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Integrated product and supply chain design at Philips Healthcare

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Integrated product and supply chain design at Philips Healthcare

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I. Abstract

This master thesis describes a research project that was conducted within Philips Healthcare. The relation between the product design and supply chain design for a specific product was investigated based on an analysis of the current supply chain and a review of relevant literature. A quantitative model was developed, that enables an objective comparison of different product and supply chain designs subject to a range of parameter settings. The model can be used to support future business decisions and encourages an integrated approach of product and supply chain design.

II. Management Summary

The motive for this master thesis project has been the trade-off between standardization and customization. This trade-off has played an essential role in business, ever since Ford decided to produce its model T in "any colour so long as it is black". In the computer industry the relevance of the trade-off is also apparent. Delaying customization until demand is known is one of the key competencies that differentiate Dell from its competitors.

In this project, the issue was explored from a product design perspective as well as a supply chain design perspective, in the context of Philips Healthcare. Philips Healthcare is a global player in the medical equipment market. The project was executed at the X-Ray factory (OXB) in Best, The Netherlands. The assignment focuses on the High-end Surgery product portfolio, which consist of two types of mobile X-Ray machines.

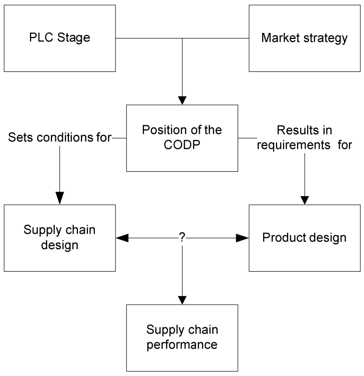
The initial assignment was to perform an independent in depth analysis and modelling of the high end Surgery supply chain taking into account possible improvement scenarios. Based on an evaluation of previous research within OXB, the following final problem statement was formulated:

> Within OXB there exists a lack of insight in the relation between the product design of the high end Surgery systems and the design of the supply chain.

The project was started with an analysis of the current product and supply chain design. The following was concluded:

- [redacted] Surgical C-arms are in the maturity stage of the product life cycle.
- [redacted] The **product design** of Surgical C-arms is characterized [redacted]
- [redacted] The **supply chain design** of surgical C-arms has the following characteristics: The main markets for surgical C-arms are [redacted]

A diagnosis was performed based on a review of existing research. The diagnosis identified a number of concepts that impact the relation between product design and supply chain design. From these concepts the following conceptual model was defined:



The conceptual model was translated into a quantitative supply chain model. The following goal was formulated:

> Enable an objective comparison of different product designs and supply chain designs, subject to different customer demand patterns, based on quantitative supply chain performance measures.

The model was developed in MS Excel. Verification and validation tests showed that the model was developed correct and satisfied the model objectives. The supply chain performance was based on a number of assumptions regarding the costs in the supply chain, which were approved by the Philips stakeholders.

Product design

Three different product designs were identified based on the position of items relative to the Customer Order Decoupling Point (CODP). The CODP is the point in the goods flow that separates forecast driven production from customer order driven production. In the model, components can either be assigned to the **platform**, meaning that they are assembled before the CODP, or are selected as **modules**, meaning that they will be added after the CODP.
The three resulting product designs are:

- All components are selected as modules
- Part of the components are assigned to the platform and the other parts are modules
- All components are assigned to the platform

For the product design consisting of one or more platforms and modules, many detailed designs are possible. It was decided to analyze two product designs in this class. In scenario A, all the common items are included in the platform (resulting in just one platform) and all the specific items are selected as modules. In scenario B, technical constraints were taken into account when selecting the items to include in the platform.

Supply chain design

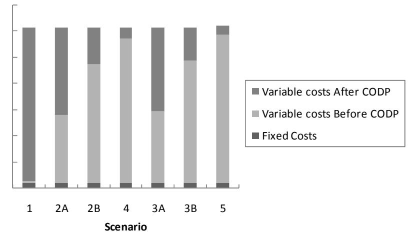
Two different supply chain designs were identified: a centralized supply chain design and a decentralized supply chain design. [redacted] and delivered to customers in three different regions. The supply chain includes three stock points: one for items, one for platforms and one for modules. The **decentralized supply chain** contains multiple platform and module stock points, close to the customer markets.

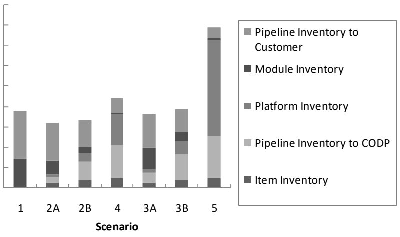
Based on the four different product designs and two different supply chain designs, eight scenarios were formulated and analyzed.

	Centralized supply chain	**Decentralized supply chain**
Only modules	Scenario 1	(Out of Scope)
One platform and multiple modules	Scenario 2A	Scenario 3A
Multiple platforms and multiple modules	Scenario 2B	Scenario 3B
Only platforms	Scenario 4	Scenario 5

Results

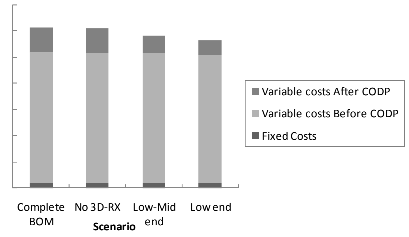
From the analysis it was concluded that [redacted]

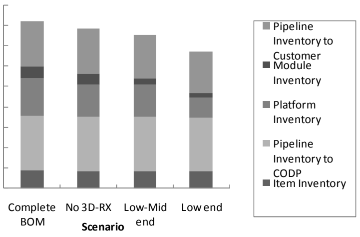




The impact of a number of parameters on the model outcome was evaluated. The total customer demand had the largest impact on the cash flow. The service level at the platform and module stock points had the second largest impact. Except for the customer demand, the impact of the **parameters** on the operating costs is relatively small compared to the impact on the inventory investment.

Finally, the effect of a decrease in the **configuration variety**, by a reduction of items was analyzed. A reduction in the number of items has a positive impact on the operating costs as well as on the inventory investment. The impact on the revenues should be considered to evaluate the net effect of a smaller configuration variety.





The master thesis project has resulted in a number of recommendations for Philips Healthcare:

- The quantitative supply chain model provides insight in the impact of different product and supply designs on supply chain performance and encourages an **integrated approach** of product and supply chain design. The **model should be applied consistently in supporting future business decisions**.
- [redacted]
- The analysis in this master thesis project was based on a limited number of scenarios. With the quantitative supply chain model many more scenarios can be evaluated. The stakeholders should consider **experimenting with different parameter settings**.

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III. Preface

Over the past five and a half years I have learned a lot about myself and the world around me. I have met many great people and shared experiences that I will remember forever. Studying at the Eindhoven University of Technology provided me with lots of challenges, on a social as well as an academic level. In the final phase of my studies, this graduation project has put me to the test on many aspects. I would like to thank all those who contributed to this master thesis in particular and shaping me as a person in general.

First of all I would like to thank Ton de Kok, my first supervisor and mentor for the past one and a half year. Although he could never really get used to my honest and to the point way of communicating, we managed to cooperate successfully. He has been a great inspiration and constantly triggered me to acquire new knowledge. I would also like to thank Arjan van Weele, my second supervisor. He showed a genuine interest in my project and his remarks were very helpful in improving my argumentation.

Secondly I would like to thank my company supervisors and colleagues. Quite a few times I was inclined to go into a lot of details and Theo Gransier reminded me in those cases to stay focused. Serge Werter provided me with helpful critical remarks (and numerous suggestions of what I should and what I should not include in this preface). Arjan den Hartog always showed interest in my personal experience of this graduation project and encouraged me to keep going. I would also like to thank all my other colleagues at Philips in Best. The lunch breaks made the days a lot more enjoyable and Ruud Lavrijssen has been a pleasure to share a room with.

Finally I would like to thank my friends and family. My friends at university supported me during the project and showed a lot of interest in the progress I made. My group of friends outside the university on the other hand enabled me to set aside my graduation project and empty my mind. I would also like to thank my parents. Despite the fact that they did not always understand the decisions I took during my student life, they always kept supporting me. I would like to thank my sister Eva, for setting such a great example in study discipline and my sister Maartje, for keeping me down to earth. Last but not least I owe a very big thank you to my boyfriend Floris. My graduation project has been a period of ups and downs and he always convinced me to take a positive view of things and have confidence in myself.

Ida Sanders
March 2009

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1. Introduction

No one who wants to buy a new car nowadays will be surprised that one can pick an exterior color, an interior to ones taste and choose from a broad range of accessories. In the car industry customization is simply taken for granted. Customization does have a premium price tag, along with a couple of weeks before your car is delivered. This trade-off between costs and customization was already recognized about a century ago, when Ford started the production of the Model T, available in red, blue, green and gray. In 1914, a year after the introduction of mass assembly, Ford decided to streamline production, and the model T became available in "any colour so long as it is black."[1] Even today the latest model Volkswagen Golf, the best sold car in the Netherlands in 2008[2], has a price mark-up for any colour other than "candy white"[3]. Clearly, the trade-off between standardization and customization still plays a role in today's business.

The computer industry is another sector where the relevance of the trade-off between standardization and customization is apparent. In 1984 Dell started with a strategy which would emerge as a major market break-through[4]. As the only computer company at the time, they sold computers directly to consumers. This approach allowed them to offer a customized product for a competitive price. The introduction of the internet further boosted the companies' success, enabling consumers to place orders anywhere and anytime. Dell has become the number two pc provider in the world. The secret behind this success is the organization of Dell's supply chain. In today's globalizing environment supply chains extend beyond company boundaries and companies are continuously faced with the decision what to make and what to buy. Close cooperation with suppliers and delaying customization until demand is known are the key competencies that differentiate Dell from its competitors[5]. Choosing which items to standardize and which items to differentiate is an essential element of Dell's strategy.

The trade-off between standardization and customization has also been the motive for this master thesis project. The issue was explored from a product design perspective as well as a supply chain design perspective, in the context of Philips Healthcare. Philips Healthcare is a global player in the medical equipment market. The medical equipment market is characterized by continuous innovation, and high quality standards. The results of the master thesis project are presented in this report. The first chapter starts with a detailed description of the project context. Next, the problem statement is formulated and the research approach for the project is explained.

1.1 Project context

In this section, the context of the master thesis project is described. The project has been executed at the X-ray factory of Philips Healthcare in Best, the Netherlands. The position of the factory within Philips Healthcare and the organization structure of the factory are described.

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[1] *Source: www.ford.com*
[2] *Source: www.bovag.nl*
[3] *Source: www.volkswagen.nl*
[4] *Source: www.dell.com*
[5] *Source: Sheffi and Rice, 2005*

1.1.1 Philips Electronics

Philips Healthcare is a sector of Royal Philips Electronics of the Netherlands. Philips was founded in 1891 and is currently headquartered in Amsterdam, the Netherlands. The company has a global presence and a multinational workforce of over 133.000 employees (June 2008). As of January 1st 2008 Philips consists of three sectors; Lighting, Consumer Lifestyle and Healthcare. Figure 1 shows the sales by sector.

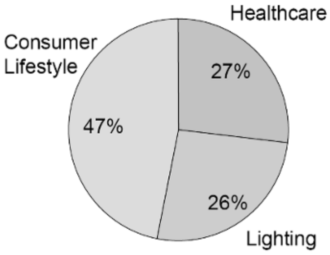

Figure 1: Sales by sector, 100% = 27.9 b €, LTM June 2008[6]

1.1.2 Philips Healthcare

The Healthcare sector of Philips is a global provider of innovative products, aimed at improving patient outcomes throughout the entire cycle of care; from prevention and screening to diagnosis, treatment, monitoring and management (Philips Annual report, 2007). Within Healthcare, five different Business Units are defined. The master thesis project was executed within the BU Imaging Systems (IS). Imaging Systems consists again of a number of business lines, one of which is General X-Ray. Figure 2 shows the sales of the Healthcare sector by geographic area and business unit.

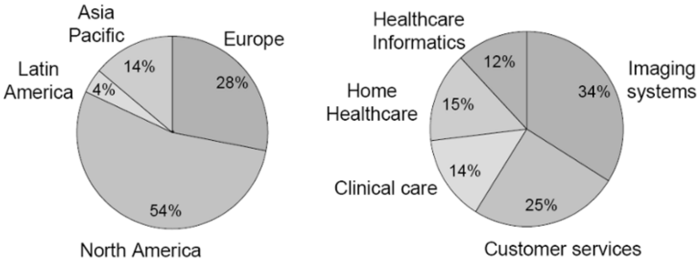

Figure 2: Sales by geographic area and business €, LTM June 2008[1]

1.1.3 Operations X-Ray Best

X-ray-tubes were the first products that were made by Philips in the medical sector, starting with the purchase of CHF Muller of Hamburg in 1895, and the introduction of the first medical X-ray tube in 1918. At the factory in Best, Operations X-ray Best (OXB) products from the General X-ray line (GXR) and the Cardio Vascular line (CV) are manufactured. OXB is part of the operations (IS Ops) department of the BU Imaging Systems and functions as a service provider to the GXR and CV business lines. IS Ops has a structure with three main departments: supply management, supply chain management and manufacturing. Supply management deals with the procurement of all the components and the relationships with suppliers. Supply chain management covers the planning and control of the production process. Manufacturing executes the production and testing of the products and monitors product quality. The master thesis project was executed within the supply chain management department. A schematic overview of the Healthcare organization and the position of the master thesis project within the organisation can be found in Figure 3.

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[6] source; Royal Philips Electronics, second Quarter 2008

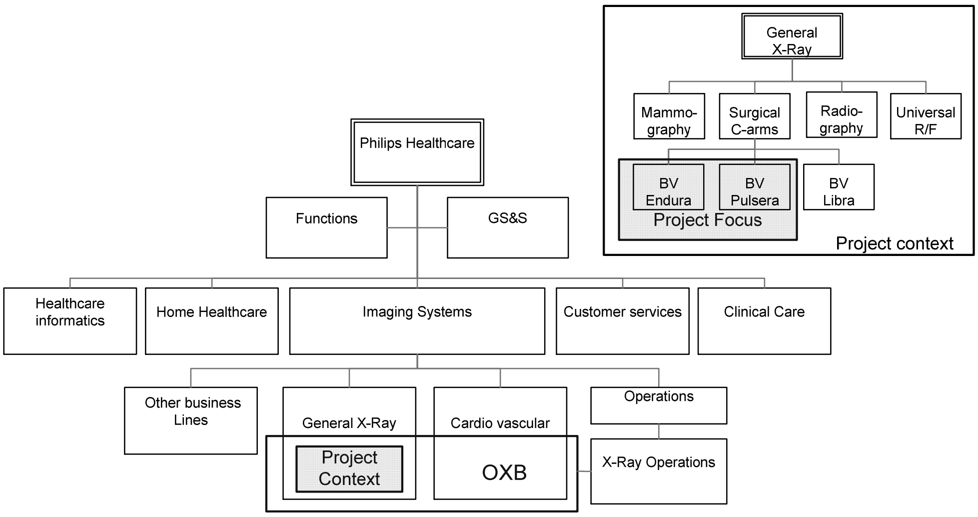

Figure 3: Organization structure of Philips Healthcare and position of the project

1.1.4 Surgical C-arms

A number of different products belong to the General X-Ray business line, among which are the Surgical C-arms. The product portfolio consists of three different types of Surgical C-arms. This project focuses on the supply chain of two types: the Type 1 and Type 2. [redacted] Surgical C-arms are used to monitor surgical interventions. They consist of two parts: a C-arm stand and a mobile view station (MVS). Currently, both are produced and tested in OXB and shipped to a customer from Best. In Figure 4 a picture of a surgical C-arm is shown.

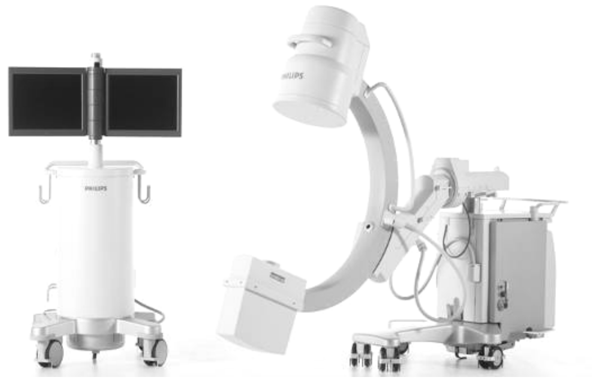

Figure 4: Type 1 MVS and stand with C-arc

1.2 Problem statement

In this section the problem statement, which is the focus of this master thesis project, is formulated. The section starts with the initial statement as formulated by the company. Based on a discussion of previous research results, a final problem statement is formulated.

