Supply Chain Performance Evaluation

Application of the synchronised base stock policy in a high-tech complex equipment supply chain with contract manufacturers

TU/e

Jip Bisschop

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Technische Universiteit Eindhoven / Eindhoven University of Technology (TU/e)
Department of Technology Management (TM)
Subdepartment of Operations, Planning, Accounting & Control (OPAC)
De Lismortel 2
PO Box 513
5600 MB EINDHOVEN

written by

Jip Bisschop
ID number 521263

under supervision of

Prof. dr. ir. Jan C. Fransoo
Professor of Operations Planning and Control
Eindhoven University of Technology

Prof. dr. Ton G. de Kok
Professor of Operations Management
Eindhoven University of Technology

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ABSTRACT

This Master's thesis describes the development of a supply chain performance evaluation model in a high-tech complex equipment supply chain with contract manufacturers. The model is based on the synchronised base stock policy complemented with classical stock control models in order to deal with lot sizing. Furthermore, an aggregation procedure has been developed for reasons of computational capacity. The model has provided insight into the relationship between the levers of supply chain performance. It has been used to substantiate supply chain strategy and to focus on supply chain performance improvement initiatives that drive supply chain performance.

MANAGEMENT SUMMARY

In 2003 the board of a complex equipment manufacturer (CEM) decided to outsource manufacturing operations to contract manufacturers in the Far East in order to reduce costs. As a result the supply chain has changed fundamentally. It is expected that the current supply chain strategy is inappropriate to control the newly arisen supply chain at operational, tactical and strategic levels.

In this project a quantitative supply chain performance evaluation (SCPE) model has been developed in order to provide insight into the relationship between the levers of supply chain performance. The model has been used to substantiate supply chain strategy and to focus on supply chain performance improvement initiatives that drive supply chain performance. The model indicates a company wide potential stock reduction of 60% by improving the forecasting performance, resulting in stock investment savings of €4.4 million in the specific supply chain that has been studied.

An extensive supply chain analysis has been performed in order to obtain the required detailed insight into the supply chain, reaching from second tier suppliers until the customer order decoupling points (CODP). The analysis has revealed that the CEM operates three inbound supply chain structures: the OEM, partial outsourced and integral outsourced supply chain. Products in the OEM supply chain are sourced with black box outsourcing. These are out of the scope of this project. Products in the partial and integral outsourced supply chain are sourced with white box outsourcing. In the partial outsourced supply chain the final assembly process is executed by the CEM, while this process is outsourced to contract manufacturers in the integral outsourced supply chain.

The cumulative lead time in the partial outsourced supply chain is structurally 10 weeks longer than in the integral outsourced supply chain. This extra lead time covers the transportation lead time from the contract manufacturer to the manufacturing facilities of the CEM in Europe and the throughput time of the final assembly process. The decision to operate a partial outsourced supply chain structure is often originated from the criticality of the final assembly process. Nevertheless, such a significant lead time difference and its impact on supply chain performance should be considered in the process of designing a product and its supply chain.

It has been shown that flexibility in the supply chains is low as a result of the large difference between the requested and available reaction time in the supply chain: the standard delivery lead time to customers is 1 to 4 weeks, while the reaction time of the supply chain (or cumulative lead time) is 30 to 50 weeks. As a result, the CEM has to anticipate future demand with a forecasting system, while lead times are buffered with stock. The supply chain analysis has demonstrated that both planning and control mechanisms do not function properly.

Demand forecasting

The current demand forecasting system of the CEM is effectuated in the manufacturing and delivery plan (MDP). This MDP is based on negotiation between the heads of manufacturing and sales, rather than on joint analysis. It is constructed quarterly and prescribes the manufacturing and delivery quantities for each product. The horizon of the MDP is restricted by the end of the fiscal year, even though suppliers are informed about future demand expectations with a rolling horizon of one year. As a result, the demand information and order releases towards suppliers are not based on the planning and control structure. Furthermore, the current planning and control structure lacks a performance monitoring system, which prevents the demand forecasting system from improving.

With statistical analysis tools it has been shown that the demand forecasting system is a source of nervousness in the supply chain. This is effectuated in the forecast error that is structurally larger than that of the most basic fact based demand forecasting model available in literature. It is argued that the poor performance is inherent to the position of the forecasting system as it has been presented in the previous paragraph. Namely, the generated forecasts are affected by the business dynamics of the CEM (e.g. the incentive structure) due to the absence of fact based analysis tools. The impact of the business dynamics can be observed in Figure 1, which shows that the forecast error develops from underestimation to overestimation during the year.

