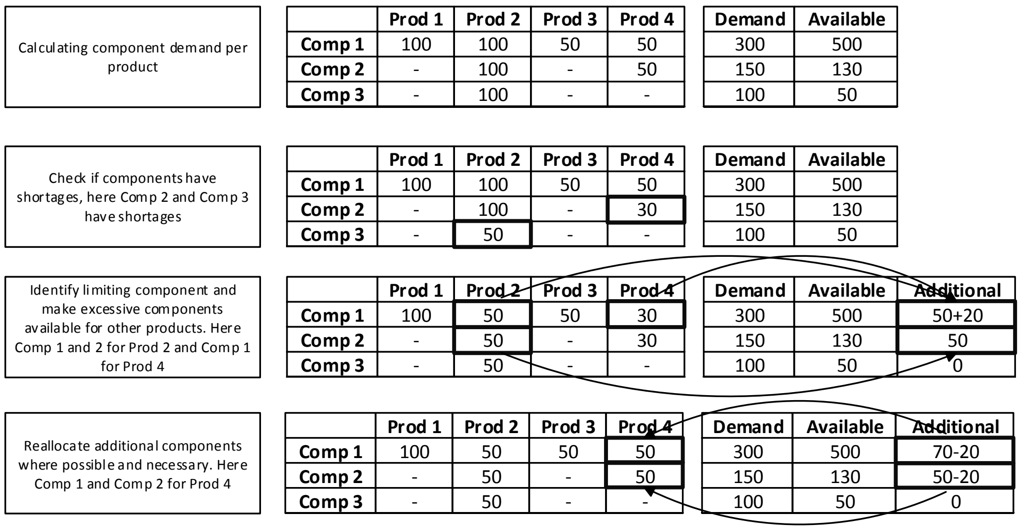


Figure 6.9. Example of the algorithm for allocation of components.

Return of data

After the completion of the simulation and calculations in the component module the output quantity of products are returned to the FGI module which calculates and presents the fill rate. The component module also presents some key data and information, such as capital tied in component buffer, internal fill rate to production and which components that cause shortages.

7 Results

The aim of this chapter is to present the findings and results of this thesis. As the outcome is an analysis tool to be deployed at BorgWarner, this chapter presents both example results and recommendations of how the tool can be used.

7.1 Overview

The output of the tool should be used as a basis for decision making in regard to the supply chain operations of BorgWarner. The tool presents data of the capital tied in inventory for both the component buffer and the FGI, service level and the overtime utilized during the simulation run. As described in Subchapter 6.2, five measures are presented for each type of the data; minimum, lower quartile, median, upper quartile and maximum value of the iterations. In the graphs of this chapter only the median value will be shown, to clarify the figures.

The tool gives the user extensive simulation possibilities depending on the specific analysis needed. The parameter settings, the number of days, number of products and number of components can be changed to fulfill the specific need. There is no theoretical limit on how many days, products or components that can be included in the tool. However, including more data prolongs the runtime of the simulation. This chapter presents a general example result and a few of the analysis possibilities made with help of the tool.

7.2 Example simulation

The example described in this section is based on real and current data at the point when the simulation was performed. Included in the simulation are the 11 products in serial production with the highest annual turnover. For each product the 10 most expensive components have been identified, leading to 46 different components being included. This covers 85% of the total capital tied in the component buffer.

The results shown are for 10%, 20% and 30% reduction of inventory in both the FGI and component buffer, as well as the normal outcome, i.e. no reduction. However, any level of reduction can be chosen by the user. The inventory level, in this example, is presented only in terms of capital tied instead of absolute inventory levels. The reason for this is that it is easier to interpret the effect on the total capital tied for all components and products, as opposed to the aggregated sum of all components and products. The user has the possibility to view both the capital tied and the inventory level.

In Figure 7.1 the simulated capital tied in inventory is shown for the three reduction levels and for the normal plan. Noticeable is that the gap between the simulations is greater during the first weeks in July, than at the start or finish of the simulation. For example, the 10% reduction simulation is 9.0% lower than the normal outcome at July 1st, but only 5.4 % lower at August 1st. Even though both the component buffer and the FGI are set to be reduced by the same amount, independent of each other, there is a dependency between the inventory levels of the two instances. If the FGI level is low, there is a greater risk of scheduling overtime, which in turn demands additional components. If there is a shortage for one component, other components might not be consumed since all components in the BOM are needed to produce the coupling. This might cause a larger build-up in the inventory and the capital tied in inventory for the component buffer is higher than expected.