1.2.1 Initial problem statement

As part of Philips Vision 2010 a number of strategic objectives has been formulated for IS Operations, including:

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Currently, the performance of OXB is most often expressed in qualitative terms, which leads to a lack of insight in the contribution to the objectives of IS Operations. Therefore an opportunity is identified to translate the qualitative OXB supply chain objectives into quantitative objectives that are understood and addressed throughout the organization. The high-end surgery supply chain is chosen as a suitable case for the focus of the project.

The initial objective of the master thesis project is formulated by the company as follows;

"*Project objective is to perform an independent in depth analysis and modelling of the high end Surgery supply chain taking into account possible improvement scenarios. This will result in a parameterized decision model that will be used as input for future business decisions or feedback on business decisions currently under consideration.*"

1.2.2 Previous research

Within Philips, an analysis to investigate improvement opportunities for the supply chain of surgical C-arms was already executed in 2008 (Werter and den Hartog, 2008). A tool was constructed that enabled comparison of different sourcing locations, factory locations and transport modes. The tool was able to provide insight in the influence of the supply chain design, on the cost price of surgical c-arms. However, the results that were obtained with the tool also emphasized the limitations that are imposed on the supply chain by the product design of the surgical c-arms. <<Confidential>>

1.2.3 Research opportunity

The management of the Business Line Surgical C-arms aims at an improvement of the gross margin, while maintaining a high quality product. The gross margin is the sales price minus cost price of products sold (= direct material + manufacturing costs).
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The design of new or improved surgical C-arms currently follows a traditional approach. First, customer specifications are defined by internal application specialists. These specifications are transferred to the product development department. When the new product has been developed the production process is adapted, and the supply chain is matched with the new requirements. The sequential development process can lead to a product design that is not optimal for the supply chain. Therefore, IS Ops would like to have more influence on the product design. To be able to specify clear requirements to the development department, more insight is needed in the relation between the product design and the supply chain design.

1.2.4 Final problem statement

From the previous discussion it becomes clear that there is a need for more insight into the relationship between the design of the high end surgery systems and the design of the supply chain. This leads to the formulation of the following problem statement:

Within OXB there exists a lack of insight in the relation between the product design of the high end Surgery systems and the design of the supply chain.

The objective is to develop a quantitative model that relates the product and process design to the design of the supply chain. The model results should indicate whether or not changing the product and process design and/or supply chain design contributes to the strategic objectives for IS Operations. The model is aimed for decisions regarding the requirements for new product generations.

As previously stated, the high-end surgery supply chain will function as a suitable case to represent general supply chain issues within OXB. The aim will thus be to formulate the model in general terms and concepts. The model will thereby be made applicable to other products besides the high-end surgery systems.

1.3 Research approach

In this section, the research approach is explained. First, the phases of the project are described. The project phases were based on theoretic models for quantitative model-based operations management research and design oriented research, which is explained in the subsequent section.

1.3.1 Project phases

The master thesis project is conducted in five phases. The first phase is the formulation of the problem statement. The phases are based on theoretic models for quantitative model-based operations research and design oriented research. Because the project combines aspects of both research methods, both types of models have been used as a reference to formulate the research approach. In Figure 5 an overview of the phases is provided, as well as a short description of the activities that were performed. The chapters of the report in which the results of the five phases have been described are indicated as well.

1.3.2 Quantitative model-based operations management research

The objective of the master thesis project is to develop a quantitative model. Bertrand and Fransoo (2004) distinguish between two types of model-based operations management research: axiomatic quantitative modelling research and empirical quantitative modelling research. Axiomatic quantitative modelling research is mainly aimed at extending models that were developed in previous research. Empirical quantitative research aims at describing measurements and findings from reality with an adequate model. The master thesis project falls in the latter category. Empirical research can be normative as well as descriptive. Normative research is primarily interested in developing policies to improve the current situation, whereas descriptive research is primarily interested in understanding the process.

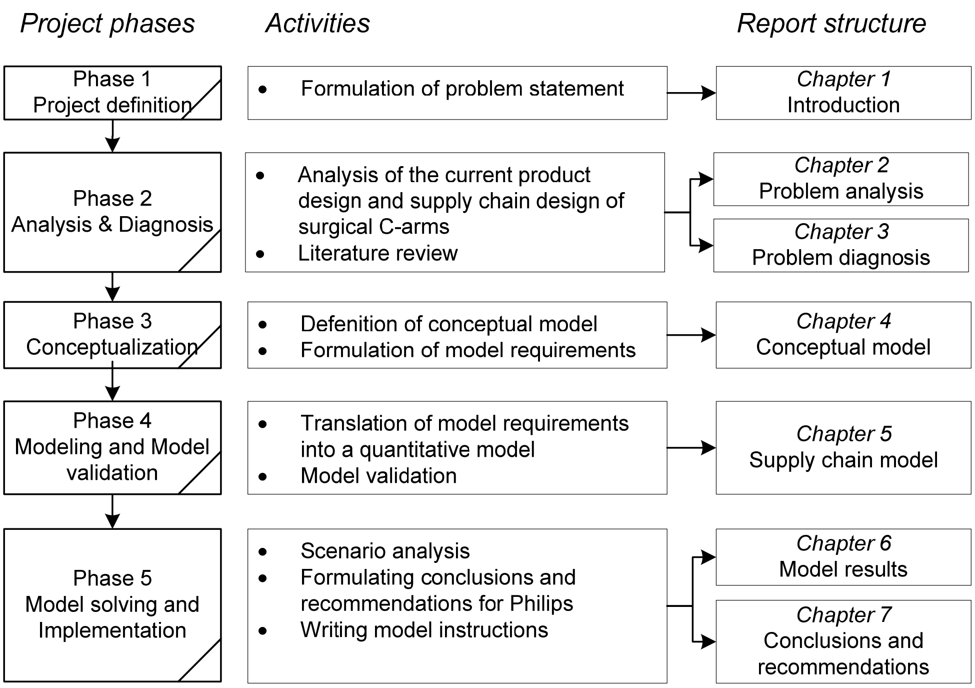

Figure 5: Phases of the research project and structure of this report

Normative claims have to be supported by a validation of the quantitative model. This is usually very difficult (Bertrand and Fransoo, 2004) because in reality there are many intervention variables and one can never be sure that a certain improvement is truly caused by one specific action. Nevertheless, this master thesis project is normative. Mitroff et al. (1974) distinguishes four phases in operational research. In the conceptualization phase, a conceptual model of the problem and system under study is made. The variables to be included in the model and the scope of the model are determined in this phase. In the modelling phase, the researcher builds a quantitative model, defining the causal relationships between the variables. In the model solving phase, mathematics is usually applied to solve the model. The final phase is the implementation of the model results.

1.3.3 Design oriented research

The master thesis project is aimed at designing a model to solve a business problem. Van Aken et al. (2004) distinguish between explanatory sciences and design sciences. The typical product of an explanatory science is a causal model, whereas the product of a design science is a technological rule or solution concept. A technological rule is a chunk of knowledge that states; if you want to achieve Y in setting Z, do X. The core of a technological rule is the X, the actual intervention, or system to be implemented. X thereby is a type of solution to a type of problem. The quantitative model that was designed in this master thesis project is aimed at comparing different solutions for the problem of choosing a product and supply chain design. A technological rule should be sufficiently tested in its intended field of use and the effect of applying the rule should be fully understood.

1.4 Conclusions

Based on the initial problem statement that was formulated by Philips Healthcare and the results of previous research, a final problem statement was formulated. The focus of the research project is the relation between the product design and supply chain design of surgical C-arms. A project plan with five phases was defined to investigate this relation. The results of the research project are presented in the subsequent chapters.

2. Problem analysis

In this chapter an analysis is performed based on the previously formulated problem statement. The logic of the PCI model by Bemelmans (1986) is followed (see Figure 6). According to Bemelmans, the control of a process always needs to be in line with the characteristics of the process. The primary process needs to be analysed, before any conclusions with regard to the control structure can be drawn. Based on the control structure, requirements can be formulated regarding the information structure within the organization. This chapter starts with an analysis of the current product design and production processes of surgical C-arms. In addition, the current control methods and the supply chain design are described.

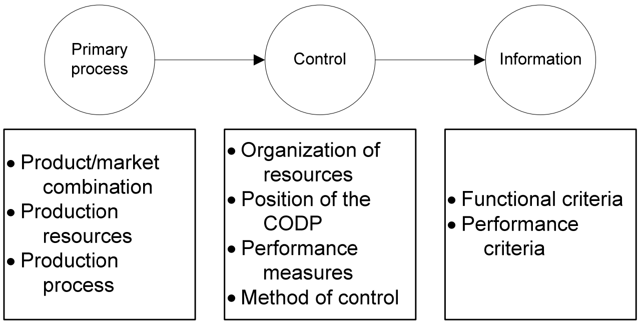

Figure 6: The PCI-model[7]

2.1 The market for Surgical C-arms

In this section, the current market for surgical C-arms is characterized and the market strategy for Surgical C-arms is explained.

2.1.1 Product application

The Type 2 and Type 1 are mobile fluoroscopy systems that can be applied to monitor surgical interventions. This means that the systems can be used during a surgery in a hospital. The system provides surgeons with a real-time image of the body-parts they are working on. The main application areas are orthopaedic, neuro, abdominal, cardio-vascular, pain management and thoracic surgery. The systems can be coupled to a hospital network to transmit patient data. The Type 1 is a more high-end application than the Type 2. The Type 1 is able to provide a higher X-ray dose and has a higher image quality. It can thereby be applied in more complicated situations.

2.1.2 Market characteristics

The market for surgical C-arms is a replacement market. This means that the majority of demand arises from the need to change a current system with a new one. This can either be because of a defect, or because of the need for a newer technology. The Type 2 and Type 1 are sold world-wide. In some countries dealers are used, whereas in others the systems are only sold through the sales organization of Philips Healthcare. [redacted] An overview of the number of systems sold per year can be found in Appendix B.1. Figure 7 shows the relative sales per geographic region.

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[7] *Adapted from: Bemelmans, 1986*

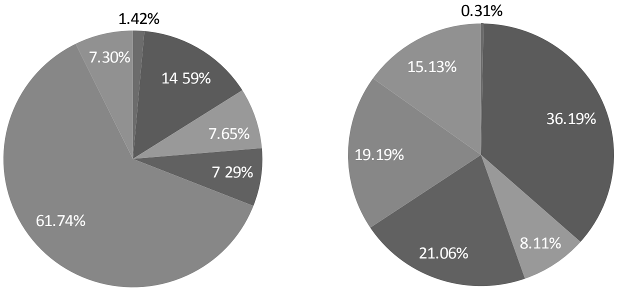

Figure 7: Relative number of systems sold[8]

The customers of Philips Healthcare consist of hospitals and private clinics. The main competitors of Philips are Siemens and General Electric (GE). In Appendix B.1 a graph of the market share per company in the North American market is included. Because the systems fall within the category of medical devices, the product quality is closely monitored by several bodies. Among these is the North American Food and Drug Administration (FDA). Because GE did not comply to FDA standards, they had to shut down their factory from January 07 until May 08 (GE Press release May 5, 2008). [redacted]

2.1.3 Market strategy

The market can be divided into a low-end segment, a mid-end segment and a high-end segment.
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2.2 Product design

In this section, the product design of the Type 2 and Type 1 is described. First, the hardware and software of the systems are described. Finally, the product development roadmap for surgical C-arms is briefly explained.

2.2.1 Hardware design

From a technical perspective most parts of the Type 2 and Type 1 are identical with exception of the power supply and electric controls. Both systems consist of a C-arm stand and a mobile view station (MVS), see Figure 8. The C-arm stand consists of a C-arm and a stand carriage with a small cabinet. The C-arm includes the X-ray tank, collimator and X-ray detector. The stand includes a computer for X-ray control (Stand Controller & Power Unit, SCPU), the power supply and a user interface panel. The MVS consist of a trolley with two displays, a user interface panel, a computer for image processing (Digital Fluoroscopy Imaging module, DFI), and optional hardware like a printer or DVD writer. The MVS and C-arm stand have to be coupled with a cable, in order to use the system. A full description of the hardware architecture can be found in Appendix B.2.

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[8] *Based on x Type 2 systems and x Type 1 systems*

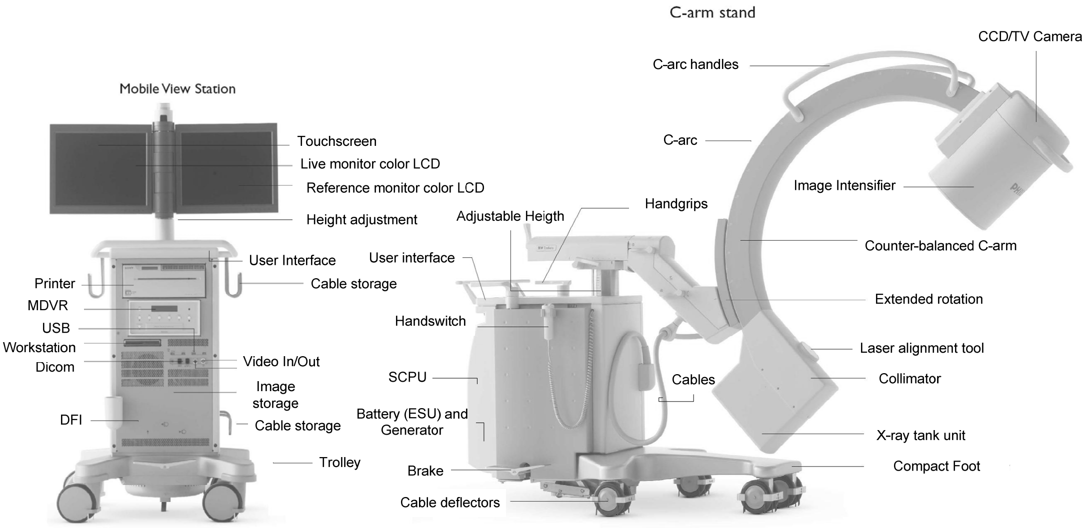

Figure 8: MVS and C-arms stand with main parts.

2.2.2 Software design

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2.2.3 Product roadmap

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2.3 Primary Processes

In this section, the primary processes for the Surgical C-arms are described. The primary processes are assembly, testing, distribution and service.

2.3.1 Assembly

Within OXB, the assembly and testing of the MVS and stand is performed. The majority of the tests are executed after the assembly of the MVS and the stand has been completed. The testing procedure is called system integration (SI). The assembly of the stand is performed at three workstations. The assembly of the MVS is performed at a single workstation. The assembly of the stand takes x on average. The assembly of the MVS takes x on average. System integration takes x for a Type 1 and x for an Type 2. In Figure 9 a timeline is presented for the processes within OXB. The first day after order release is used to collect the right materials on the shop floor.

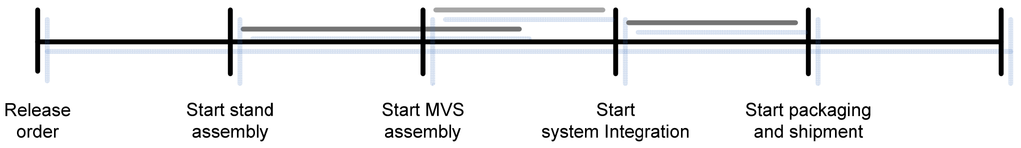

Figure 9: Type 1 and Type 2 production timeline.

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Flowcharts of the assembly processes for the MVS and Stand are included in Appendix B.5.

2.3.2 Testing

Because surgical C-arms use X-radiation, there are strict regulations regarding the performance of the systems. In order to guarantee the safety of patients and personnel, the X-Ray dose has to stay within certain limits. A number of bodies, like the FDA and KEMA, monitor the adherence to these regulations and perform regularly inspections. To comply with all regulatory constraints, a broad range of tests is executed during the production process.
<<Confidential>>
A flowchart of the SI process is included in Appendix B.6.

2.3.3 Distribution

When the product has been assembled and tested, the distribution process is started. To protect the Surgical C-arm from damage, it is packaged in a wooden box.
<<Confidential>>

2.3.4 Service

On a system level, the BU GXR guarantees x years service support, after production of the last system of a specific type. A Customer Service Agreement (CSA) can be closed when the system is sold. In the CSA the service that will be provided is specified. Certain parts and components of the surgery systems have been selected as Field Replacement Units (FRUs), which are kept in inventory by the service organization. Whenever possible, the FRU's are defined at a level that is also used within operations. Also, the FRU-s can preferably be tested separately. The service organization uses x main warehouses, in different geographic regions, from which the FRU-s can be ordered. A part of the FRU-s is repairable, which means that they are repaired by either Philips or a supplier and reused as a spare part.