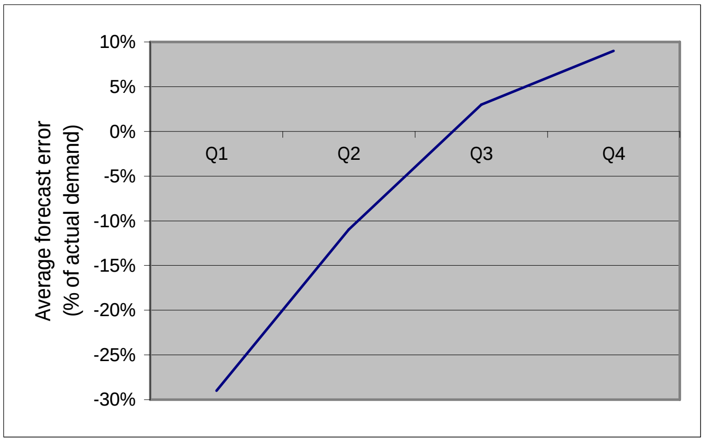

Figure 1: Direction of the forecast error

The developed SCPE model enables the quantification of the impact of the poor performance of the forecasting system on the integral supply chain performance. In Figure 2 it can be observed that a stock investment savings of approximately 60% (€4.4 million) can be achieved by introducing a simple fact based forecasting system in the specific supply chain that has been studied only. These savings are completely cashed in by the CEM, while the introduction of an improved forecasting system is easily extended company wide resulting in savings that are a multiple of the above mentioned €4.4 million. An advanced demand forecasting system would further improve the accuracy of the forecasts and as a result the stock investment savings will increase even further.

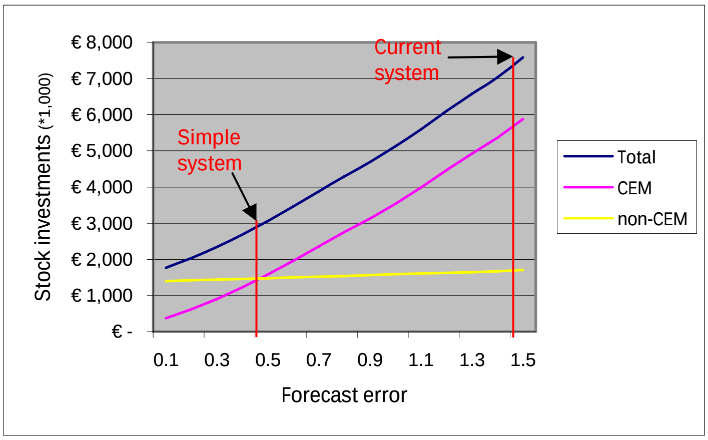

Figure 2: Impact of the forecast error on the stock investments

The improvement of the forecasting system would significantly reduce the nervousness in the supply chain. As a result, the impact of supply chain performance improvement initiatives will significantly increase. For instance, it would facilitate the implementation of lead time reduction programs and supplier performance projects. In conclusion, the nervousness created by the forecasting system is a root cause of excessive stock, long lead times, unnecessarily high commitments, inflexibility and inefficiency in the supply chain.

Stock control

The supply chain analysis has revealed that the stock control system of the CEM does not function properly. First, the target stock levels are based on experience, rather than on fact based analysis. Second, the target stock levels are determined with historical demand data instead of future demand expectations. Third, the target stock levels are violated heavily resulting in excessive stock investments and poor customer service performance. In Figure 3 it can be observed that the aggregate stock levels fluctuate heavily during the year, while the aggregate demand is relatively stable. The stock level expressed in weeks of supply is three times higher during the highs than during the lows.