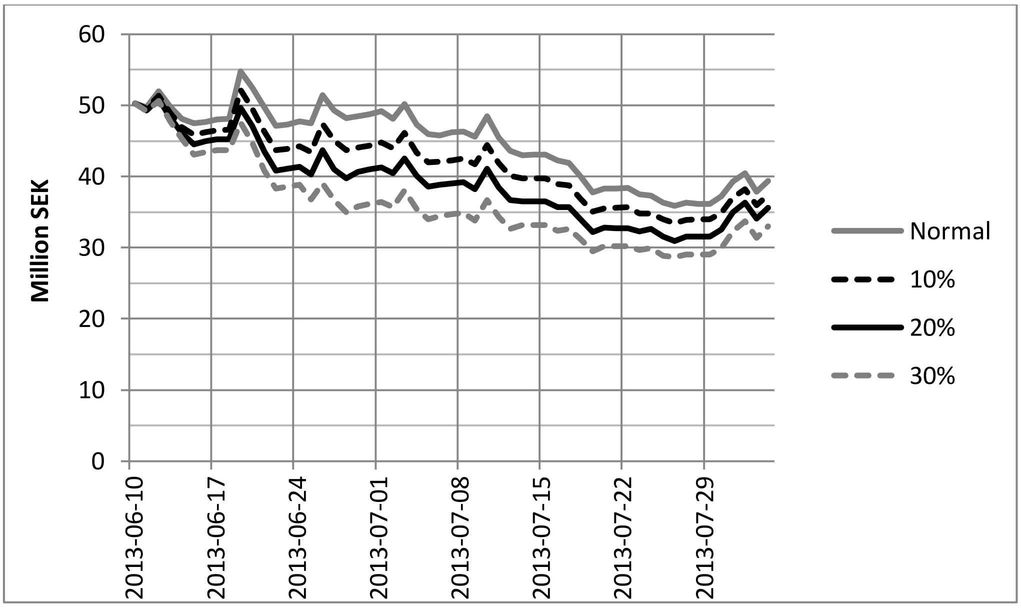


Figure 7.1. The capital tied in inventory over the entire simulation run.

The capital tied in inventory is, on average, 44.6 Million SEK for the normal simulation. For the reduced simulations the capital tied reductions corresponds to 6.4%, 12.3% and 19.0% respectively, see Table 7.1.

Table 7.1. Overview of the results of the example simulation.

	Normal	10% reduction	20% reduction	30% reduction
Avg. capital tied in inventory	44.6 MSEK	41.7 MSEK	39.1 MSEK	36.1 MSEK
Issued over-time	898 units	1227 units	1467 units	1622 units
Avg. service level	89.3%	87.3%	86.8%	85.2%

Reducing the inventory levels also affect the over-time production required, in order to try to meet the customer demand, see Figure 7.2 and Table 7.1. The amount of over-time required is almost twice as much for the 30 % reduction level than for the normal simulation. This additional over-time is associated with an extra cost for BorgWarner and should be considered when making decisions about inventory reductions.

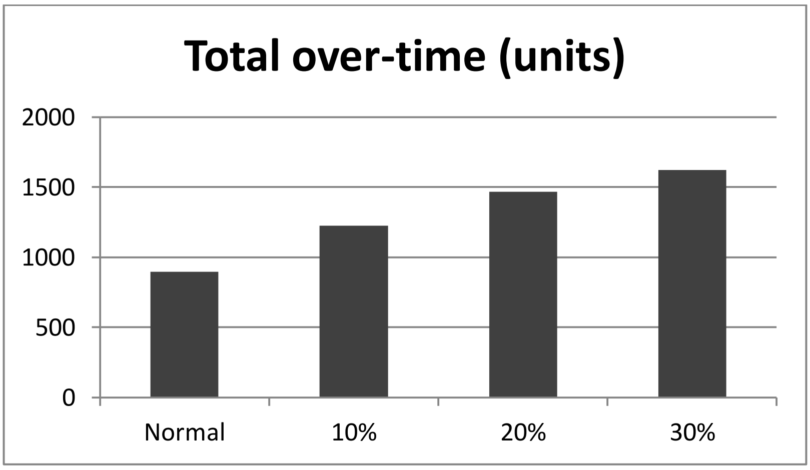


Figure 7.2. The total production over-time needed during the simulation run.

As shown in Figure 7.3, the median of the service level is lowered when the inventory level is reduced. Lowering the inventory level with 10 % reduces the service level with 2 percentage points on average. Reducing the inventory level with 30% decreases the service level with 4 percentage points, see Table 7.1. After four weeks in the simulation, the service level, for all simulations, steadily decreases for three week and the reason is probably that BorgWarner has reduced capacity during the vacation period while the customers are still producing and demanding couplings.