2.4 Resources

In this section, the resources that are used in the primary processes related to Surgical C-arms, are described.

2.4.1 Personnel

All the mounting activities that are part of the assembly process of Surgical C-arms are performed manually. In total x workers (FTE) are employed on the assembly line of the MVS and the Stand. Some of the assembly workers are able to perform multiple steps in the assembly process, although most of the workers are either working on the line of the MVS or on the line of the Stand. [redacted] Besides assembly workers, a lot of indirect personnel is involved in the assembly of the surgical C-arms. These are a line manager, trouble-shooters, a quality engineer, and a shop floor controller. For the testing process, [redacted] In total x testers (FTE) are employed in the testing process of surgical C-arms. In general, the education level of the testers is higher than the education level of the assembly workers. A limited number of the testers can also perform mounting activities.

2.4.2 Equipment

The assembly is performed on a floor with ElectroStatic Discharge (ESD). All the operators wear ESD coats and shoes. The equipment for assembly mainly consists of small tools, like screwdrivers. Furthermore some lifting equipment is installed, for easy handling of heavy parts. Finally, test equipment for the high-voltage tests is present on the shop floor. A number of parts that are used in the assembly of the stand and MVS have to be traceable. Therefore, the serial numbers of the parts have to be registered. System integration is performed in a test box constructed of lead because X-radiation does not penetrate through lead. The testing procedure is set up with a minimum exposure to X-radiation for the operators. Specific equipment is needed to execute the X-radiation tests.

2.4.3 Materials

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In Figure 10, the relative purchasing volume for every geographic region is shown.

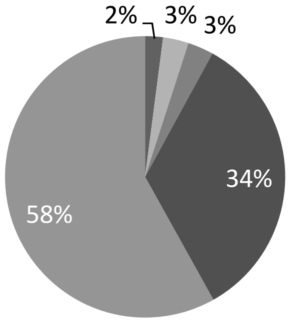

Figure 10: Relative volume purchased[9]

A large part of the volume purchased for the assembly of surgical C-arms consists of components and subassemblies. For these components and subassemblies a number of manufacturing activities has already been performed by a contract manufacturer. All the components of surgical C-arms that are purchased by Philips fall into three commodity categories: mechanical components, electrical components and X-Ray specific components. Figure 11 shows the relative contribution of each of these categories to the total purchasing volume.

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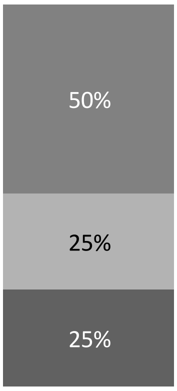

Figure 11: Relative contribution of commodities purchased[10]

2.5 Production planning and control

In this section, the production planning and control methods within OXB are explained. First, a high level description of the order fulfilment process is given. Next, the production planning

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[9] *Based on the value of purchased materials for x Type 2 systems and x Type 1 systems*

[10] *Based on the Type 2, Type 3 and Type 1 (2007)*

process is explained and the BOM structure that is used in planning and production is described. Finally, the inventory control policy used within OXB is described.

2.5.1 Order fulfilment

A customer order is placed by the customer at the Global Sales and Services (GS&S) organization. A sales representative chooses the right system specifications based on the customer preferences. The system specifications are entered into the sales catalogue and a list of configuration codes is created. The order is screened by a sales order manager to check if the chosen combination of functionalities can be provided. Next, a production slot is allocated to the order and the order is translated to a production order. At the start of the production slot, the order is released by the shop floor controller. The MVS and the stand are assembled and all the materials that were used are registered in an ERP System. After the assembly, the stand and MVS are coupled and tested. Finally, the system is packed and shipped to the customer and an invoice is sent. The GS&S organization provides training and installation of the system at the customer.

2.5.2 Planning process

Every year an aggregated sales forecast is made for the surgical C-arms, the Annual Operational Plan (AOP), and the required number of production slots is calculated. A production plan for the upcoming months is made in a monthly meeting, the Monthly Order and Production Schedule (MOPS). The starting point of the MOPS proposal is the AOP. Initially, x% of the production plan is planned in the first half-year and x% in the second half-year. This is done to ensure that sufficient capacity and material is available to produce the demand in the first half-year, even when the demand is higher than expected. Also, the average order intake in the past months is calculated. This average order intake is used to predict what the order intake will be in the coming months. The number of orders that have already been placed at OXB determine whether the production plan for the next month is raised or lowered. Finally, seasonal effects and a sales forecast are taken into account and decisions are compared with the available capacity. A more detailed description of the MOPS process can be found in Van Straaten (2007).

The MOPS reflects the number of production slots that are needed on a weekly basis. Incoming orders are allocated to a production slot by the sales order manager.
As shown in Figure 12, the number of incoming orders, as well as the number of systems that are shipped each week varies. At the end of the year, the number of incoming orders increases relative to the number of shipments. This is due to the fact that the Philips wants to minimize the on-hand inventory at the end of the year. A large part of the orders is therefore planned at the start of the next year.

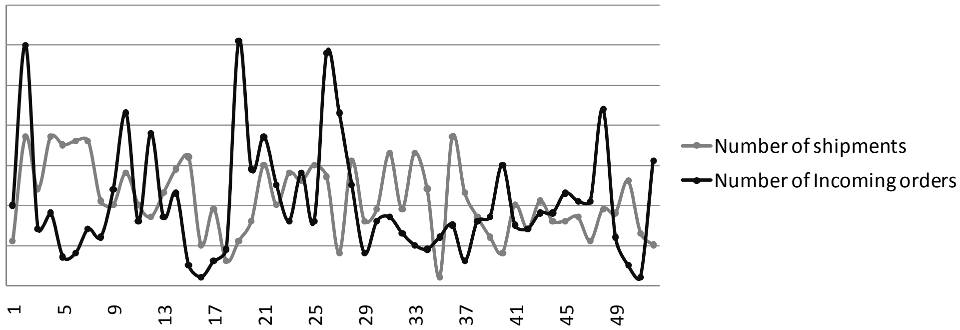

Figure 12: Shipments and incoming orders for the Type 1 (2008)

Based on the MOPS, the Master Production Schedule is generated to ensure capacity and the material requirements planning (MRP-I) is made. The materials are planned with an ERP

system. The MRP-I is calculated on basis of the material needed for the closed slots and open slots, and a routing file. For the slots that are already allocated to a customer order, the BOM is used. For the slots that have not been allocated to a customer order, the P-BOM is used. This is a BOM that includes the expected percentage of occurrence for each component.
The P-BOM is based on historical data. In the routing file it is stated what material is needed at which stage of the production, which determines the material needs in time. A more detailed description of the MRP-I logic can be found in Van Straaten (2007).

2.5.3 BOM structure

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2.5.4 Inventory control

The inventory control policy of the components is based on an ABCD classification. The items in class A represent the items with the highest turnover (in €), whereas the items in class D represent the lowest turnover.
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In Table 1 an overview of the inventory control policies for class A, B, C and D items is presented.

	Control concept	Supplier Location	Turnover %	Safety days	Delivery Frequency	Lower stock level	Upper Stock level
A							
B							
C							
D							

Table 1: Inventory control policies for ABCD items

2.6 Conclusions

The aim of this master thesis project is to create insight in the relation between the product design of the high end Surgery systems and the design of the supply chain. Therefore, the current product design and supply chain design of surgical C-arms were analyzed.
From the analysis the following conclusions can be drawn:

[redacted]

- The current product design of surgical C-arms consists of a stand with a C-arc and an MVS, which are controlled by a number of software packages. [redacted]
- Surgical C-arms are assembled based on customer orders. The assembly process involves mainly mounting activities; the process is complicated by the large amount of customer specific options. Surgical C-arms need to be tested extensively due to regulatory constraints.

[redacted] The main production resources are labour and materials. [redacted]

- The production planning for surgical C-arms is reviewed on a monthly basis, to match supply with demand. The number of incoming orders, as well as the number of systems that are shipped each week varies. The production planning and control process is complicated by a BOM structure with many levels.

To model the relation between the product design and supply chain design, a quantitative approach has been chosen. As explained in Section 1.2.2, the research question follows from a previous project in which a supply chain model was developed. This model started with the current product design of the surgical C-arms and the current market locations. [redacted] The current market locations were categorized into geographic regions. Scenarios were formulated with product locations near to the main market locations. Finally, the transport mode could be varied between air freight and sea freight. Figure 13 shows the concepts that were incorporated in the tool and the relations between these concepts.

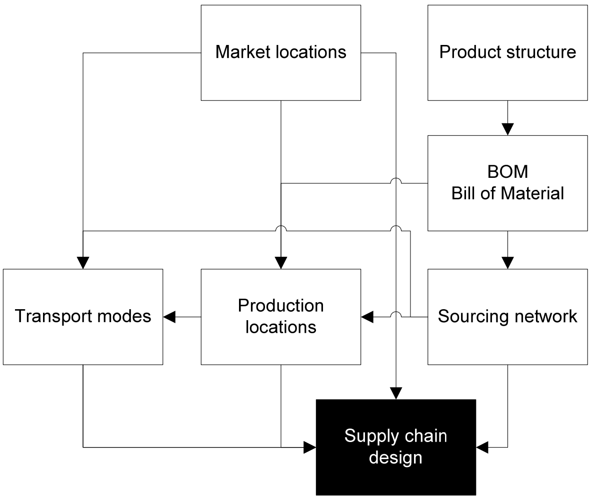


Figure 13: Conceptual model Werter and den Hartog

Clearly, the supply chain model that was developed by Werter and den Hartog already incorporates quite a number of concepts related to the product and supply chain design. In the next chapter, literature related to product and supply chain design is discussed, to evaluate which other concepts need to be considered in the quantitative supply chain model resulting from the master thesis project.

3. Problem Diagnosis

As previously stated, the objective of this research project is to develop a quantitative model that relates the product design of Surgical C-arms, to the design of the supply chain. This chapter starts with a summary of previous research in which this relation has been discussed. The product design and supply chain of Surgical C-arms are positioned in different frameworks. This is followed by a more detailed discussion of some of the key concepts that play a role in the different frameworks.

3.1 Product design versus supply chain design

A number of complementary theories have been developed that relate the product design to the design of the supply chain. Fisher (1997) argued that the first step in devising an effective supply-chain strategy is to consider the nature of the demand for the products the company supplies. He distinguishes between functional products and innovative products. Surgical C-arms belong to the category of innovative products. Innovative products are characterized by a high product variety, a relatively high contribution margin and a relatively short make-to-order lead time. The appropriate supply chain for this type of products is a market-responsive supply chain. Fine (2000) observes that supply chain designs are not stable, but change over time in a cycle from integral/vertical supply chains to horizontal/modular supply chains. The speed of changes depends on the speed of innovation in the industry. [redacted]

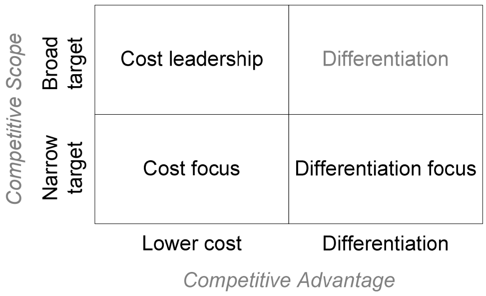
Aitken et al. (2003) relate the design of the supply chain to the product life cycle (PLC). As mentioned before, Surgical C-arms are in the maturity stage of the PLC. In this stage, he suggests that a pull based (or Kanban) supply chain is most appropriate. Christopher et al. (2006) propose a taxonomy to guide the selection of an appropriate global supply chain strategy. The key dimensions of the taxonomy are replenishment lead times and predictability/variability of demand. [redacted]. Ultimately Simchi-Levi et al. (2008) propose a framework that combines the previous theories. The framework uses demand uncertainty and product introduction frequency as the main product-process characteristics. [redacted] An extensive explanation of the different frameworks can be found in Appendix A.1.

Although all the models follow a somewhat different approach in describing this relation; a number of concepts play a key role in multiple frameworks. In the following sections, the relevance of these concepts for the quantitative supply chain model is discussed.

3.2 Market characteristics

According to Fisher (1997), the starting point in designing the right supply chain is the nature of the demand for the products the company supplies. He determines whether a product is functional or innovative, based on aspects like stage in the PLC, demand predictability, product variety, and market standards for lead times and service. Subsequently, the supply chain is matched according to this typology. Aitken et al. (2003) also emphasize the importance of market circumstances by defining order winners and order qualifiers for each stage of the PLC. Christopher et al. (2006) incorporate market circumstances in their model with the term ‘predictability’, which should be based on a continuous assessment of the product range and market characteristics.

All of these market typologies can be linked to the generic market strategies of Porter (1985). Porter distinguishes between the competitive scope of a product and the competitive advantage. According to his typology the competitive advantage of a product can either be differentiation from competitors, or a focus on a low price. Combined with the differentiation between a broad, or a narrow market scope, this leads to four different market strategies. Figure 14 shows a matrix of Porter’s generic strategies. [redacted]



Competitive Scope		Competitive Advantage: Lower cost	Competitive Advantage: Differentiation
	Broad target	Cost leadership	Differentiation
	Narrow target	Cost focus	Differentiation focus

Figure 14: Porter’s generic strategies (Porter, 1985)

Although the choice of a certain market strategy should be in line with the product and supply chain design, this relation cannot be modelled quantitatively. A differentiation strategy, for example, can only be executed when the product design enables differentiation. However, no minimum or maximum exists for the number of components that can be differentiated.

3.3 The customer Order Decoupling Point

Aitken et al. (2003), as well as Christopher et al. (2006) and Simchi-Levi et al. (2008) differentiate between push- and pull based supply chains. A push system schedules the release of work based on demand, while a pull system authorizes the releases of work based on system status (Hopp and Spearman (2001). A combination of a push system and a pull system can be found in a supply chain as well. The place of the customer order decoupling point (CODP) is an important supply chain characteristic in this context. The CODP is defined by Wikner and Rudberg (2005) as:

"The point in the goods flow that separates forecast driven production from customer order driven production”.

Another name for the CODP is the push-pull interface, which divides a production process into push- and pull segments. In general, the position of the CODP is chosen based upon the level of customization of the product. All activities in the supply chain that are customized and targeted at a specific customer are performed after the CODP, while all activities in the supply chain performed before the CODP are standardized (Hoekstra and Romme, 1992).

The position of the CODP is also related to a supply chain strategy called postponement or late differentiation. Postponement is an organizational concept whereby some of the activities in the supply chain are not performed until customer orders have been received.

Postponement can occur along the entire supply chain, from the procurement of parts to the final delivery to the customer. Christopher et al. (2006) suggest that postponement can be used to integrate the lean and agile supply chain philosophies. Postponement can be enabled through changes in the manufacturing-distribution process or the product architecture. Swaminathan and Lee (2003) distinguish three enablers of postponement:

- Process standardization
- Process re-sequencing
- Component standardization

Process standardization should be applied to the first steps of the process across a product line. Process re-sequencing is a complementary approach, in which common components are added at the beginning of the process. With component standardization, the number of common components relative to specific components is increased. Substantial reductions in the inventory holding costs may be obtained by applying postponement.

A number of quantitative models have been developed that investigate postponement. Lee and Tang (1997) describe a simple model that captures the costs and benefits associated with delayed differentiation. The total relevant costs in the model consist of the total investment cost for redesigning the product, the total processing costs and the total inventory costs. A supply chain with N operations is modeled as a system with N single echelons. The echelons are controlled with a service level and an order-up-to policy. Demand is assumed to follow a normal distribution. A system with two end products is modeled. Standardization, modular design and process restructuring are compared with the model, by choosing the point of differentiation in the supply chain. Swaminathan and Tayur (1998) develop a discrete time model of an assembly process based on semi-finished products called vanilla boxes. The assembly capacity of the manufacturer is finite and stochastic demand for multiple products occurs. A two stage stochastic programming framework is formulated. In the first stage, the configuration and inventory levels of the vanilla boxes is chosen. In the second stage, the vanilla boxes are allocated to different products with limited capacity. The objective is to minimize the sum of stock-out costs and holding costs. A heuristic was developed to solve the program for large BOM structures.