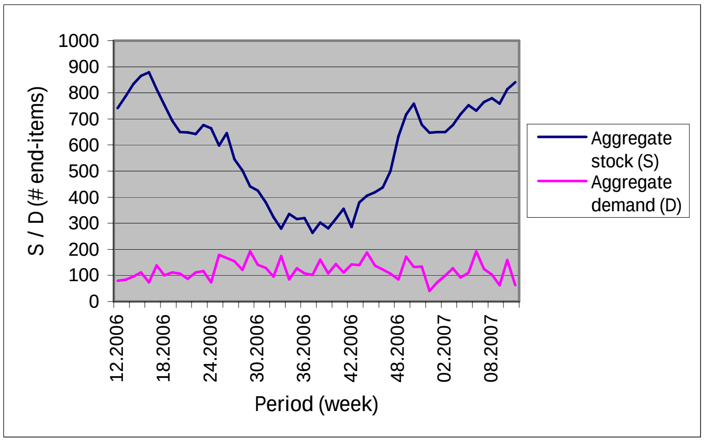

Figure 3: Aggregate stock levels

The consequence of these uncontrolled stock levels is a poor customer service performance. The service levels of the manufacturing organisation are structurally lower than the target of 95% that has been established in cooperation with the internal customers. In Table 1 the customer service performance presented for the two manufacturing units of the CEM: CLIP defines the accuracy of the delivery moments confirmed by the manufacturing organisation; SLIP defines the customer service performance with regard to the agreed delivery lead times; RLIP defines the customer service performance with regard to the delivery moments requested by the internal customers.

	A	B	Target
CLIP	93%	89%	95%
SLIP	77%	63%	
RLIP	49%	34%	

Table 1: Service levels

Strategic focus in the supply chain

Based on the supply chain analysis and the developed SCPE model it is argued that the CEM should focus its supply chain strategy on:

- Improving the demand forecasting system
  The CEM should urgently improve the customer demand forecasting system in order to stabilize supply chain operations. The system should be fact based in a joint analysis between the manufacturing and sales organisations.

- Decoupling the manufacturing & delivery plan from the supply chain operations planning
  The MDP should only be used as an aggregate planning and control mechanism for balancing *aggregate* demand, supply and capacity. It incorporates political aspects (e.g. sales budget), while planning decisions in the upstream supply chain should be shielded from that.

- Transforming from a delivery oriented to a service oriented supply chain
  For each product-market combination a target service level has to be determined, for which the manufacturing organisation is responsible and accountable. As a result, the manufacturing organisation pursues a long term objective, instead of chasing individual orders.

- Formalizing and updating the current stock control system
  The current stock control system has to be updated accordingly. Fact based stock control models should be implemented in which stock level settings in the ERP system are based on quantitative analysis.

- Reducing lead times of contract manufacturers
  Performance improvement in the upstream supply chain should be focused on lead time reduction of the pipelines between the Far East and the CODPs. The fixed fence in the contract with contract manufacturers should be reduced, in addition to business process alignment in order to realize pipeline length reduction. The contract manufacturers should pursue a lean manufacturing strategy with Just-In-Time delivery from their suppliers.

PREFACE

This Master's thesis is the result of a nine-month graduation project undertaken within the manufacturing department of a complex equipment manufacturer. It marks the culmination of the five-year Master's degree program in Industrial Engineering and Management Science that I have been pursuing at the Eindhoven University of Technology. I would like to take this opportunity to express my gratitude towards the people that have supported me throughout my graduation project and Master's degree.

I thank my company supervisor for providing me with the opportunity to apply my industrial engineering skills to real life. His guidance was pivotal in helping me to stay focused on developing practical but foremost acceptable outcomes. It could not have been easy to trust a young graduate with the issues we encountered.

I thank my colleagues. Despite not being a direct stakeholder of the project, they provided me with assistance and information on repeated occasions. Furthermore, I thank my closest colleagues for their support, the small talks and the many laughs.

I thank Jan Fransoo for his guidance and support during the past year. It is unbelievable that someone as overloaded as Jan is able to display the engagement he does. His ability to motivate and inspire ensured that the project exceeded expectations by challenging me to translate quantitative engineering results into practical business language. It would have been impossible for me to obtain the aforementioned results without the help of Ton de Kok. He put his knowledge and time at my disposal, despite this intruding on his own personal time. I cannot recall Ton sending me one e-mail during office hours. It has been tremendously stimulating to work together with these two leading scientists.

To conclude, I owe a large debt of gratitude to my parents, family and friends who have enabled me to prosper. And Kim, you of all know I always save the best for last.

Jip Bisschop

October 2007

"I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a very meagre and unsatisfactory kind."

William Thomson, Baron Kelvin, 1824-1907

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CHAPTER 1, INTRODUCTION

In this chapter the project is positioned in its context. First, the initial scope of the project is defined. Second, the research model and the structure of the report are presented.