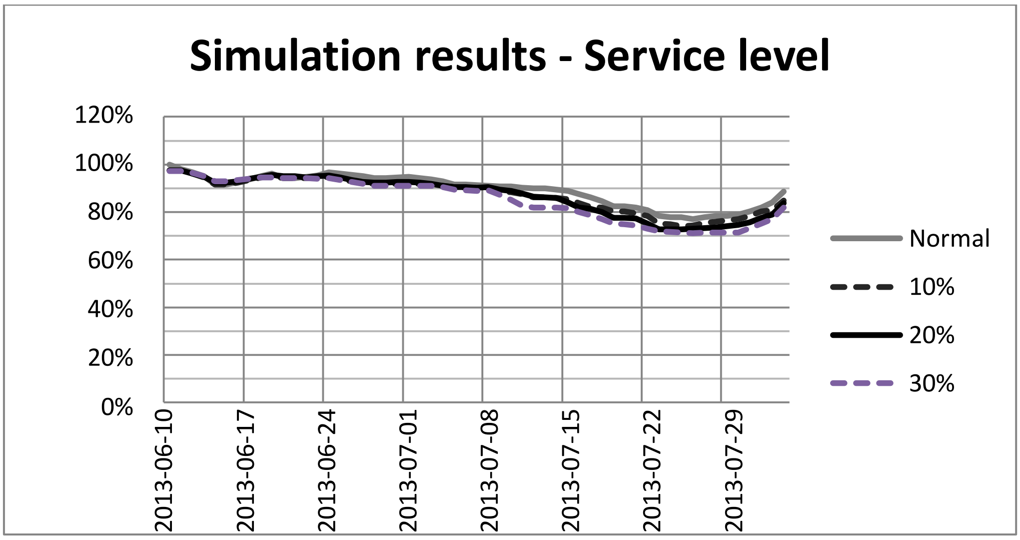


Figure 7.3. The service level over the entire simulation run.

When making decisions about inventory reductions, BorgWarner needs to consider the cost of keeping inventory as well as the cost of missing a delivery to the customer. The additional cost of issuing over-time should also be considered since the amount of over-time is likely to increase as the inventory is reduced.

7.3 Additional results and use of the tool

Even though the purpose of this thesis has been to investigate the correlation of inventory and service levels at BorgWarner, there are additional results that can be obtained from the tool. Adjusting any of the input parameters will show the effect on the three measures described in the section 7.2 above. For example, the effect of changed freeze times can be investigated by changing the freeze time parameter in the tool and observing the effect on the inventory level and service level.

The tool has been developed for the logistics manager of BorgWarner, in particular, to be able to quantify the effect changes of the inventory level has on the service level. This is valuable in tactical decision making about the size of inventory in each instance. The results of a simulation can also be used as a support tool by the material and production planners when making the ordering and production plans. Today the planners only work with static planning and do not consider any of the possible risks or deviations that might occur during the planning horizon. The planners can use this thesis' analysis tool to identify when additional orders are likely to be needed and change the plan accordingly.

8 Conclusion

This chapter concludes this master's thesis and presents the conclusions that can be drawn from this thesis. The authors discuss the fulfillment of the thesis' purpose, the data gathering and development process as well as the difficulties throughout the development. Finally, a few recommendations for future research are presented.

8.1 Fulfillment of purpose

As described in Chapter 1 the purpose of this thesis is to investigate how changes in the component and FGI affect the service level with regard to the processes and activities in BorgWarner's internal supply chain. The outcome of the thesis is an analysis tool for evaluating the effect a changed inventory level has on the service level and capital tied in inventory at BorgWarner.

Through the empirical research in Chapter 4, the data analysis in Chapter 5 and the model development in Chapter 6, the authors claim to have fulfilled the purpose of this thesis and to have answered the research questions.

The first research question concerned the risks and uncertainties associated with the value chain of BorgWarner:

- *What are the risks and uncertainties that exist in the value chain?*

This research question is first and foremost answered by the value stream mapping in Chapter 4. Through the extensive process mapping conducted during the initial phase of this thesis, the principal risks and uncertainties could be identified and quantified which resulted in Chapter 4. The risks were all allocated to a specific activity in the value chain, e.g. machine breakdowns are represented by the performance measurement, OEE.

The second research question concerned the effect the risks and uncertainties have on the inventory level in each instance:

- *How do these risks and uncertainties affect the inventory levels?*

This research question is partly answered by the value stream mapping as well, but in order to understand the effect and the relationship between the risks and the actual inventory levels, an analysis was conducted. The principal problem is that the internal supply chain of BorgWarner is a complex multi-echelon inventory system with many activities and processes. It is intuitively very difficult to draw any conclusions about how a certain risk affects the inventory levels. In order to solve this problem, the analysis model in Chapter 6 was developed to provide a simulated environment, where the effect of each isolated risk can be studied by changing the parameters.