Gupta and Benjaafar (2004) extend earlier models on delayed differentiation by considering load dependent lead times. The focus of the article is on the impact of the point of differentiation on the inventory of semi-finished goods. A two-stage system is considered in which one or more platforms are made to stock in the first stage and differentiated in the second stage. In the model, demand for products follows a Poisson process and inventories are managed according to a base-stock policy. Each stage in the assembly process is treated as a single-server queuing system, with exponentially distributed processing times. Expressions for the expected inventory and backorders are derived, as well as the average order fulfillment time and the proportion of orders that exceed a critical delivery-time target. The latter two measures express the service level of the system. Wong et al. (2009) extend the model of Gupta and Benjaafar to allow a broader range of assembly configurations to be compared.
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3.4 Supply chain design

Based on the position of the CODP, Wikner and Rudberg (2005) derive a classification with four general supply chain types. These four types are Make-to-Stock (MTS), Assemble-to-Order (ATO), Make-to-Order (MTO) and Engineering-to-Order (ETO). Figure 15 illustrates the position of the CODP for these four supply chains.

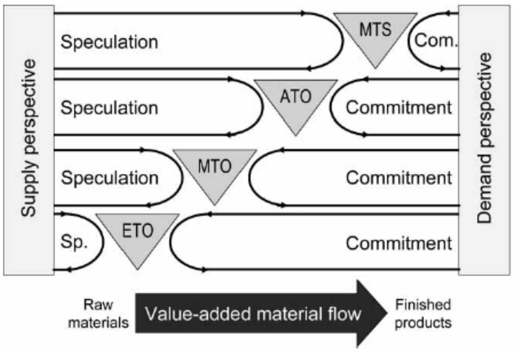

Figure 15: The CODP at different positions in the supply chain[11]

The supply chain design of the surgical C-arms can be classified as Assemble-to-Order. An ATO system is characterized by the structure of the production network. Multiple components are combined into multiple products and some components are common, whereas others are specific. Demand occurs only for products, but the system keeps inventory of components. A product is assembled only in response to customer demand (Song and Zipkin, 2003). Typically, ATO systems are applied to complex products, with a relatively low volume and high mix of custom components. Examples of ATO systems can be found in the automotive and machine industry. In Figure 16 a simple example is provided of the general structure of an ATO system.

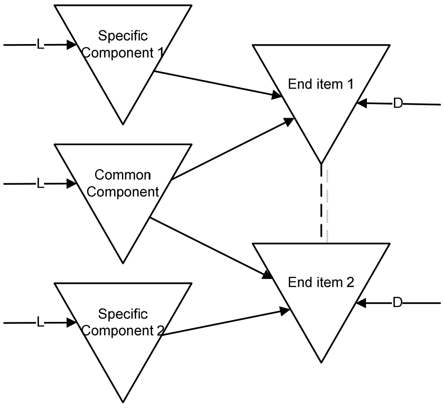

Figure 16: Simple ATO system

In Sanders (2008) recent papers related to ATO systems are discussed. In general, the research on ATO systems places much emphasis on the complexity of an ATO network. It was concluded that current quantitative research on ATO systems mainly focuses on the optimization of inventory policies. The focus of this stream of research is the trade-off between inventory investments and customer service level. Because an ATO system is a combination of a divergent and a convergent network, optimal inventory policies can not be calculated. Near-optimal policies for ATO systems apply base stock policies in which an order-up-to level is calculated.

Sanders (2008) also discussed models related to supply chain network design. The globalization of markets has changed the distribution of the inventory investment and financial risks across the supply chain. This might lead to decentralized control and local optimization in each echelon of the supply chain. It was concluded that most research on global supply chain design has a rather limited scope and many critical parameters are not included. The development of a model, that includes both a comprehensive method to

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[11] *Adopted from Wikner and Rudberg (2005)*

calculate all supply chain related costs and incorporates the stochastic character of ATO systems, was identified as an opportunity for future research. In the quantitative supply chain model, resulting from this master thesis project an attempt is made to include both of these aspects.

3.5 Outsourcing

One of the main results of globalization is the increased use of outsourcing. When a functionality previously manufactured internally is shifted to a supplier, this is referred to as outsourcing. Many different definitions of outsourcing exist, but a few common characteristics can be defined (Van Weele, 2005):

- Outsourcing always involves the transfer of activities that were previously executed in-house to an external party.
- Resources, which may include assets as well as people, go over to that party.
- There is an extended relationship between the parties involved for a longer period of time.
- In the outsourcing process the buyer is exposed to new costs and risks.

There are a number of rationales behind outsourcing. The most commonly used theories are core competence theory, transaction cost theory and agency theory. In Table 2 a short explanation of each theory is given. [redacted]

Core competence theory	Increasing the focus on the development and protection of core competencies means that strategic choices have to be made. Competencies that are considered non-core can therefore be outsourced to external parties.
Transaction cost theory	Investments, including investments in outsourcing help reduce transaction costs, and in turn, reduce the size of the firm, making it more productive.
Agency theory	As a firm grows in size and its supply chains and employee interactions increase, the owners need to increase the number of employees who work as agents to support the complexity of the organization. Outsourcing saves the firm time, improves its control over its business activities and requires fewer employees.

Table 2: Rationales behind outsourcing[12]

[redacted] Prahalad and Hamel (1994) define a competence as a bundle of skills and technologies. The distinction between a core and non-core competence is based on three criteria. A core competence must make a disproportionate contribution to customer perceived value; be competitively unique and be extendable to new products or services. <<Confidential>>
Van der Burg (2007) performed a master thesis project on purchasing strategies in various life cycle stages at Philips Healthcare.

Clearly, outsourcing can have a significant impact on the design of a supply chain. Not only the physical structure of the supply network changes due to outsourcing, but outsourcing can also cause a shift of the CODP. The CODP is shifted downstream when a part of the production process, that was first fulfilled based on customer orders, is outsourced to a

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[12] *Adopted from Schniederjans et al. (2005) and Prahalad and Hamel (1994)*

contract manufacturer, where this manufacturer's items are ordered from stock. <<Confidential>>
The quantitative supply chain model resulting from this project can be used as a decision support tool when outsourcing is considered. Although outsourcing is not explicitly included in the model, a quick overview can be obtained of which part of the costs and investment are influenced by an outsourcing decision.

3.6 Product design

Fine (2000) describes the development of supply chains over time and relates this to the design of the product. In his view, supply chains move from vertical supply chains with an integral product design to horizontal supply chains with a modular product design. Also Simchi-Levi et al. (2008) include product structure in their framework. A Modular product design and an integral product design are two general types of product architectures. The architecture of a product is defined by Eppinger and Ulrich (2004) as:

"The scheme by which the functional elements of a product are arranged into physical building blocks and by which the building blocks interact".

The functional elements of a product are the individual operations and transformations that contribute to the overall performance of the product. The building blocks are organized collections of physical elements of a product, like parts, components and subassemblies. In Table 3 the main differences between a modular and an integral architecture are presented.

Modular architecture	***Integral architecture***
Building blocks implement one or a few functional elements in their entirety.	Functional elements of the product are implemented using more than one building block and a single building block implements many functional elements.
The interactions between building blocks are well defined and are generally fundamental to the primary functions of the product.	The interactions between building blocks are ill defined and may be incidental to the primary functions of the product.

Table 3: Modular Versus Integrated Architectures[13]

Modular architectures allow product variety without the need to redesign the entire product. A modular system is composed of units (or modules) that are designed independently but still function as an integrated whole. Modularity is achieved by partitioning information into design rules and parameters. The design rules are choices that affect subsequent design decisions. Ideally, the design rules are established early in a design process and communicated broadly to those involved. Design rules fall into three categories (Baldwin and Clark, 2002):

1. An architecture, which specifies which modules will be part of the system and what their functions will be.
2. Interfaces that describe in detail how the modules will interact, including how they will fit together, connect and communicate.
3. Standards for testing a module's conformity to the design rules and forms measuring one module's performance relative to another.

Sanchez (2004) defines two forms of modularity. The first is technical modularity, which is achieved when the design rules by Baldwin and Clark are followed. The second form of modularity is strategic modularity, which requires that the product architecture is first strategically decomposed, before the product is made technically modular. The strategic decomposition of the product means that each function that is perceived as a differentiating

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[13] *Properties adopted from Eppinger and Ulrich (2004)*

element in the market should be designed in a single component. The interfaces between the strategic modules should enable variations and innovations in the product design by easy substitution of a group of components.

Another design strategy, which is related to modularity, is a platform design strategy. A platform is a collection of common components to which specific components can be added (Eppinger and Ulrich, 2004). The use of a platform in combination with modular specific components enables delayed product differentiation. The advantage of a platform architecture is that variety can easily be included in the product range without adding tremendous complexity to the manufacturing system. The product architecture thereby becomes an important determinant of the performance of the supply chain.

From the theories above can be concluded that a product design can be characterized by the mapping of product functions to physical building blocks. In Section 2.2.1 the physical building blocks of the surgical C-arms have been explained. [redacted] A full description of the functional architecture can be found in Appendix B.7.
<<Confidential>>

This shows that there is a strong relation between the design of a product and the design of the supply chain. The quantitative supply chain model should allow for a variation of the product design.

3.7 Supply chain performance

As defined before, the objective of this master thesis project is to develop a quantitative model that relates the product design to the design of the supply chain. In Section 3.1 a number of models were discussed that describe this relation. All of these models have a qualitative character. Moreover, the models focus on the relation between product design and supply chain design at a strategic level. Quantitative models that explicitly focus on the relation between the product and process design and the supply chain design have not yet been developed. In order to quantify this relation, supply chain performance measures are needed.

The performance of a supply chain can be expressed with many different metrics. Gunasekaran et al. (2001) provide a literature review of supply chain performance measures. Based on the measures, which were found in a broad range of articles, a framework was designed which distinguishes between strategic, tactical and operational measures. As a secondary classification, the measures were defined as either financial or non-financial. Also, the measures were assigned to the appropriate supply chain stage; plan, source, make, deliver and customer service.Taken together, these three representations of metrics should give a clear picture of which metric should be used for the objective at hand, where it can be used, and who will be responsible for it.

Beamon (1999) states that supply chain models have predominantly utilized two different performance measures: cost; and a combination of cost and customer responsiveness. Costs may include inventory costs and operating costs. Customer responsiveness measures include lead time, stock-out probability, and fill rate. Beamon suggests that a supply chain measurement system must place emphasis on three separate types of performance measures: resource measures, output measures, and flexibility measures. The goal of these measures is described in Table 4. The supply chain performance measurement system must contain at least one individual measure from each type, which should coincide with the organization's strategic goals. This measurement system allows study of the interactions among the measures and can ensure a minimum level of performance in different areas.

	Goal	**Purpose**
Resources	High level of efficiency	Efficient resource management is critical to profitability
Output	High level of customer service	Without acceptable output, customers will turn to other supply chains
Flexibility	Ability to respond to a changing environment	In an uncertain environment, supply chains must be able to respond to change

Table 4: Goals of performance measure types[14]

Christopher and Ryals (1999) discuss the role of supply chain management in creating share holder value. Royal Philips Electronics is a listed company, with shares listed on the stock exchanges of Amsterdam and New York. Philips therefore aims at creating shareholder value. In September 2007, Vision 2010 was announced, which included the target to provide significant shareholder value by doubling the EBITA per share by 2010 (Philips Annual report 2007). Christopher and Ryals (1999) differentiate between four drivers of shareholder value;

- Revenue growth
- Working capital efficiency
- Fixed capital efficiency
- Operating cost reduction

All four of these are influenced by supply chain performance. Furthermore they highlight the importance of free cash flow in generating shareholder value. A supply chain strategy should be aimed at accelerating cash flow, because risk and time adjustments reduce the value of later cash flows, and increasing the level of cash flow. This can be achieved by compressing the total pipeline time in the supply chain. The shorter the pipeline, the less working capital is locked up in it and the more responsive the company can be to customer demand.

As explained in Section 1.2.1 the current supply chain performance of IS Ops is mainly expressed in qualitative terms. Based on the previous literature a number of quantitative measures which are relevant for Philips should be selected, which are incorporated in the quantitative supply chain model.

3.8 Conclusions

From this diagnosis it can be concluded that several models have been developed on the relation between the product design and the design of the supply chain. A number of common concepts were discussed with regard to their relevance for the quantitative supply chain model. The following conclusions can be drawn:

[redacted] The starting point for deriving a supply chain strategy is the market strategy for a product. [redacted]

- An important supply chain characteristic is the place of the customer order decoupling point (CODP), which divides a production process into push- and pull segments. [redacted] The supply chain model should enable this quantitative analysis.

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[14] *Adopted from Beamon (1999)*

- <<Confidential>>
- In general, two types of product designs can be identified, which are a modular design and an integral design. These two product designs should be combined with different types of supply chains. [redacted] In the quantitative supply chain model a variation of the product design should be included.
- To quantify the relation between product design and supply chain design, performance measures are needed. Because Philips is a listed company, performance measures that reflect the effect on shareholder value should be included.

4. Conceptual model

Based on the analysis of the current product and process design of surgical C-arms and the subsequent diagnosis, a conceptual model was derived. In this chapter, the conceptual model is explained and requirements for the quantitative supply chain model are formulated.

4.2 Model concepts

In this section, the conceptual model of the relation between the product design and supply chain design is described. In Chapter 3, the relevant concepts regarding this relation were discussed. These concepts were used to construct the conceptual model. In Figure 17 an overview of the model is shown. The model starts from the market characteristics of the product and the PLC stage. Based on these two concepts the ideal position of the CODP is derived. The position of the CODP sets conditions on the design of the supply chain and results in requirements for the product design. The relations of interest are the relation between the product design and supply chain design and the resulting supply chain performance. In the subsequent sections, the use of the concepts in the supply chain model is discussed in more detail.

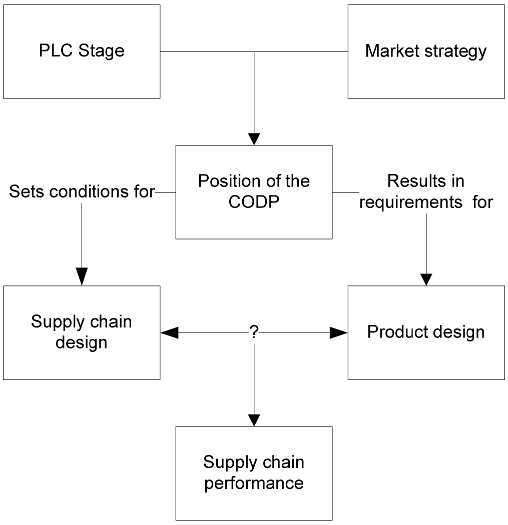

Figure 17: Overview of the conceptual model

4.1.1 Position of the CODP

According to the literature discussed in Chapter 3, the position of the CODP is fundamental to the supply chain strategy. Two types of strategies can be distinguished; a push-based strategy with a focus on efficiency and a pull-based strategy with a focus on customer responsiveness. Also, many models include combinations of these two strategies. The Customer Order Decoupling Point divides the supply chain into two parts:

- *The Forecast driven part*; activities in this part of the supply chain are based upon a forecast of customer demand. This part is positioned before the CODP.
- *The Order driven part*: activities in this part of the supply chain are based upon realized customer orders. This part is positioned after the CODP.

4.1.2 Supply chain design

In the previous chapter, the supply chain of surgical C-arms was characterized as an ATO system. An ATO system has a complicated network structure of component inventories. These inventories can be hold in one location, but also across multiple locations. In the model, supply chain design is defined as the layout of the ATO network. This network includes market locations, sourcing locations, manufacturing locations, stock points and distribution modes. The position of the CODP sets conditions on the supply chain design. If for example the supply chain strategy is a pull-based strategy with a focus on customer responsiveness, this should be supported by a location of the CODP near the customer market. The supply chain design leads to a certain performance of the supply chain, as mentioned previously.

4.1.3 Product design

In Section 3.6, different types of product designs have been discussed. In the model, product design is expressed in terms of the degree to which the architecture can be classified as integral versus modular. Therefore two sets of system components are defined:

- *The platform*; which is a set of components with an integral design. The platform is always assembled at the beginning of the supply chain. Typically the number of different platforms is limited.
- *Modules*; which is a set of components with a modular design. Modules are independent of each other and can be added on top of the platform. Typically the number of modules is greater than the number of platforms. Modules enable differentiation of the product based on customer wishes.

In the model, it is assumed that components can either be assigned to the platform or considered a module. Technical constraints caused by the current product design do not need to be taken into account in the model.

4.1.4 Supply chain performance

From the discussion in Section 3.7 it can be concluded that a broad range of supply chain performance measures is available. For the supply chain model it is important to incorporate measures that can be linked to the four drivers of shareholder value and the cash flow in the supply chain. A further selection of supply chain measures was made based on a meeting at Philips, with stakeholders from different departments involved in this master thesis project. The meeting has resulted in the following measurements:

- Lead time from order entry to order delivery
- Ability to meet customer demand within the required lead time
- Total operating costs of the supply chain
- Cash flow

4.2 Model requirements

The requirements for the quantitative supply chain model are explained in this section. First, the goal of the model is formulated. Second, the scope of the model is set.