1.1. Initial scope

In 2003 the board of a complex equipment manufacturer (CEM) decided to outsource manufacturing operations to contract manufacturers in the Far East in order to reduce costs. As a result the supply chain changed fundamentally: from a vertical integrated supply chain to a virtual integrated supply chain (Fine, 1998). In the former situation the CEM operated local manufacturing and sourcing functions in Europe; suppliers were located in close proximity to the manufacturing operations. (see Figure 1.1) In the new situation, manufacturing operations are also located in the Far East, including a supply base in that region. This virtual integrated supply chain faces increased complexity and long lead times caused by long physical distances. (see Figure 1.2)

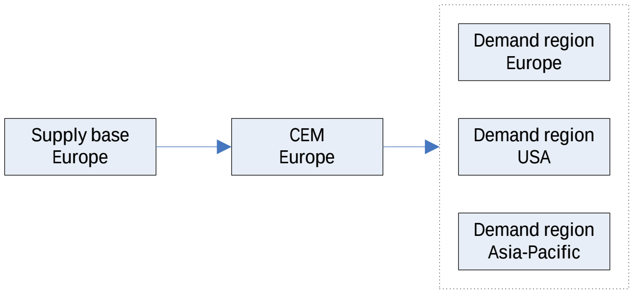


Figure 1.1: Vertical integrated supply chain

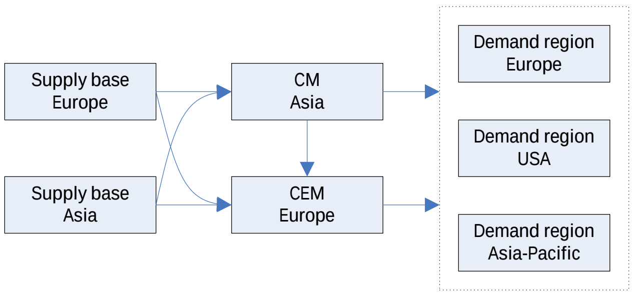


Figure 1.2: Virtual integrated supply chain

So the CEM has become dependent on contract manufacturers for the delivery of components. The availability of these components is critical in supply to customers. Therefore, it is crucial to manage these contract manufacturers efficiently, including their supply bases. The CEM expects that the current supply chain strategy may be inappropriate to control the virtual integrated supply chain at operational, tactical and strategic levels. Therefore, this strategy has to be verified and the corresponding operations planning and control models have to be updated. This project focuses on the redefinition of the supply chain strategy of the CEM with regard to the contract manufacturers located in the Far East and their suppliers, referred to as the second tier supply base.

1.2. Research model

The project is executed according to the solution oriented approach of Kempen and Keizer (2000) because this methodology is specifically developed to support business problem-solving projects (Van Aken et al, 2007). It provides ten sequential steps that can be divided into five phases according to the regulative cycle (Van Strien, 1975). The phases are orientation, analysis, design, implementation and evaluation. Figure 1.3 summarizes the research model according to the design oriented approach of Verschuren and Doorewaard (1995). It also provides the structure of this report.