The last research question concerned how changes in the inventory levels will affect the service level towards the customers:

— *How do changes in the inventory levels of each instance affect the service level?*

This research question is answered by the feature to reduce the inventory levels in the analysis tool. By performing simulations, with different inventory reductions in the analysis tool, the effect on the service level can be observed.

8.2 Evaluation of the chosen approach

The authors of this thesis conclude that the chosen approach has been very effective and has contributed to both the validity and the final result of the thesis. By studying the system first-hand through the value stream mapping phase, the authors were able to rely on primary data and to identify the root cause of the risks. Through this approach a thoroughly understanding of the studied system was achieved, which resulted in a solid foundation for the development of the analysis tool.

Through the data analysis phase the authors were also able to create a solid foundation of data through the use of existing theories on statistics and inventory control. By performing the data analysis themselves, the authors gained considerable knowledge about how each component of the real-life system could be represented in a computerized system. On the foundation of the first-hand data gathering and the data analysis, a simulation model with reasonable assumptions was developed.

8.3 Difficulties during the thesis

The principal problem encountered during this thesis was the vastness and complexity of the studied system. Since the studied system is a multi-echelon inventory system with several inter-dependent activities it has been extremely hard to investigate each entity to the full extent. Despite of this, the system was separated into manageable entities that could be developed independently based on reasonable assumptions.

8.4 Recommendations for future research

As mentioned in Section 8.3 one of the principal problems was the vastness of the studied system. Due to the vastness, some assumptions and approximations had to be made in order to produce input data that was representative and reliable. A suggestion for future research is an extensive mapping of each input parameter for the analysis tool. By refining and updating the parameters with better data, a more accurate result could be obtained from the analysis tool. For example, the supplier's delivery reliability could be mapped extensively. Currently, very little data exists for this activity and it is difficult to evaluate the root cause of the problem in order to be able to make reasonable predictions about future performance.

Another research topic closely related to this study is the investigation of the current customer delivery policies. The policies currently in effect were agreed upon during lower demand levels and incur high capital tied in inventory costs for BorgWarner. By investigating and evaluating the delivery policies the inventory levels could be optimized while maintaining a high level of service towards the customers.

9 References

Arbnor, I. & Bjerke, B., 1997. *Methodology for Creating Business Knowledge,.* Newbury Park, CA: Sage Publications.

Axsäter, S., 2006. *Inventory Control.* 2nd ed. New York: Springer Science+Business Media, LCC.

Björklund, M. & Paulsson, U., 2003. *Seminarieboken - att skriva, presentera och opponera.* Lund: Studentlitteratur AB.

Blom, G. et al., 2005. *Sannolikhetsteori och statistikteori med tillämpningar.* 5th ed. Lund: Studentlitteratur AB.

Borg, J., 2013. *BorgWarner Introduction.* Landskrona: BorgWarner TorqTransfer Systems AB.

BorgWarner Inc., 2011. *2011 Annual Report on Form 10 - K.* [Online] Available at: http://www.borgwarner.com/en/Investors/AnnualReports/Pages/annual_report_2011.aspx
[Accessed 18 February 2013].

BorgWarner Inc., 2011. *BorgWarner Finalizes Aquisition of Haldex Traction Systems.* [Online] Available at: http://www.borgwarner.com/en/News/PressReleases/BWNews/2011-02-01_BWFinalizesAcquisitionOfHaldexTractionSystem.pdf
[Accessed 18 February 2013].

BorgWarner Inc., 2013. *BorgWarner official homepage.* [Online] Available at: http://www.borgwarner.com/en/Products/Pages/Product-Detail-Search.aspx?k=%20&r=productfamily%3D%22Haldex%C2%AE%20FWD/AWD%20Systems%22
[Accessed 2 April 2013].

BorgWarner TTS, 2012. *TTS Way.* Landskrona: BorgWarner TorqTransfer Systems.

BorgWarner TTS, 2013. *Data Excerpt from Axapta.* Landskrona: BorgWarner TorqTransfer Systems .

Cederfeldt, J., 2013. *Interview Logistics Manager* [Interview] (11 February 2013).

Christopher, M., 2005. *Logistics and supply chain management: creating value-adding networks.* 3rd ed. Harlow: Pearson education.

Dal, B., Tugwell, P. & Greatbanks, R., 2000. Overall equipment effectiveness as a measure of operational improvement - A practical analysis. *International Journal of Operations & Production Management,* 20(12), pp. 1488-1502.

Franke, T. M., Ho, T. & Christie, C. A., 2012. The Chi-Square Test: Often Used and More Often Misinterpreted. *American Journal of Evaluation,* 33(3), pp. 448-458.