4.2.1 Model Goal

The goal of the quantitative supply chain model is to support future business decisions with regard to the product design and the supply chain design for surgical C-arms. The model should enable an objective comparison of different product designs in combination with different supply chain designs. Also, the model should be able to evaluate the effect of different demand patterns and variations of other parameters. To quantify the relation between product design and supply chain design, not only the supply chain design itself, but also the performance of the supply chain has to be modelled. The model goal is therefore formulated as follows:

> Goal of the model is to enable an objective comparison of different product designs and supply chain designs, subject to different customer demand patterns, based on quantitative supply chain performance measures.

As previously stated, the intended use of the model is to formulate requirements for the product design. The model can be used to support decisions with regard to new product releases. The model expresses the trade-off between changes in the product design and the performance of the supply chain in quantitative terms. The expected users are engineers from IS Ops.

4.2.2 Model Scope

Although the model can be applied to any product, which is assembled from multiple components [redacted] The model focuses on the hardware design of the product, although customization options by software were also taken into account. The supply chain of the Type 1 is considered from sourcing (first tier) to delivery to a customer or key market. The service supply chain is not included in the scope of the model. The performance of the supply chain is limited to the previously formulated performance measures. Effects on the capacity in the supply chain and other performance measures are not included in the model.

4.3 Conclusions

In this chapter the relations that are incorporated in the quantitative supply chain model were explained. Also the model requirements were set. In summary, the model should be able to perform the following functions:

- Enable a scenario analysis with different product designs.
- Enable comparison of different supply chain designs
- Simulate the effect of different demand patterns
- Express the performance of the supply chain.

5. Supply Chain model

In this chapter the quantitative supply chain model is described. The chapter starts with a description of the input parameters, followed by an explanation of the model calculations and a description of the model output parameters. The quantitative supply chain model was programmed in MS Excel, using a Visual Basic Macro. The focus of this chapter is on the modelling approach. Also the relevant assumptions are mentioned. The chapter is concluded with a validation of the supply chain model.

5.1 Model input

In this section, the main input of the supply chain model is explained. The inputs are product design, supply chain design and customer demand.

5.1.1 Product design

In Section 4.1.3 the product design was defined based on the distinction between platforms and modules. The position of the **CODP** results in requirements with regard to the items that are included in the platforms or selected as modules. Modules are the components that enable product differentiation to match customer's wishes; it does not make sense to assemble modules before the CODP. Therefore it is assumed in the supply chain model, that modules are assembled after the CODP and the platform is assembled before the CODP. As a consequence, the input of the model is a combination between a product design and the position of the CODP, as schematically depicted in Figure 18.

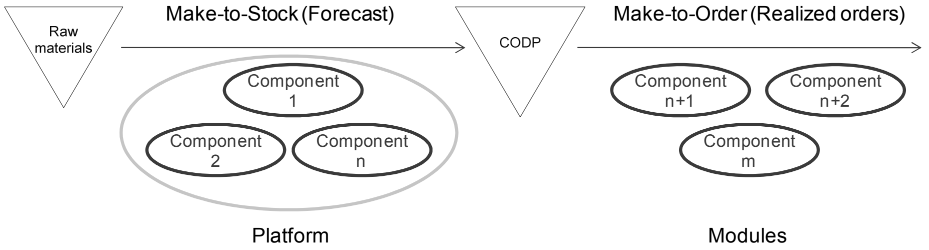

Figure 18: Product design as model input.

Components can either be assigned to the **platform**, meaning that they will be made to stock, or are selected as **modules**, meaning that they will be added based on a customer order. Three different scenarios are investigated in the model:

1. All components are selected as modules
2. Part of the components are assigned to the platform and the other parts are modules
3. All components are assigned to the platform

In the first scenario all the components are added based on a customer order. [redacted]. In the second scenario a part of the product is made to stock, and a part is customized to order. This scenario incorporates the concept of late differentiation or postponement. Within this scenario a choice still has to be made which items should be included in the platform and which items should be added as components. In the third scenario all the components (with the exception of loose items) are assembled to stock. Given the fact that there are multiple items with 2 or more variants, a large number of different platforms are made to stock in this scenario. The platforms are however ready to be delivered to a customer and the software can be customized upon delivery.

[redacted]. The highest level consists of the product end items (PEI-s), as defined by the ERP system. The selection of options to be included in a customer order takes place at the PEI level. This means that if a PEI is selected, all the lower-level items are also selected. The Type 1 consists of x PEI-s, which are software as well as hardware components and also include loose items like manuals and sterile covers. The diversity of PEI types results in a very uneven distribution of material value among the items. Figure 19 shows a Pareto chart of the relative contribution to the turnover for the Type 1 for the x most contributing PEIs.

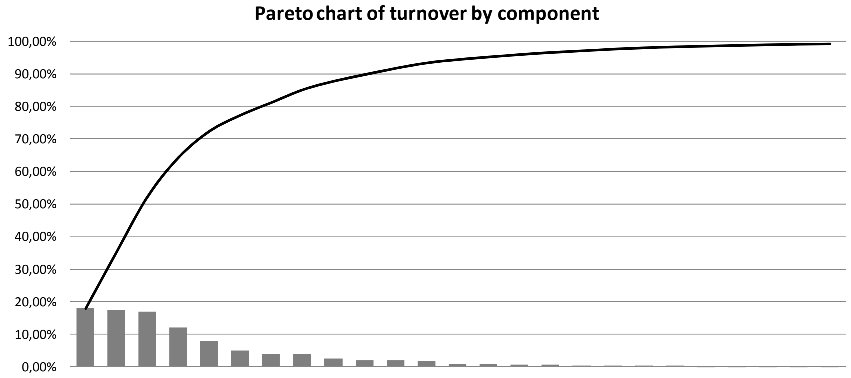

Figure 19: Pareto chart of turnover by component

Based on their negligible contribution to the turnover it was decided to exclude x PEI-s from the model. The x remaining PEI-s were mapped to the flowcharts in Appendix B.5. It became clear that some of the PEI-s could not be mapped to one single step in the process. This was experienced as a problem, because this limits the option to model the execution of some of the assembly steps before the CODP and others after the CODP. Therefore, PEI-s that contained a collection of items were split up into their relevant level 2 parts. [redacted] Another problem that occurred when matching the PEI-s to assembly steps was that in some of the optional steps a predetermined combination of PEI-s is used. [redacted] In these cases, multiple PEI-s were combined into one item.

The selection procedure resulted in a final list containing x items, with in total x item-variants of the Type 1 that were viewed as relevant by Philips stakeholders. The items were structured by assigning a component number and a variant number. Table 5 shows a part of the resulting BOM structure that was used in the model. The first column contains the number of the item, the next column the number of the variant and the third column contains a combination of both, which is the unique identification number of the item. [redacted].

5.1.2 Supply chain design

In the previous chapter, the supply chain design has been defined as the layout of the supply chain network. The first supply chain design that was evaluated is the current supply chain design. In the current supply chain all the procured components are stocked at the factory in Best. The surgical C-arms are assembled in Best and delivered to customers in different regions. This supply chain design is defined as a **centralized supply chain**. In the model, a distinction is made between three regions, Europe, the Middle East and Africa (EMEA), North and South America (Americas) and Asia, Australia and New Zeeland (APAC). Figure 20 shows a schematic overview of the centralized supply chain. The supply chain includes three stock points: one for items, one for platforms and one for modules. If a product design is selected with only platforms, there is no module stock point. If a product design is selected with only modules, there are no item and platform stock points.

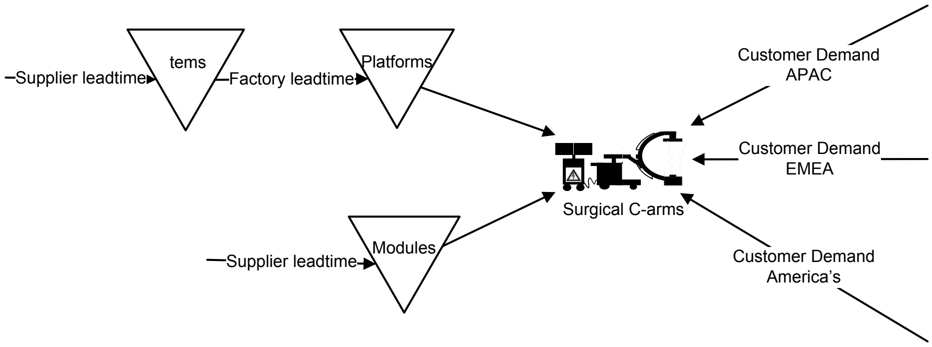

Figure 20: Centralized supply chain design

Next to the centralized supply chain, a supply chain design was evaluated, which contains stock points close to the market. This supply chain is defined as a **decentralized supply chain**.
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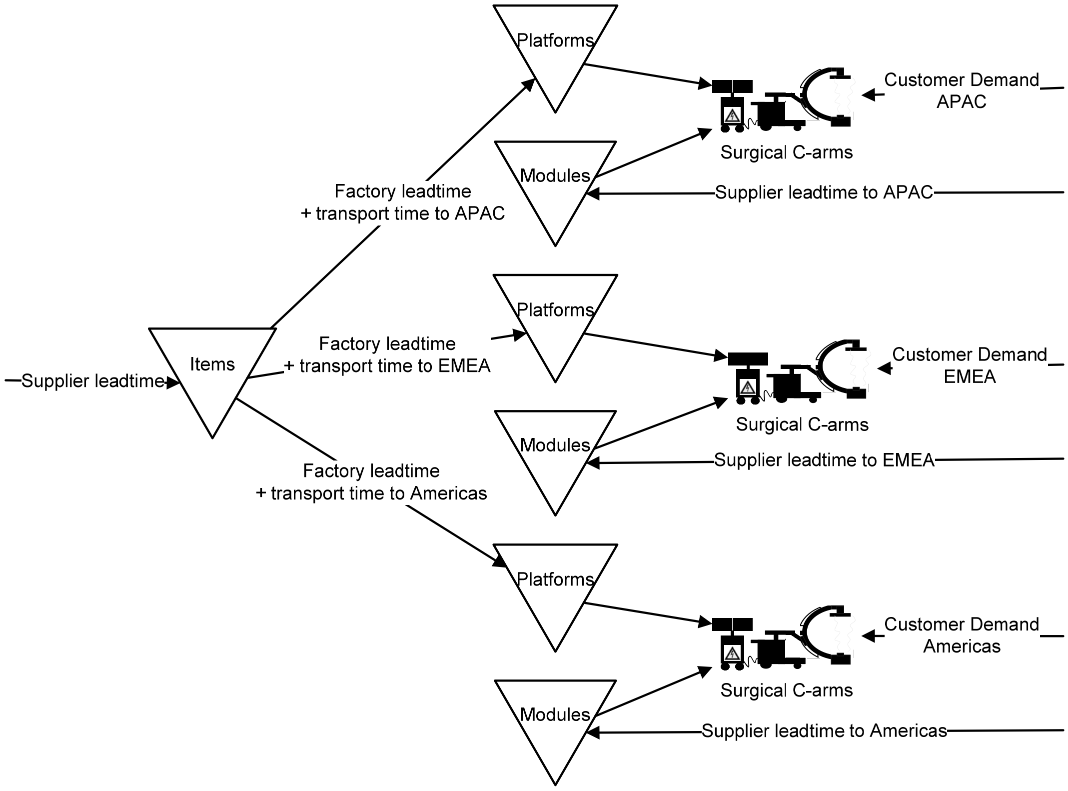

Figure 21: Decentralized supply chain design

[redacted]
the distribution mode can be varied in the model.
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The effect on costs as well as lead time is included in the model.

Besides the distribution mode, also the throughput time before and after the CODP can be varied. This modelling approach has been chosen, because the **throughput times** depend on the planning systems that are used in the factory and in the merge centers. Because no data is available with regard to the effect of different planning mechanisms, the throughput time can be varied manually. Finally, the **supplier lead times** are included in the model. Because the items in the model were selected from the level 1 and 2 items of the BOM, many of these are FERTs and do not have a supplier lead time. For these items, the supplier lead time was based on the lead time of the lower level component that represented most of the item value. The additional lead times from suppliers to the merge centers and the coefficient of variation of the supplier lead times can be varied manually, because data is not available.

5.1.3 Customer demand

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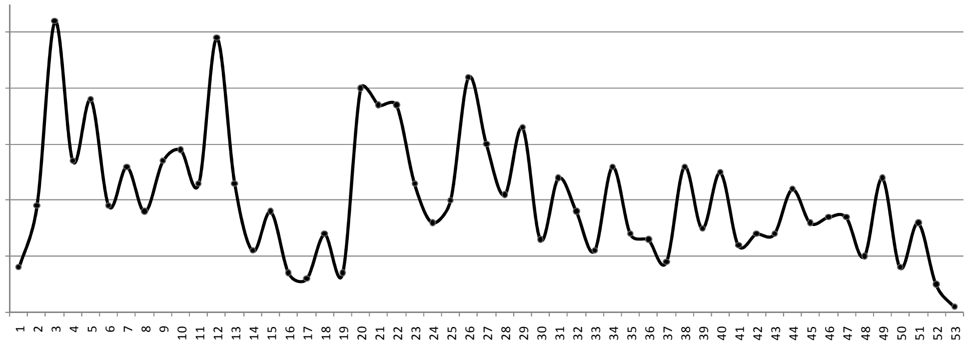

Figure 22: Demand pattern for the Type 1 by RDD (2008)

To calculate the **inventory** levels that are needed in the supply chain, the demand pattern of the [redacted] needs to be fitted to a theoretical distribution. Silver et al. (1998) describe inventory models based on the assumption of demand following a normal distribution. If the ration σ_L/μ_L is greater than 0.5 however, they advise to consider using another distribution than the normal distribution. If the demand distribution is skewed to the right, the use of a Gamma distribution should be considered.

In Appendix B.8 a number of goodness-of-fit tests for the demand distribution in 2006, 2007 and 2008 are included. The Kolmogorov-Smirnov one-sample test is the most powerful test when a sample distribution is compared with a theoretical distribution (Cooper and Schindler, 2003). <<Confidential>>

From the total demand, the expected demand for items, modules and platforms is derived. Also the standard deviation of the demand for items, modules and platforms needs to be derived. The following notation will be used:

$$E[D] = \textit{Expected total demand}$$

$$\sigma^2(D) = \textit{Variance of total demand}$$

$$E[D_i] = \textit{Expected demand for item } i$$

$$\sigma^2(D_i) = \textit{Variance of demand for item } i$$

$$\pi = \textit{the probability that an item is selected by a customer}$$

The derivation of the expected demand is relatively straight forward. For each order, the demand for a specific item is either 1 or 0. The expression for the expected demand is derived as follows:

$$I_n \begin{cases} 1 \; with\, probability & \pi \\ 0 \; with\, probability & 1-\pi \end{cases}$$

$$E[I_n] = \pi$$

$$E[D_t] = E\left[\sum_{n=1}^{D} I_n\right]$$

$$= \pi \cdot E[D]$$

The standard deviation of demand is calculated with the following expression:

$$\sigma^2[D_t] = \pi(1-\pi)E[D] + \pi^2 E[D^2] - \pi^2 E^2[D]$$

$$= \pi(1-\pi)E[D] + \pi^2 \sigma^2[D]$$

The full derivations of these expressions can be found in Appendix A.2. The value for π is calculated for each item, based on historical data from 2008. Because the demand for items differs per region, the π values were also differentiated per region. For platforms, the π values were calculated as the product of the π values for the individual items that are included in the platform. It has to be noted that this is an approximation, because correlations between the demands for individual items are ignored. For items with a sum of π value for the variants that is less than 1 a dummy had to be created, when these items were included in the platforms. The dummy represents the option of not selecting any variant of the item. Another limitation of the model is that the maximum value of π is 1. For items that can be included in a system multiple times, dummy items need to be created. Appendix B.9 shows an overview of all the items that were included in the model and their π values.

5.2 Model Calculations

In this section, the calculations that are performed by the supply chain model are explained. First, the policy that is used in for the inventory control of the items, modules and platforms is explained. Next, the calculation of cost parameters in the model is described.

5.2.1 Inventory policy

As previously mentioned, optimal inventory policies for **ATO** systems do not exist. In Sanders (2008) a number of inventory policies for ATO systems were reviewed. Most of these inventory policies use a base-stock policy, because of their intuitive appeal and practical relevance. De Kok and Fransoo (2003) discuss the application of pure base stock policies on ATO systems. They state that the application of pure base-stock policies to an ATO system leads to the undesirable property that end items with additional components have a lower service level than end items with fewer components. As the former are typically high-end products with a higher margin, pure base stock policies are far from optimal in the case of ATO systems.