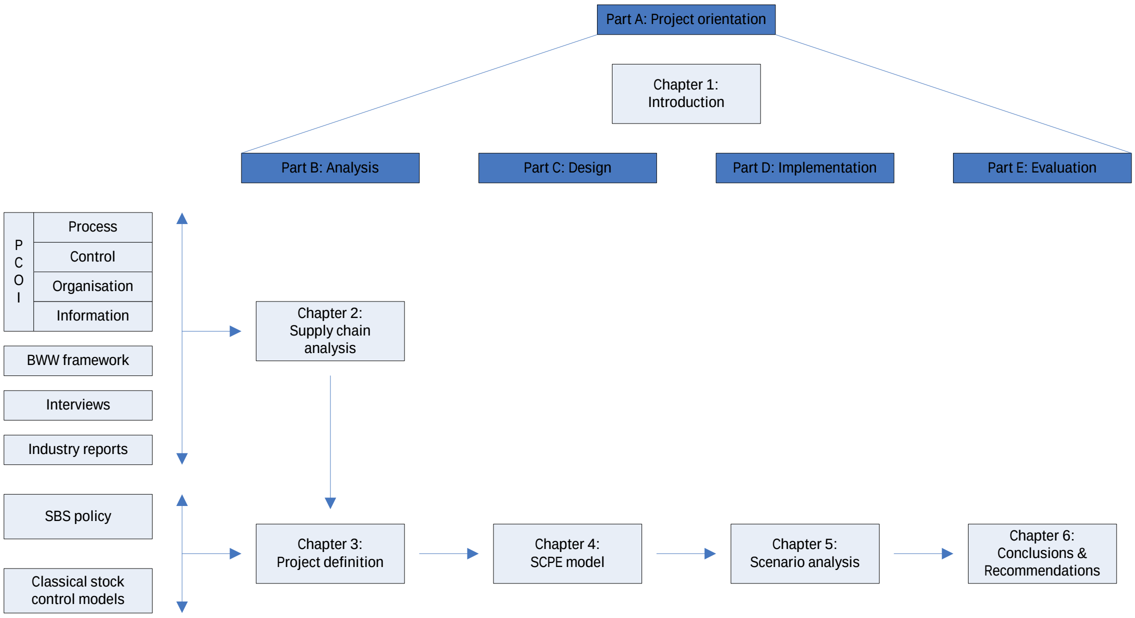


Figure 1.3: Research model

The objective of the orientation phase is to identify and specify the key targets of the project and to become familiar with the processes of the organisation. This is done by conducting interviews with key persons in the organisation.

In the analysis phase the required detailed insight into the supply chain is gained. For this purpose, the PCOI framework is used (Bemelmans, 1986). This framework provides a structured approach of the analysis of operational processes from the perspective of improving the corresponding planning and control structure. The PCOI framework distinguishes between the elements process, control, organisation and information. Specifically for the control element, the BWW framework is used (Bertrand et al, 1998). This framework for production control and material management provides a deeper understanding of the relation between planning and control processes and the operational processes of an organisation.

Based on the results of the analysis phase, a final research project is defined and the design phase is started. The supply chain analysis has revealed that the CEM has no insight into the relation between the supply chain parameters and supply chain performance. As a result, it has been decided to develop a supply chain performance evaluation model in order to substantiate the earlier mentioned supply chain strategy. The supply chain performance evaluation model is based on the synchronised base stock (SBS) policy as defined by De Kok and Fransoo (2003), complemented with classical stock control models. The model is implemented with a software tool that is linked to a standard spreadsheet and database program. This enables quick and structured analysis of different scenarios in order to evaluate different supply chain strategies.

The implementation phase has been intertwined with the design phase. The scenarios have been established in close cooperation with the senior management. In addition, the results have been shared with the managers responsible for the supply chain strategy in order to provide the required insights for its redefinition. To conclude, in the evaluation phase the relevant conclusions are drawn and recommendations for further research are provided.

During the entire project, data has been gathered by interviews with employees at different positions in the organisation. Each interview has been summarized and was offered for correction to the interviewee. If data appeared to be controversial, the interviewees were confronted with this and they were asked for an explanation.

1.3. Structure of the report

This report is organised as follows: Chapter 2 presents the results from the supply chain analysis. Chapter 3 proposes the project definition. Chapter 4 defines the supply chain performance evaluation model. Chapter 5 presents the results from the scenario analysis. Chapter 6 provides the conclusions and recommendations for further research. Lists of abbreviations, definitions and symbols, and tables of figures and appendices have been added from page 58 onwards.

1.4. Conclusions

The supply chain of the CEM has transformed from a vertical to a virtual integrated supply chain, elicited by the strategic decision to outsource manufacturing operations to contract manufacturers in the Far East. As a result the current supply chain strategy and corresponding operations planning and control models are expected to be inappropriate. This project provides insight into the relation between supply chain performance and supply chain parameters, in order to redefine this strategy. The project and this report are structured according to the five phases of the solution oriented approach. The next chapter presents the results from the analysis phase.

CHAPTER 2, SUPPLY CHAIN ANALYSIS

In the previous chapter the initial scope of the project has been defined based on which the analysis phase has been initiated. In this chapter the results of the supply chain analysis are presented following the structure of the PCOI framework. First, the supply chain structure and parameters are defined. Second, the planning and control structure of the supply chain is described by means of the BWW framework. Third, the organisational context of the supply chain is provided. Fourth, the key information systems supporting the planning and control structure and organisation are described. To conclude, a synthesis of the results of the supply chain analysis is presented.

2.1. Supply chain structure

The supply chain is defined as the chain of processes that purchase raw materials, transform them into semi-finished and ultimately marketable products and distribute these to the end-customers. (Lee & Billington, 1993) Several supply chains together form a supply network, which is a network of activities transforming inputs into outputs using available resources (De Kok & Fransoo, 2003). The supply network is described by the bill of materials (BOM) and the bill of processes (BOP).