Gammelgaard, B., 2004. Schools in logistics research? A methodological framework for analysis of the discipline. *International Journal of Physical Distribution & Logistics Management,* 34(6), pp. 479-491.

Hines, P. & Rich, N., 1997. The seven value stream mapping tools. *International Journal of Operations & Production Management,* 17(1), pp. 46-64.

Hopp, W. J. & Spearman, M. L., 2000. *Factory physics.* 2nd ed. Boston: McGraw-Hill Publishing.

Höst, M., Regnell, B. & Runeson, P., 2006. *Att genomföra examensarbete.* Lund: Studentlitteratur.

ISO, 2009. *Technical Specification: Quality management systems — Particular requirements for the application of ISO 9001:2008 for automotive production and relevant service part organizations.* s.l.:International Organization for Standardization.

Jacobs, F. R. & Weston Jr, T., 2007. Enterprise resource planning (ERP)—A brief history. *Journal of Operations Management,* 25(2), pp. 357-363.

Jalote, P., 2008. *A Concise Introduction to Software Engineering.* London: Springer-Verlag.

Kovács, G. & Spens, K. M., 2005. Abductive reasoning in logistics research. *International Journal of Physical Distribution & Logistics Management,* 35(2), pp. 132-144.

Laguna, M. & Marklund, J., 2005. *Business Process Modeling, Simulation and Design.* Upper Saddle River, NJ: Prentice Hall.

Law, A. M. & Kelton, W. D., 2000. *Simulation Modeling and Analysis.* 3rd ed. Singapore: McGraw-Hill Book Co.

Lumsden, K., 2006. *Logistikens grunder.* 2nd ed. Lund: Studentlitteratur.

Manos, T., 2006. Value Stream Mapping - an Introduction. *Quality Progress,* 39(6), pp. 64-69.

Mattsson, S.-A., 2003. Några synpunkter på att reducera kapitalbindning. *Bättre produktivitet,* Issue 1.

Mattsson, S.-A. & Jonsson, P., 2003. *Produktionslogistik.* Lund: Studentlitteratur.

McCutcheon, D. M. & Meredith, J. R., 1993. Conducting case study research in operations management. *Journal of Operations Management,* 11(3), pp. 239-256.

Palm, J. & Sahlé, E., 2013. *Interview Production Planners* [Interview] (6 February 2013).

Pepper, M. & Spedding, T., 2010. The evolution of lean Six Sigma. *International Journal of Quality and Reliability Management,* 27(2), pp. 138-155.

Rother, M. & Shook, J., 1992. *Learning to see - Value stream mapping to create value and eliminate muda.* 1.2 ed. Brookline, Massachusetts, USA: The lean enterprise institute.

Sargent, R. G., 2010. *Verification and Validation of Simulation Models.* Baltimore, Winter Simulation Conference.

Sridharan, V. & LaForge, R. L., 1994. Freezing the Master Production Schedule: Implications for Fill Rate. *Decision Sciences,* 25(3), pp. 461-469.

Suciu, E., Apreutesei, M. & Arvinte, I. R., 2011. Value stream mapping - a lean production methodology. *The Annals of the Stefan cel Mare University of Suceava, Fascicle of the Faculty of Economics and Public Administration,* 11(1), pp. 184-191.

Svensson, M., Larsson, V. & Kutlešovski, D., 2013. *Interview Material Planners* [Interview] (05 February 2013).

Voss, S. & Woodruff, D. L., 2005. *Introduction to Computational Optimization Models for Production Planning in a Supply Chain.* 2nd ed. Berlin - Heidelberg: Springer-Verlag.

Yin, R. K., 2003. *Case study research: design and methods.* 3rd ed. Thousand Oaks: Sage Publications.