De Kok and Fransoo (2003) suggest the use of a class of policies called synchronized base-stock policies. The main complexity of an ATO system arises from the fact that there exists no clear decision making hierarchy about order releases. Order releases lead to a certain echelon inventory position for every component, which determine the coverage of future demand for end-items. Due to uncertainty in future demand and interactions between components caused by shortages, the coverage of the components over time is not clear. To apply a synchronized base stock policy, a natural decision making hierarchy can be created that enables the synchronization of order release decisions over time. Synchronized base stock policies are not cost optimal, but any set of customer service level constraints can simultaneously be satisfied.

The calculation of the synchronized base stock policy requires a highly complicated algorithm. As the main goal of the model is not to optimize inventory levels, but to enable a comparison of different supply chain designs, it was decided not to apply a synchronized base stock policy. Following the approach of Cohen and Lee (1988) the supply chain is decomposed into single echelon models. Each sub- model is optimized, subject to a service target defined for each stock point. The inventory at the stock point is controlled with a periodic review, order-up-to policy, the so-called ***R,S* policy**. When the service levels at the upstream echelons in the supply chain are set sufficiently high, the system decouples and each stage/item can be analyzed in isolation, so that the *R,S* policy results in a reasonable approximation of the performance of the system.

In the *R,S* policy, the physical stock is reviewed with a period *R*. An order is placed for an item, if the physical stock is below the order-up-to-level *S*. Orders arrive after a lead time *L*. Figure 23 shows an example of the inventory level over time, resulting from an *R,S* policy, with stochastic demand. In the graph, $X(t)$ represents the stock that is physically on hand, $Y(t)$ represents the stock that is on hand, plus what has already been ordered. Given the distribution of demand, the item lead time and the setting of *S* and *R*, a **service measure** can be calculated. The *P2* service measure expresses the long-run fraction of total demand, which is being delivered from stock on hand. It is also known as the fill-rate. In the model, the *P2* can be chosen, and the *S* level is derived. Once the *S* level has been derived, also the average stock on hand can be calculated. Besides the average stock on hand, also the pipeline stock is needed. The average stock on hand and the pipeline stock affect the cash flow in the supply chain and are required to calculate the inventory holding costs.

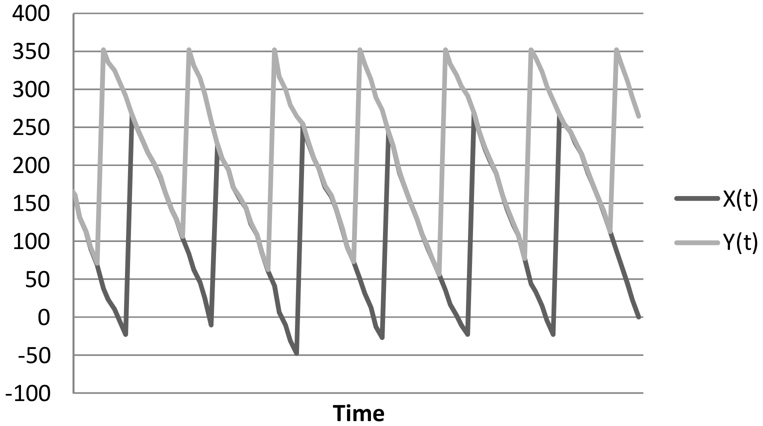

Figure 23: Example of the *R,S* policy

The derivation of the expression for *P2* uses two assumptions:

- Subsequent orders cannot overtake each other, thus an order placed later can not arrive earlier.
- All demand which can not be met immediately from stock is backordered.

The full derivation of *P2*, as well as the average inventory and the pipeline inventory can be found in Appendix A.3.

$$P_2 = 1 - Fraction\ \ of\ demand\ delivered\ as\ a\ backorder$$

$$P_2 = 1 - \frac{1}{E[D(0,R]]}(E[(D(R+L_1]-S)^+] - E[(D(0,L_0]-S)^+])$$

In the model, *P2* can be chosen and the equation has to be solved for *S*. To solve the equation, the binary search method is applied. In this method, an interval is chosen, in which the solution is expected to be. By creating a smaller interval at each iteration, the solution becomes more accurate. In the model, an interval between a minimum *S* (S min) and a maximum *S* (*S max*) is chosen. With an *S* that is the average of *S min* and *S max*, the *P2* value is calculated. If the calculated *P2* value is higher than the chosen *P2* level, *S max* becomes the average and S min stays the same. If the calculated P2 value is lower than the chosen *P2* level, *S min* becomes the average and *S max* stays the same. This procedure is repeated until the calculated *P2* is equal to the chosen *P2* with an accuracy of a specified number of digits.

5.2.2 Cost parameters

In the previous chapter, the **performance measures** for the supply chain were defined. One of the performance measures is the total operating costs in the supply chain. The **operating costs** consist of a number of cost components. The following partition is used in the model:

- Material costs
- Handling costs
- Inbound distribution
- Labour costs
- Costs of floor space
- Depreciation of fixed assets
- IT costs
- Shares and other costs (overhead costs)
- Outbound distribution costs
- Inventory holding costs
- Import duties
- Project implementation costs

The material costs are equivalent to the total value of procured items and are naturally defined at the item level. The other costs are currently not directly related to an item. To show the effect of the product design on the operating costs in the supply chain, it is not sufficient to calculate the costs on a product level.
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An overview of the assumptions that were made to calculate the remaining cost parameters can be found in Appendix B.10. All the costs were calculated on a yearly basis. Because most of the fixed costs are allocated to the entire surgical C-arms product line and not only to Type 1 systems, it was decided to scale the demand for Type 1 systems to the total demand. [redacted]

5.3 Model output

The output of the model was expressed in a number of performance measures as specified in Section 4.1.4. In the following sections, the performance measures are explained shortly.

5.3.1 Lead times

In the model, two measures of lead time were included. The first measure is the average customer lead time. This is the time from the moment that a system is ordered, to the moment of delivery. This time consists of the time needed for assembly at the CODP and the time needed for transport to the customer. The second measure is the average throughput time of a system in the entire supply chain. It is assumed that waiting times are included in the assembly time that is specified as input to the model. Congestion of the system that may arise from high utilization rates is not considered. This time consists of the time needed for assembly of the platforms, the transport to the CODP and the customer lead time. Both times are expressed in weeks.

5.3.2 Customer service

As explained in Section 5.2.1 the service level of the stock points in the supply chain can be set as input parameters. These service levels express the long term average availability of individual items. From a customer point of view, it would be interesting to derive an expression for the service level of a complete system. A system consists of a set of items, for which the demand is not independent. It is therefore mathematically intractable to derive the service level for a system, based on the service levels of the individual items. Besides that, the supply chain model ignores the dependence between stock points, which further complicates the calculation of a customer specific service level. Therefore the customer service is only expressed at an item level, which is an input parameter to the model, rather than an output parameter.

5.3.3 Operating costs

The operating costs in the supply chain are expressed in different categories, as summed up in Section 5.2.2, with the exception of the project implementation costs, which are only included in the cash flow. A split has been made between the costs before and after the CODP. The costs for system integration can be split up manually in a part before the CODP and a part after the CODP. This modelling approach has been chosen, because it depends on the content of the platforms which part of the testing procedure can be performed before the CODP. If a decentralized supply chain has been selected, the costs after the CODP are split by region.
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5.3.4 Inventory investment

The inventory investment was put together from the investment in five different inventory categories. These are the item inventory (or raw material inventory), the pipeline inventory to the merge centers, the module inventory at the merge centers, the platform inventory at the merge centers and the pipeline inventory to the customer. For the item inventory and the module inventory, a part of the inventory was defined as consignment stock, for which the investment is paid by the supplier. The value of the inventories was based on the material costs plus the added value in the supply chain. If a decentralized supply chain has been selected, the investments after the CODP are split by region.

5.3.5 Cumulative Cash flow

The cumulative cash flow resulting from the selected product design and supply chain design is calculated in the model, based on a comparison with a base case scenario. [redacted]

[redacted] The difference in the revenues with the base case is calculated, as well as the difference in the inventory investment relative to the base case. The revenues are based on the variable operating costs and a gross margin that can be specified in the model. The difference in revenues is assumed to stay equal and contribute to the cash flow in all x years. The difference in inventory investment is a one time investment that is incurred in the first year. The investment that is needed to change the product design and supply chain design is a one time investment that is also incurred in the first year. An effective tax rate on operating income of x% was applied, which is a Philips standard.

5.4 Model Validity

The correctness of the supply chain model has been assessed in a number of verification and validation steps. Verification tests whether or not the model runs as intended. Validation tests the agreement between the behaviour of the model and the real world system it represents (Gass, 1983). The model was programmed in MS Excel, using a macro in Visual Basic. Verification was performed by checking and debugging the code with Visual Basic. Also the model was tested with a simple product structure. For the inventory policy parameters, the spreadsheet "Classical Inventory models" by de Kok (2004) was used as a comparison. Finally the performance of the model was evaluated, which was assessed adequate for the intended purpose. A number of validation steps were taken. The first step was checking the assumptions underlying the model, in a discussion with stakeholders of Philips. The next step was to check the results of the inventory policy calculations with the actual inventory levels at Philips[redacted] As a third step, the total supply chain costs and inventory investment resulting from the model, for parameter settings matching the current situation, were checked by Philips and approved. Finally, a sensitivity analysis was performed. A detailed description of the model validation can be found in Appendix A.4.

5.5 Model limitations

The quantitative supply chain model has a number of limitations that will be discussed shortly. First of all, the model only considers one level of the BOM structure of a product. When differentiation takes place at lower levels, the model needs to be extended. A second limitation is the fact that the model only includes two supply chain designs, whereas in practice many other configurations are possible. As a third limitation, the assumption of non-correlated demand for items is not true in practice. Customers who select a view forum will often also select a DVD recorder and high bright displays for example. A fourth limitation is created by the calculations, which are based on the optimization of independent single-echelon models. Through this modelling approach, the inventory levels and resulting costs computed for each alternative will be too high. It is however assumed that the ordering of alternatives with respect to performance criteria is insensitive to this approach. Finally, the allocation of the cost parameters is based on a large number of assumptions that should always be taken into account when results of the model are evaluated. Although there clearly are a number of limitations to the applicability of the model, the goal as formulated in Section 4.2.1 is perceived to be met. The current approach should be seen as a first step in a structural concurrent product, process and supply chain design process.

5.6 Conclusions

In this chapter the quantitative supply chain model was explained. The main model inputs are the product design, the supply chain design and customer demand. The output of the supply chain model consists of a number of performance measures. These are calculated based on an *R,S* inventory policy and a number of assumptions regarding the costs in the supply chain.

The model was verified and validated to a sufficient extent. The model has a number of limitations, but the goal of the model is perceived to be met.

6. Model results

In this chapter the results of the quantitative supply chain model are analysed and discussed. The chapter starts with a scenario analysis of different product designs and supply chain designs. Next, the effect of a number of parameters on the outcome of the model is evaluated in a sensitivity analysis. Finally, the effect of configuration variety is analysed, by evaluating the model results for four different BOM structures, with different numbers of items.

6.1 Scenario analysis

In Section 5.1.1 three different product designs of surgical C-arms were explained. In Section 5.1.2 two supply chain designs for surgical C-arms were explicated. The combination of these three product designs with two supply chain designs leads to six different scenarios. It has to be noted, that for the second type of product design consisting of one or more platforms and modules, many detailed designs are possible. In cooperation with Philips stakeholders it was decided to analyze two product designs in this class. In scenario A, [redacted] In scenario B, [redacted] All the other items were selected as modules. In appendix B.12, scenario A and B are compared in more detail. An overview of the different scenarios can be found in Table 6.

	Centralized supply chain	**Decentralized supply chain**
Only modules	Scenario 1	(Out of Scope)
One platform and multiple modules	Scenario 2A	Scenario 3A
Multiple platforms and multiple modules	Scenario 2B	Scenario 3B
Only platforms	Scenario 4	Scenario 5

Table 5: Scenarios for analysis

Scenario 1 represents [redacted]

Scenario 4 and 5 (all the items included in platforms) represent the situation in which the hardware is fully made to stock and customization is executed with software licenses. Loose items were not included in the platforms, because it does not make any sense to keep fixed combinations of the platforms and those items in stock. The parameter settings that were used in the scenario analysis can be found in Appendix B.12. It was assumed that the total throughput time remains constant, but the amount of time that is spent before and after the CODP changes. The c.v. of the throughput time before the CODP is also assumed to be constant, which means that the standard deviation changes with the average throughput time. Finally, the percentage of the costs of system integration (testing) that is incurred before and after the CODP is changed when the CODP is shifted.

6.1.1 Operating costs

Figure 24 shows a graph of the operating costs for the different scenarios. The graph shows a clear difference in the distribution of the costs relative to the CODP. The total costs on the other hand remain relatively stable. The difference between a centralized supply chain and a decentralized supply chain, with the same product design is also relatively small.

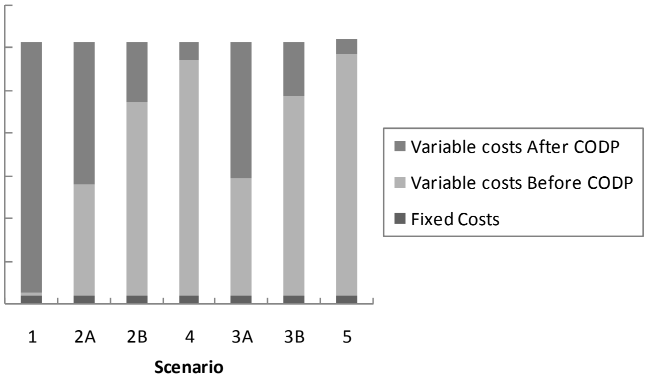

Figure 24: Scenario analysis: Operating costs (Million)

6.1.2. Inventory investment

Figure 25 shows a graph of the inventory investment for the different scenarios. The inventory investment for a similar product design is higher in a decentralized supply chain, than in a centralized supply chain. This is caused by the increased number of stock points, which all require a safety stock, to maintain their service level. It has to be noted that a part of this effect may be caused by the local optimization of each stock point. The model thereby overestimates the necessary inventory levels.

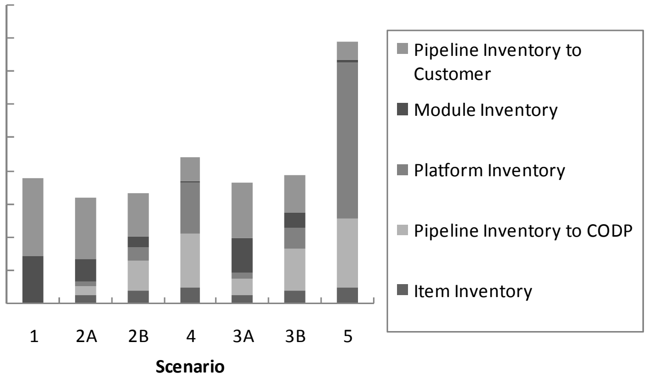

Figure 25: Scenario analysis: Inventory investment (Million)

6.1.3 Cumulative cash flow

By combining the operating costs and the inventory investment, the cumulative cash flow over five years is calculated for each scenario. The cumulative cash flows are shown in Figure 26. [redacted] Because the operating costs are approximately equal for all scenarios, the patterns of the cumulative cash flows are similar. The levels are however not the same, due to the significant difference in inventory investment.

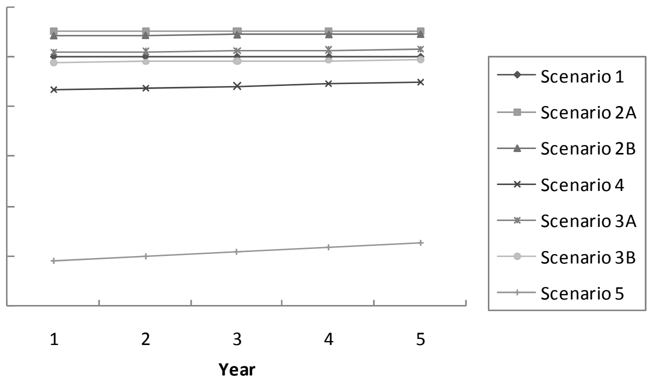

Figure 26: Scenario analysis: Cumulative cash flow (Million)

6.1.4 Lead times

Table 7 shows the average order throughput time and the average customer order lead time for the different scenarios. It can be concluded that the customer order lead time is shorter for the scenarios with a decentralized supply chain design.

Scenario	**Average order throughput time**			**Average customer order lead time**		
	APAC	EMEA	Americas	APAC	EMEA	Americas
1						
2A						
2B						
4						
3A						
3B						
5						

Table 6: Scenario analysis: Lead times

6.1.5 Conclusions

Table 8 summarizes the results of the scenario analysis.
<<Confidential>>

Scenario	**Total supply chain costs (k€)**	**Total Inventory Investment (k€)**	**Cum. Cashflow year 5 (k€)**
1			
2A			
2B			
4			
3A			
3B			
5			

Table 7: Key results scenario analysis

6.2 Sensitivity analysis

In this section the influence of a number of parameters on the model outcomes is discussed. [redacted]

[redacted] For each parameter, the setting that was used in the scenario analysis is called the 'base case'. The cash flows for the different parameter settings are calculated relative to the cash flow of the base case, which is consequently set at 0. An overview of the results of the sensitivity analysis can be found in Appendix B.13.

6.2.1 Transport mode

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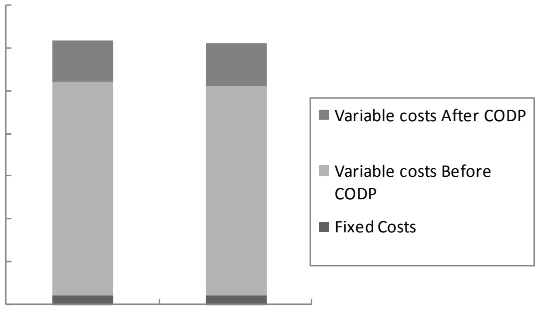

Figure 27: Operating costs for different transport modes (Million)

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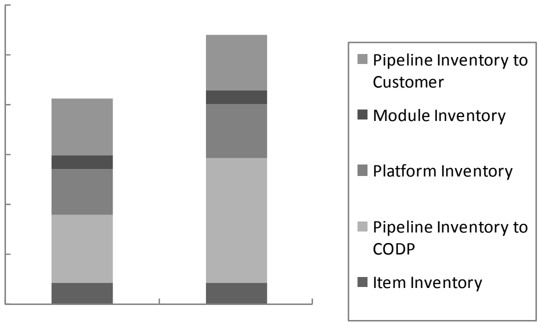

Figure 28: Inventory investment for different transport modes (Million)

6.2.2 Service levels

The service level *P2*, which is the long-run fraction of total demand that is being delivered from stock on hand, was varied between x%, x% and x%. As illustrated in Figure 29 and Figure 30, a higher service level mainly impacts the necessary inventory investment. The *P2* was varied for the raw material inventory, as well as for the inventory at the CODP (modules and platforms). The *P2* at the CODP has a bigger impact than the *P2* of the raw materials. This can be explained by the higher value of the items kept in inventory. The *P2* levels did not impact on the throughput times and customer lead times.

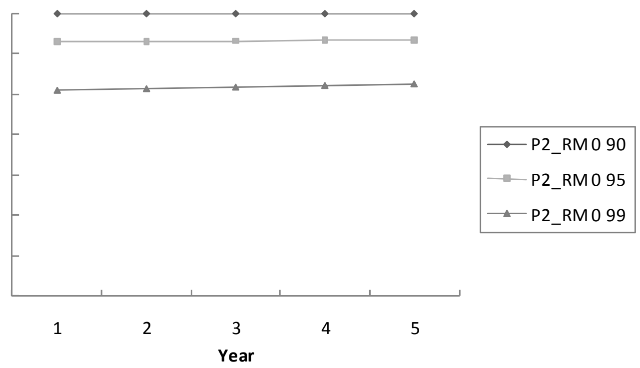

Figure 29: Cumulative cash flow for different P2 levels of raw materials (Million)

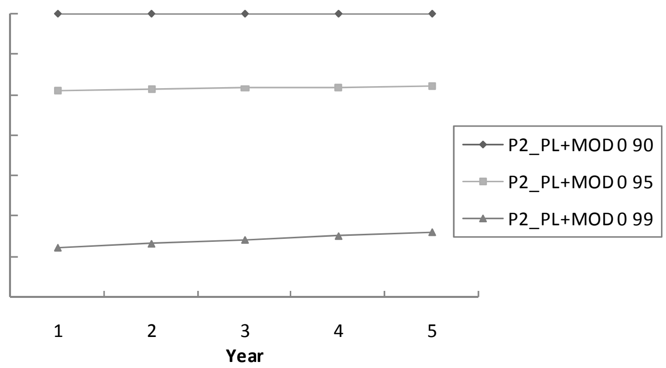

Figure 30: Cumulative cash flow for different P2 levels at the CODP (Million)

6.2.3 Supplier lead times

[redacted] Figure 31 shows the effect of different values for this coefficient of variation. A larger uncertainty in supplier lead times results in a higher inventory investment and slightly higher operating costs.

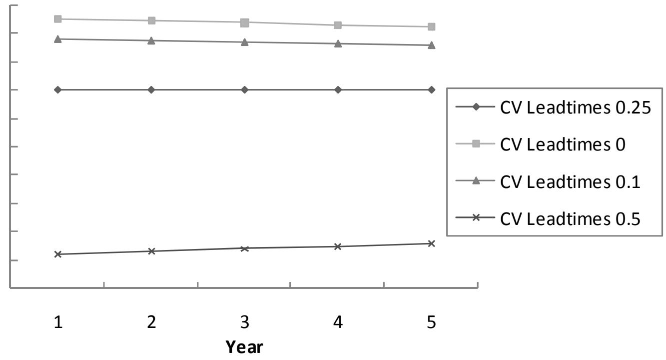

Figure 31: Cumulative cash flows for different c.v.'s of supplier lead times (Million)

[redacted]

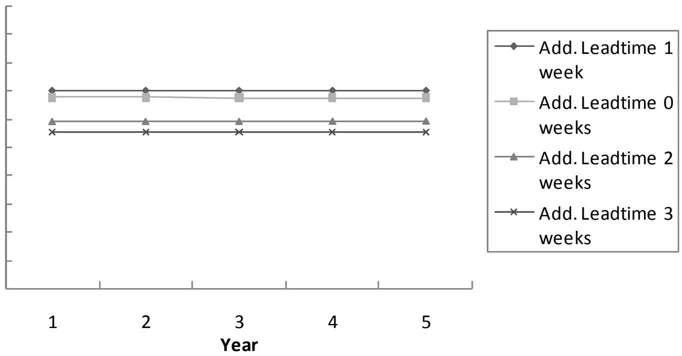

Figure 32: Cumulative cash flows for different additional supplier lead times (Million)

[redacted]

6.2.4 Factory lead time variation

In the scenario analysis the c.v. of the factory lead time was kept constant at x. In the sensitivity analysis, the c.v. of the factory throughput time was varied. As can be noted from Figure 33 a larger standard deviation requires a larger inventory investment. The operating costs seem to behave a bit strange in the graph. A larger c.v. results in lower operating costs, resulting in a rising cash flow resulting from a c.v. of x. This can be explained by the fact that the model calculates the revenue based on a gross margin on the variable costs. As the variable costs are higher for a larger c.v. the revenues also increase. In this case, this has a larger effect than the difference in inventory investment. The revenue calculation might need to be changed, to reflect what happens in reality. The customer lead time is not impacted by a larger c.v. of the throughput time, because orders are delivered from the CODP.

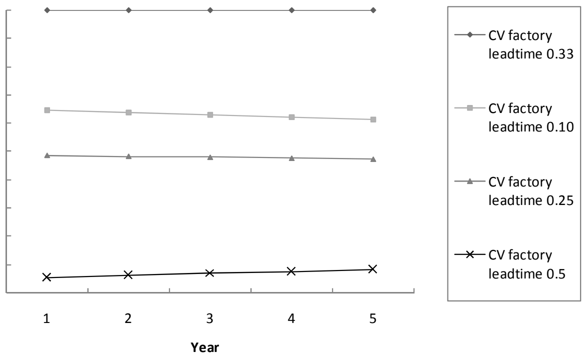

Figure 33: Cumulative cash flows for different c.v.'s of factory lead times (Million)

6.2.5 Customer demand

In the previous calculations, the total demand was assumed to be equal to the MOPS of 2009 for Type 2 and Type 1 systems. This means the total demand was set at x systems. Figure 34 shows the effect on the cash flow, when the total demand is changed. The impact on the inventory investment is relatively small compared to the impact on the operating costs. The impact of the customer demand on the operating costs is also extremely large compared to the other parameters. The customer demand did not have any impact on the throughput times and customer lead times.

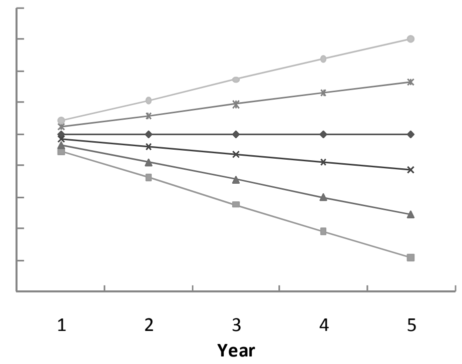

Figure 34: Cumulative cash flows for different settings of total demand (Million)

6.2.6 Forecast errors

In the previous section the limited impact of the total customer demand on the inventory investment was discussed. Demand is however not stable over time. The inventory investment is based on a forecast of this demand, instead of the actual demand. The impact of the forecast error on the cash flow was thus evaluated. Because different lead times apply to the items in the supply chain, not all items which are used in the same final product, are controlled based on the same forecast. In other words, the forecast errors differ across the supply chain. The impact of the forecast error was therefore approximated by varying the standard deviation of the expected demand. The standard deviation expresses the natural level of demand uncertainty and forms an upper limit to the forecast error. The cash flows resulting from different settings of the standard deviation are illustrated in Figure 35. A reduction of the standard deviation results in a smaller inventory investment and somewhat lower operating costs. The order of magnitude is comparable to the effect of variation in the supplier lead times. [redacted]

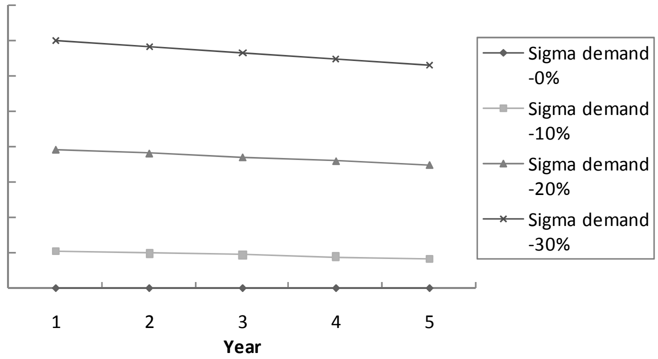

Figure 35: Cumulative cash flows for different forecast errors (Million)

6.2.7 Conclusions

From the sensitivity analysis it concluded <<Confidential>>

6.3 Configuration variety analysis

<<Confidential>>

6.3.1 Operating costs

Figure 36 shows the operating costs for the different BOMs. The operating costs decrease, when more options are excluded from the BOM. As explained in Section 5.2.2 the majority of the cost parameters is not variable with the number of items, which is evident from the operating costs. Still, the difference between the scenario with the complete BOM and the scenario with only low end systems is about x%.

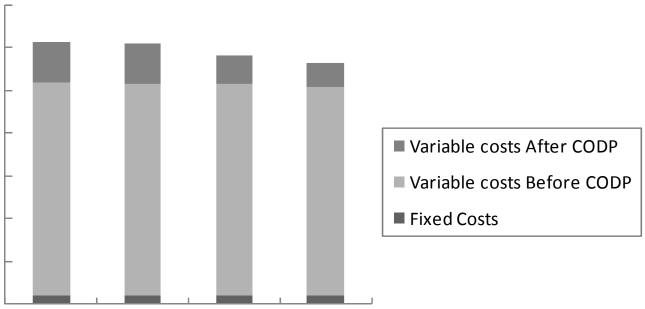

Figure 36: Configuration variety analysis: Operating costs (Million)

6.3.2 Inventory investment

The BOM does not only affect the operating costs, but also the inventory investment is affected, as shown in Figure 37. A decrease in the number of items included in the BOM results in a decrease in the inventory investment, in particular on the platform inventories, the module inventories and the pipeline inventories to the customer. The difference in total inventory investment between the scenario with the complete BOM and the scenario with only low end systems is about x%.

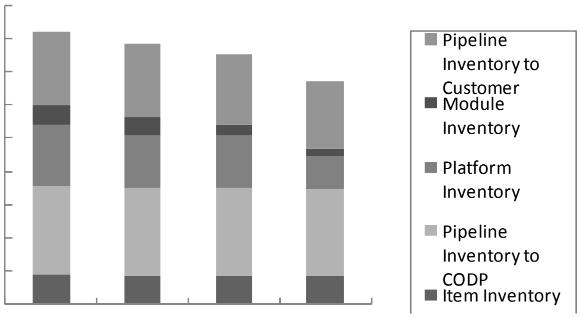

Figure 37: Configuration variety analysis: Inventory investment (Million)

6.3.3 Conclusions

It can be concluded that <<Confidential>>

6.4 Conclusions

<<Confidential>>

7. Conclusions and Recommendations

In this final chapter, the conclusions and recommendations resulting from the master thesis project are presented. In addition, areas for further research are indicated.

7.1 Conclusions

The objective of this master thesis project was to perform an in-depth analysis and modelling of the high end Surgery supply chain, resulting in a parameterized decision model. It was decided to focus the model on the relation between the product design of the high-end Surgery systems and the design of the supply chain.

The project was started with an analysis of the current product and supply chain design. Based on the analysis the following was concluded:

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Based on a review of existing research a diagnosis was performed. The diagnosis identified a number of concepts that impact the relation between product design and supply chain design. From these concepts a conceptual model was defined and a quantitative supply chain model was developed. The model was developed in MS Excel. Verification and validation tests showed that the model was developed correct and satisfied the model requirements. The goal of the quantitative supply chain model is to enable an objective comparison of different product designs and supply chain designs, subject to different customer demand patterns, based on quantitative supply chain performance measures. The supply chain performance is calculated with an R,S inventory policy and a number of assumptions regarding the costs in the supply chain.

With the quantitative supply chain model, the relation between the product design and supply chain design for surgical C-arms was analyzed. The following was concluded:

- The quantitative supply chain model provides a comprehensive overview of the effect of different product and supply chain designs, on the specified supply chain performance measures, subject to a broad range of parameter settings and encourages an **integrated approach** of product and supply chain design.
- <<Confidential>>

Previous research on the relation between product design and supply chain design is mainly of a qualitative nature. Quantitative research in this area has postponement as a focal point. The combination with different supply chain designs has not yet been modeled. This master thesis project shows that the development of quantitative models that include both product and supply chain design represent a valuable research contribution with practical relevance.

7.2 Recommendations

The master thesis project resulted in a number of recommendations for Philips Healthcare:

- The quantitative supply chain model provides insight in the impact of different product and supply designs on supply chain performance. The **model should be applied consistently in supporting future business decisions**.
- <<Confidential>>

7.3 Further research

A number of limitations of this research project were formulated. This leads to the following opportunities for further research:

- The quantitative supply chain model can be extended with **load dependent lead times**, to provide more insight in the height of pipeline inventory levels.
- The quantitative supply chain model does not take into account the **production planning and control mechanisms** that are applied in the supply chain. Further research is needed to evaluate the effect on supply chain costs and lead times.
- The quantitative supply chain model was based on an *R,S* inventory policy, which is not optimal for an ATO system. The model could be extended to include a **multi-echelon inventory policy**.
- Finally, the model was tested on one specific product. The generalization of the model to **other products** is another area for further research.