10 Appendices

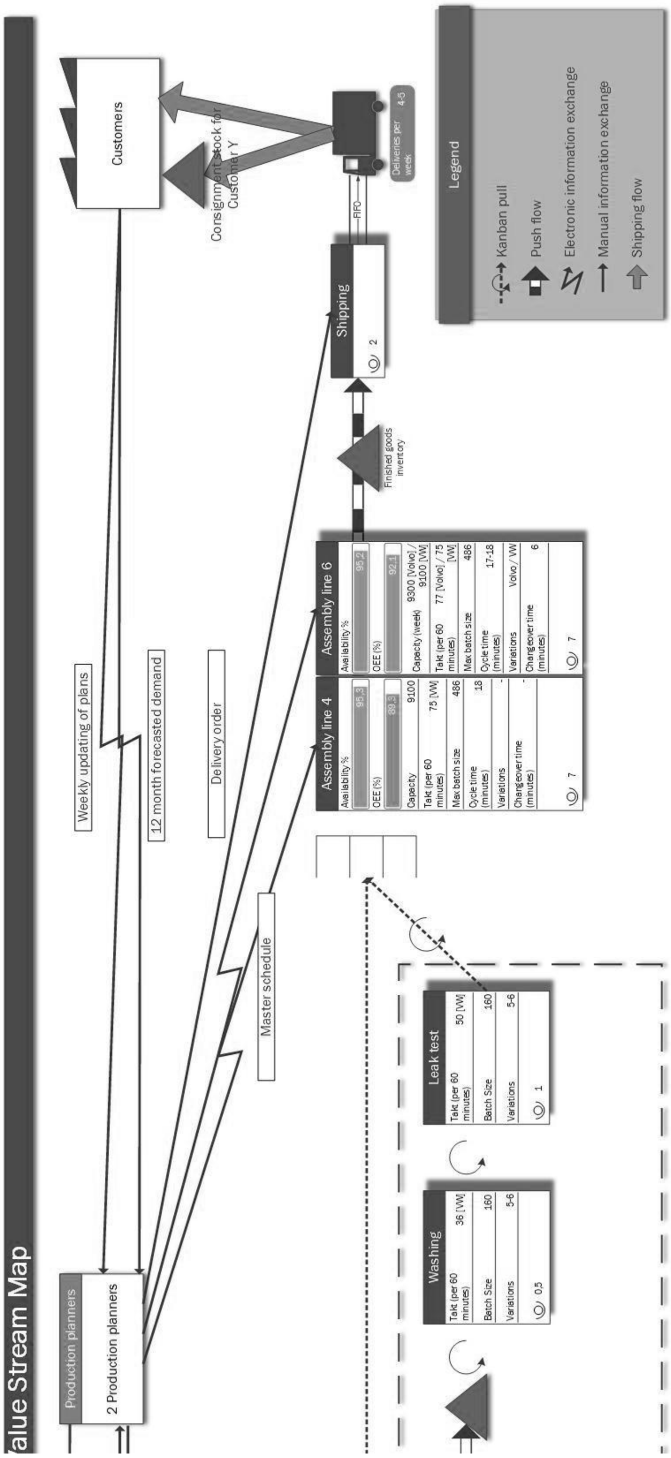
This chapter contains the appendices for this master's thesis.

A. Process family matrix

Table 10.1. Process family matrix for the products and activities at BorgWarner.

Generation	**Customer**	**Product**	Demand forecasting	Component ordering	Goods recieving	Incoming inspection (components)	(Components storge)	Machining (coupling house)	Deburring (coupling house)	Sealing (coupling house)	Washing & leak test (coupling house)	Generation 4 assembly line	Generation 5 assembly line	Collect finished goods from assembly	(Finished goods inventory)	Direct delivery to customer	Delivery to customer consignment stock
4	Y	1	X	X	X	X	X	X	X	X	X	X		X	X		X
4	Y	2	X	X	X	X	X					X		X	X		X
4	Y	3	X	X	X	X	X					X		X	X		X
4	Y	4	X	X	X	X	X					X		X	X		X
4	Y	5	X	X	X	X	X					X		X	X		X
4	Y	6	X	X	X	X	X					X		X	X		X
4	X	7	X	X	X	X	X					X		X	X	X	
4	X	8	X	X	X	X	X					X		X	X	X	
4	X	9	X	X	X	X	X					X		X	X	X	
5	X	1	X	X	X	X	X	X			X		X	X	X	X	

B. Value stream maps for Gen4 and Gen5



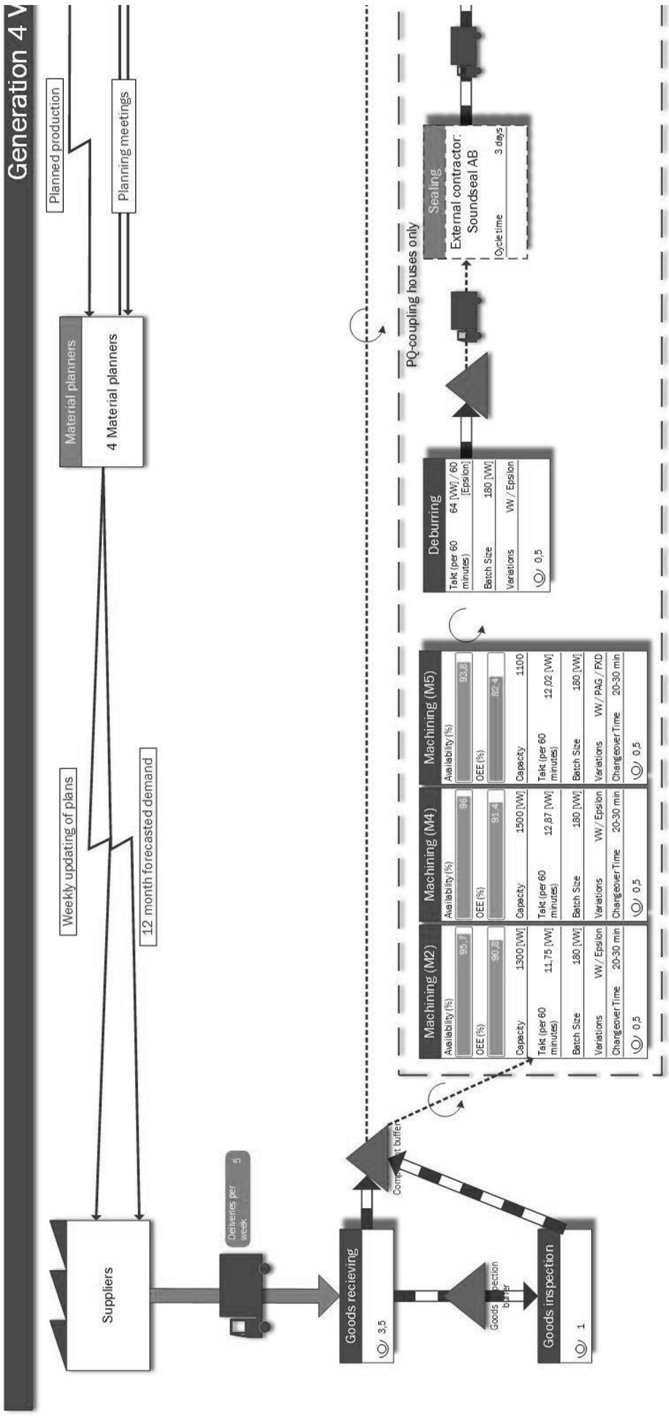


Figure 10.1. Gen4 value stream map.

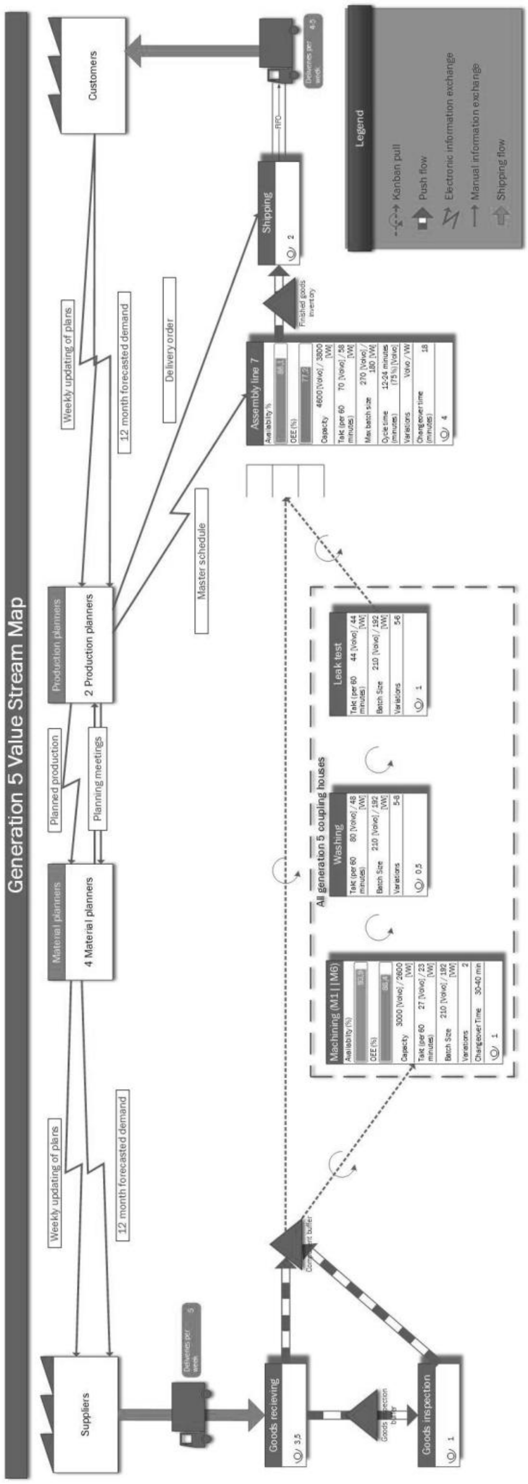

Generation 5 Value Stream Map
Customers
Suppliers
Material planners
4 Material planners
Production planners
2 Production planners
Weekly updating of plans
12 month forecasted demand
Planned production
Planning meetings
Master schedule
Delivery order
Goods recieving
Goods inspection
Machining (M1 | | M6)
Washing
Leak test
All generation 5 coupling houses
Assembly line 7
Shipping
Legend
Kanban pull
Push flow
Electronic information exchange
Manual information exchange
Shipping flow

Figure 10.2. Gen5 value stream map.