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List of abbreviations

AOP	Annual Operations Plan
APAC	Asia Pacific
ATO	Assemble-to-Order
BOM	Bill of Material
BOP	Bill of Processes
BU	Business Unit
	“Beeeld Versterker” (image intensifier)
CODP	Customer Order Decoupling Point
CSA	Customer Service Agreement
C.V.	Coefficient of Variation
DFI	Digital Fluoroscopy imaging
EMEA	Europe Middle East and Africa
ERP	Enterprise Resource Planning
ESD	Electro Static Discharge
ETO	Engineering-to-Order
FDA	Food and Drug Administration
FERT	German abbreviation used in SAP
FRU	Field Replacement Unit
GE	General Electric
GS&S	Global Sales & Services
GUI	Graphical User Interface
GXR	General X-Ray
FTE	Full Time Equivalent
HAWA	German abbreviation used in SAP
II	Image Intensifier
IS	Imaging Systems
IS Ops	Imaging Systems Operations
LATAM	Latin America
LTM	Last Twelve Months
MOPS	Monthly Order and Production Schedule
MRP-I	Material Requirements Planning I
MTS	Make-to-Stock
MTO	Make-to-Order
MVS	Mobile View System

NA	North America
OXB	Operations X-Ray Best
P-BOM	Percentage Bill of Material
PCI	Primary process, Control and Information
PEI	Product End Item
PLC	Product Life Cycle
RDD	Requested Delivery Date
SAP	An enterprise resource planning system
SCPU	Stand Controller and Power Unit
SMI	Supplier Managed Inventory
SMOI	Supplier Managed and Owned Inventory
SI	System Integration
US	United States
ZMAT	German abbreviation used in SAP

Appendices

Appendix A.1 Frameworks from literature

Fisher (1997) explicitly addressed the relation between properties of a product and the management of the supply chain. He argued that the first step in devising an effective supply-chain strategy is to consider the nature of the demand for the products the company supplies. In his view, a supply chain has two types of functions: a physical function and a market mediation function. The former includes all the conversion steps from raw materials to finished goods and transportation. The latter has the purpose of matching consumer preferences with supplies to the market. Based on his experience, Fisher distinguishes two types of products: functional products with predictable demand and innovative products with unpredictable demand. The appropriate supply chain for innovative products is a market-responsive supply chain. The primary focus of this type of supply chain is a quick market response, whereas the primary focus of a physically efficient supply chain is cost minimization. **Table 9** shows the characteristics of the different supply chain strategies.

	Physically Efficient Process	Market-Responsive Process
Primary Purpose	Supply predictable demand efficiently at the lowest possible cost	Respond quickly to unpredictable demand in order to minimize stockouts, forced markdowns, and obsolete inventory
Manufacturing focus	Maintain high average utilization rate	Deploy excess buffer capacity
Inventory strategy	Generate high returns and minimize inventory throughout the chain	Deploy significant buffer stocks of parts or finished goods
Lead-time focus	Shorten lead time as long as it doesn't increase cost	Invest aggressively in ways to reduce lead time
Approach to choosing suppliers	Select primarily for cost and quality	Select primarily for speed, flexibility, and quality
Product-design strategy	Maximize performance and minimize cost	Use modular design in order to postpone product differentiation for as long as possible

Table 8: Physically Efficient vs. Market-Responsive Supply Chains[15]

Fine (2000) proposes a framework for strategic supply chain design, based on fast clock speed industries, such as the computer industry. From these industries he observes that supply chain designs are not stable, but change over time in a cycle from integral/vertical supply chains to horizontal/modular supply chains, which is schematically depicted in **Figure 38**.

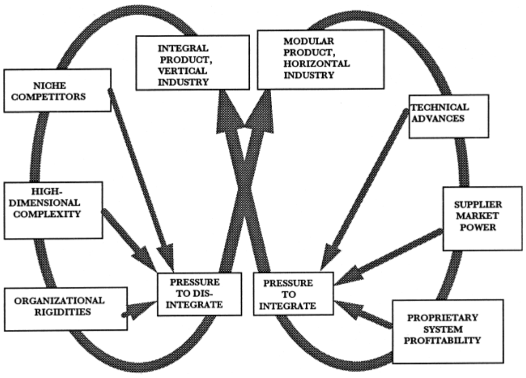

Figure 38: From an integral/vertical supply chain, to a horizontal/modular supply chain[16]

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[15] *Adopted from Fisher (1997)*

When the industry structure is vertical and the product architecture is integral, forces of disintegration push towards a horizontal and modular configuration. These forces include:

- The entry of niche competitors hoping to pick off discrete industry segments.
- The challenge of keeping ahead of the competition across the many dimensions of technology and markets required by an integral system.
- The bureaucratic and organizational rigidities that often settle upon large, established companies.

On the other hand, when an industry supply chain has a horizontal/modular structure, another set of forces push toward more vertical integration and integral product architectures. These forces include:

- Technical advances in one subsystem can make it the scarce commodity in the chain, giving market power to its owner.
- Market power in one subsystem encourages bundling with other subsystems to increase control and add more value.
- Market power in one subsystem encourages engineering integration with other subsystems to develop integral solutions.

The speed of changes depends on the clock speed of the industry, which is the speed of innovation. In order to stay competitive the three-dimensional concurrent engineering (3-DCE) approach is proposed. In this approach it is recognized that interactions between product, process and supply chain development exist. It is suggested that these overlapping activities should be undertaken concurrently.

Aitken et al. (2003) relate the design of the supply chain to the product life cycle (PLC). Based on a case study at a UK Lighting company, the right supply chain design for each stage in the PLC is derived. In each stage, the focus should be on the order winners, while the order qualifiers are of secondary importance. **Figure 39** shows the order winners and order qualifiers in each stage of the PLC and the appropriate supply chain design.

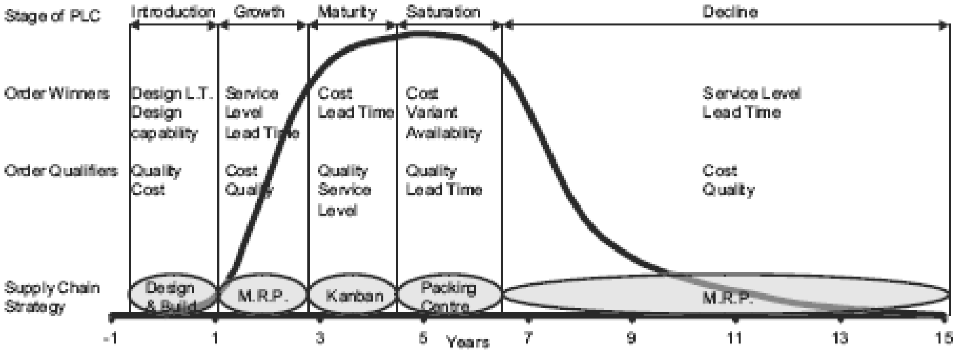

Figure 39: Generic supply chain designs for each stage in the PLC[17]

Christopher et al. (2006) propose a taxonomy to guide the selection of an appropriate global supply chain strategy. The key dimensions of the taxonomy are replenishment lead times and predictability/variability of demand. The origin of the taxonomy is the combination of lean and agile supply chain strategies. The focus of lean thinking has been on the reduction or elimination of waste. Agility on the other hand is concerned primarily with responsiveness, which is the ability to match supply and demand in turbulent and unpredictable market circumstances. Christopher et al. suggest that the lean and agile philosophies can complement each other, when appropriate aspects are carefully selected and integrated. What is needed is a continuous assessment of the product range and market characteristics, which they summarize

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[16] *Adopted from Fine (2000)*

[17] *Adopted from Aitken et al. (2003)*

as predictability. Against the predictability a number of alternative options for supply chain design exist, which depend upon supply lead times. **Figure 40** shows the resulting framework.

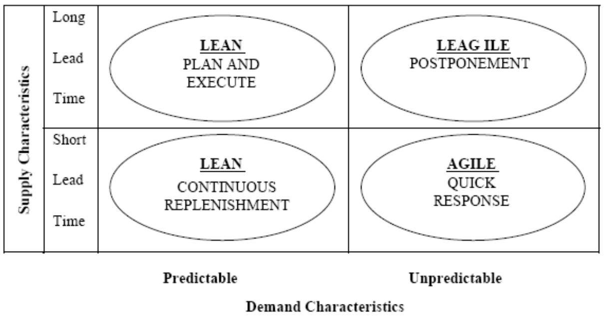

Figure 40: The combination of lean and agile supply chain strategies[18]

Ultimately Simchi-Levi et al. (2008) propose a framework that combines the previous theories. They build their theory upon two interacting chains that can be found in many organizations; the supply chain and the development chain. The supply chain can be characterized by:

- Demand uncertainty and variability
- Economies of scale
- Lead time

The development chain can be characterized by:

- Technology clockspeed
- Make/buy decisions
- Product structure

Based on these characteristics they provide a two dimensional framework for matching product design and supply chain strategy as shown in **Figure 41**.

The framework of Simchi-Levi et al. uses demand uncertainty and product introduction frequency as the main product-process characteristics.

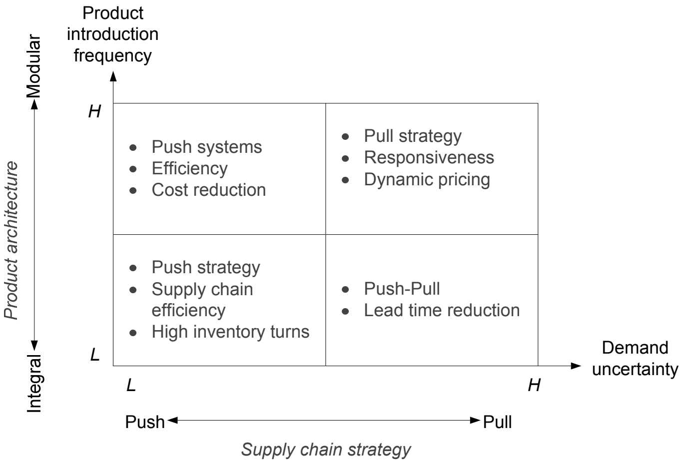

Figure 41: Matching product design and supply chain strategy[19]

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[18] *Adopted from Christopher et al. (2006)*

[19] *Adapted from Simchi-Levi et al. (2008)*

Appendix A.2 Derivation of demand parameters

$E[D] - Expected\ total\ demand$

$\sigma^2(D) = Variance\ of\ total\ demand$

$E[D_i] = Expected\ demand\ for\ item\ i$

$\sigma^2(D_i) = Variance\ of\ demand\ for\ item\ i$

$\pi = the\ probability\ that\ an\ item\ is\ selected\ by\ a\ customer$

$$I_n \begin{cases} 1\ with\ probability & \pi \\ 0\ with\ probability & 1-\pi \end{cases}$$

$E[I_n] = \pi$

$E[I_n^2] = \pi^2$

$\sigma^2[I_n] = \pi - \pi^2 = \pi(1-\pi)$

$$E[D_i] = E\left[\sum_{n=1}^{D} I_n\right]$$

$$= \sum_{m=0}^{\infty} E\left[\sum_{n=1}^{m} I_n\right] P\{D = m\}$$

$$= \sum_{m=0}^{\infty} m \cdot \pi \cdot P\{D = m\}$$

$$= \pi \cdot E[D]$$

$$E[D_i^2] = E\left[\left(\sum_{n=1}^{D} I_n\right)^2\right]$$

$$= \sum_{m=0}^{\infty} E\left[\left(\sum_{n=1}^{m} I_n\right)^2\right] P\{D = m\}$$

$$= \sum_{m=0}^{\infty} \left(\sigma^2\left(\sum_{n=1}^{m} I_n\right) + E^2\left[\sum_{n=1}^{m} I_n\right]\right) P\{D = m\}$$

$$= \sum_{m=0}^{\infty} (m\sigma^2(I_n) + m^2 E^2[I_n]) P\{D = m\}$$

$$= \pi(1-\pi) \sum_{m=0}^{\infty} mP\{D = m\} + \pi^2 \sum_{m=0}^{\infty} m^2 P\{D = m\}$$

$$= \pi(1-\pi)E[D] + \pi^2 E[D^2]$$

$$\sigma^2[D_i] = \pi(1-\pi)E[D] + \pi^2 E[D^2] - \pi^2 E^2[D]$$

$$= \pi(1-\pi)E[D] + \pi^2 \sigma^2[D]$$

Appendix A.3 Calculations of the R,S Policy

$X(t) = \mathit{net\ stock\ at\ time\ t}$

$D(t_1, t_2] = \mathit{demand\ during\ the\ interval}\ (t_1, t_2]$

$B(t_1, t_2] = \mathit{demand\ backordered\ in}\ (t_1, t_2]$

$x^{+} = \max(0, x)$

$R = \mathit{review\ period}$

$L_t = \mathit{delivery\ time\ of\ the\ replenishment\ order\ placed\ at\ time}\ t = \tau_t$

$P\{\ldots\} = \mathit{Probability}$

$E[\ldots] = \mathit{Expectation}$

$\sigma^2(\ldots) = \mathit{Variance}$

$P_2 = 1 - \mathit{Fraction\ of\ demand\ delivered\ as\ a\ backorder}$

$$P_2 = 1 - \frac{(\mathit{the\ expected\ quantity\ backlogged\ in\ a\ replenishment\ cycle})}{\mathit{the\ expected\ demand\ in\ a\ replenishment\ cycle}}$$

$$P_2 = 1 - \frac{E[B(L_0, R + L_1]]}{E[D(L_0, R + L_1]]}$$

$E[D(L_0, R + L_1]] = E[D(0, R]]$

$X(L_0) = S - D(0, L_0]$

$X(R + L_1) = S - D(0, R + L_1]$

$E[B(L_0, R + L_1]] = (D(R + L_1] - S)^{+} - (D(0, L_0] - S)^{+}$

$E[D(0, R + L_1]] = (R + E[L])E[D]$

$\sigma^2[D(0, R + L_1]] = (R + E[L])\sigma^2(D) + \sigma^2(L)E^2[D]$

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

In general: $E[(D(x - S)^{+}] = \int_S^{\infty} (x - S)\, f(x)\, dx$

For a Gamma distribution: $F(x) = F_{\alpha,\mu}(x) = \int_S^{\infty} (x - S)\, \mu \frac{\mu^{\alpha}}{\Gamma(\alpha)} x^{\alpha - 1} e^{-\mu x} dx$

$$F(x) = \frac{\Gamma(\alpha + 1)}{\Gamma(\alpha)} \int_S^{\infty} \mu^{\alpha + 1} x^{\alpha} \frac{e^{-\mu x}}{\Gamma(\alpha + 1)} dx - S \int_S^{\infty} \mu^{\alpha} x^{\alpha - 1} \frac{e^{-\mu x}}{\Gamma(\alpha)} dx$$

$$F(x) = \alpha\left(1 - \Gamma_{\alpha + 1, \mu}(S)\right) - S\left(1 - \Gamma_{\alpha, \mu}(S)\right)$$

$$\alpha = \frac{E^2(D)}{\sigma^2(D)}$$

$$\mu = \frac{\alpha}{E(D)}$$

Appendix A.4 Model validation

Verification

The model was programmed in MS Excel, using a macro in Visual Basic. The program was split into a number of sub procedures, which can run independently. By executing parts of the code during the development of the model, the code was checked and debugged if any errors occurred. When the model was completely programmed, it was tested with a simple product structure of only 2 items with 2 variants each and integer numbers for all cost parameters. By using this input, results of the model could easily be calculated manually. These results were compared with the model output. The results matched and it was concluded that the calculations were correct. For the inventory policy parameters, the spreadsheet "Classical Inventory models" by de Kok (2004) was used as a comparison. It was concluded that the results of the model matched the results of this sheet. Finally, the performance of the model was evaluated. It appeared that, when too many items are included in the platforms, the computer might run out of memory, because all the possible combinations of variants can not be calculated. Nevertheless, for the largest relevant collection of platform items for the Type 1, there was no problem encountered. For a product design with x items in the platform and x different platform combinations, a calculation time of 33 minutes was recorded on a desktop with 3.23 GB Ram memory and a 2.33 GHz dual processor. It was concluded that the performance of the model is adequate for the intended purpose.

Validation

The first step that was undertaken to validate the model was checking the assumptions underlying the model. The assumptions were discussed with stakeholders of Philips and the model was adapted if necessary. The assumptions regarding the cost parameters in the model were checked by the financial controller of OXB and approved. The next step was to check the results of the inventory policy calculations with the actual inventory levels at Philips. First, the actual service level for raw materials was estimated. This estimation was based on an analysis of all deficiencies [redacted] (see Appendix B.11). It has to be noted that items for which no deficiencies occurred are not included in the list. Therefore, the overall average service level is probably even higher. For the validation of the inventory calculations it was decided to set the service level equal to x%.

The remaining input parameters were set according to the current situation. The only parameter for which no data was available [redacted]. With these parameters, and a product design consisting of only modules, combined with a centralized supply chain design, the average inventory for the modules at the CODP was calculated in the model. <<Confidential>>

As a third step, the total supply chain costs and inventory investment resulting from the model, for parameter settings matching the current situation, were checked by the financial controller of OXB and approved. Finally, a sensitivity analysis was performed, to check the behaviour of the model, when parameters were varied within a realistic range. It was concluded that the behaviour of the model corresponds with the expected behaviour of the real world system. The sensitivity analysis is discussed in more detail in section 6.2. [redacted] The aim of validation is to increase the degree of confidence that the results of the model will occur under the conditions assumed (Gass, 1983). With the described procedure, this goal has been met sufficiently.