C. Monthly deviations of OEE

Table 10.2. Number of observations, mean and standard deviation of the OEE of the assembly lines per month and total.

	Line A			Line B			Line C		
	Mean	*Std. dev*	*# of obs*	*Mean*	*Std. dev*	*# of obs*	*Mean*	*Std. dev*	*# of obs*
Jan-12	0,887	0,084	71	0,924	0,081	73	0,855	0,066	2
Feb-12	0,847	0,120	72	0,932	0,053	73	0,448	0,000	1
Mar-12	0,916	0,053	76	0,947	0,047	77	0,968	0,000	1
Apr-12	0,886	0,094	65	0,916	0,093	65	0,699	0,185	16
May-12	0,881	0,097	71	0,916	0,081	73	0,822	0,325	20
Jun-12	0,884	0,138	68	0,877	0,171	70	0,804	0,253	36
Jul-12	0,888	0,071	52	0,880	0,087	56	0,605	0,351	14
Aug-12	0,890	0,107	66	0,884	0,125	65	0,795	0,226	39
Sep-12	0,913	0,085	70	0,913	0,204	70	0,842	0,168	36
Oct-12	0,911	0,090	77	0,946	0,065	77	0,705	0,256	43
Nov-12	0,923	0,081	74	0,942	0,068	74	0,763	0,164	39
Dec-12	0,893	0,084	44	0,951	0,031	56	0,705	0,282	13
Jan-13	0,906	0,070	62	0,935	0,065	71	0,812	0,202	26
Feb-13	0,872	0,085	57	0,916	0,125	68	0,808	0,214	19
Mar-13	0,901	0,053	23	0,916	0,046	23	0,800	0,112	7
Total	**0,893**	**0,094**	**948**	**0,922**	**0,103**	**991**	**0,772**	**0,239**	**312**

D. Operating hours for the assembly lines

Table 10.3. Normal (X) and overtime (O) operating hours for line A, B & C.

Day	Shift	Line A	Line B	Line C
Monday	Night	X	X	
	Morning	X	X	X
	Afternoon	X	X	X
Tuesday	Night	X	X	
	Morning	X	X	X
	Afternoon	X	X	X
Wednesday	Night	X	X	
	Morning	X	X	X
	Afternoon	X	X	X
Thursday	Night	X	X	
	Morning	X	X	X
	Afternoon	X	X	X
Friday	Night	X	X	
	Morning	X	X	X
	Weekend shift	X	X	
Saturday	Weekend shift	X	X	1st O
Sunday	Weekend shift	X	X	
Over time	Night before Saturday	1st O	1st O	
Over time	Night before Sunday	2nd O	2nd O	

E. Parameters for the machining department

Table 10.4. Parameters for the machining department.

	Lathes	Deburring	Sealing	Washing	Leak test
OEE (per machine)	0,908/0,914/ 0,824/0,884	N/A	External	N/A	N/A
# of machines	6	1	External	2	6
Takt	27/23/12	64/60	External	80/48/36	44/50
Batch size	180/210/192	180	External	210/192/ 160	210/192/ 160
Changeover time	30-40 min	-	External	-	-
Generation	Gen4/Gen5	Gen4	Gen4	Gen4/Gen5	Gen4/Gen5

F. Supplier delivery precision

Table 10.5. Supplier delivery precision, in percent, during 2012.

2012	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Supplier 7	Supplier 8	Supplier 9	Supplier 10	Supplier 11	Supplier 12
Jan	83,3	100	100	100	100	100	100	100	100	100	100	N/A
Feb	54,2	100	100	100	100	100	100	100	100	100	100	N/A
Mar	58,1	74,1	100	100	100	100	100	100	100	100	100	N/A
Apr	47,6	72,7	94,1	100	100	100	100	100	100	100	100	100
May	43,3	100	100	100	100	100	100	100	100	100	100	100
Jun	62,5	90,9	80,8	100	80,6	100	100	100	100	100	100	100
Jul	87,5	100	100	100	100	88,2	100	60	87,5	96,2	96	100
Aug	96,8	100	86,4	100	100	95	100	100	100	95,7	94,6	100
Sep	100	93,9	100	100	100	100	100	100	100	100	96,4	100
Oct	93,5	95,7	100	100	100	100	100	87,5	55,6	93,9	100	100
Nov	100	100	100	100	100	100	100	100	100	87,9	77,4	100
Dec	100	100	95,7	100	100	100	96,2	100	100	89,7	100	100