2.1.1. Bill of materials

The product portfolio of the CEM consists of 36 complex systems that can be differentiated according to the production capacity of the system. The low and medium volume systems are sourced from original equipment manufacturers (OEM). The high volume systems are manufactured in-house.

The BOM of a complex system can be described conceptually as in Figure 2.1. A complex system consists of several levels of components. On the highest level a component is defined as a module. The common product body is the part of the system that executes the process. This module is accompanied by configuration items. The modules support the common product body in executing the operational processes of the complex system. Commercial items are optional and are added on customer request. Modules can be optional as well.

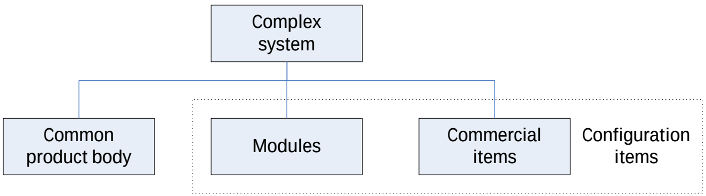


Figure 2.1: Bill of materials

A common product body consists of units. A unit is a complex component consisting of many parts and is sourced from a contract manufacturer or manufactured by the CEM internally. A unit is assembled from subassemblies. A subassembly is a less complex component consisting of fewer parts. A part is the lowest level of the BOM; it cannot be subdivided into a more detailed level. During this project, an item is referred to as a unique instance of a component, independent of the level in the BOM.

2.1.2. Bill of processes

The supply chain or BOP can be described conceptually as in Figure 2.2. In the outbound supply chain the end-product is distributed to customers directly via local sales organisations (LSO) or indirectly via dealer networks. The CEM owns the LSOs, while dealers are independent. The LSO is responsible for sales, service and distribution in a specific country or geographical region. It is supplied by a configuration centre. In the configuration centre products are customized based on customer specific needs; specific languages are applied, software is installed and configuration items are added. The CEM has a configuration centre in each demand region supplying LSOs in that specific region with a fixed frequency. These configuration centres are located in the United States of America (USA), Europe and Asia.

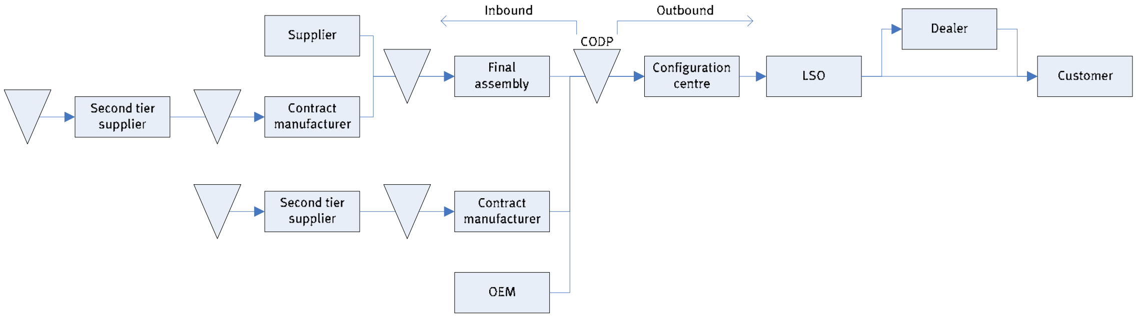


Figure 2.2: Supply chain of the CEM

The configuration centres keep modules in stock. This is the point in the supply chain where the goods flow becomes customer driven instead of forecast driven. It is defined as the customer order decoupling point (CODP). (Bertrand et al, 1998) This means that the configuration centre is controlled by customer orders, while the inbound supply chain is forecast driven. This project focuses on the inbound supply chain.

Three different inbound supply chain structures can be distinguished: the partial outsourced, integral outsourced and OEM supply chain. According to Van Weele (2002) the partial and integral outsourced supply chains correspond with partial subcontracting. This means that the contract manufacturer merely executes the manufacturing operation, while the CEM is responsible for product development and other processes in the value chain. In the partial outsourced supply chain, the final assembly process is executed by the CEM. The units that enter the final assembly process are supplied by unit contract manufacturers, while subassemblies and parts that support the final assembly process are sourced from other suppliers. Components are stocked at the second tier supplier, the contract manufacturer, and the inbound and outbound goods flow of the final assembly stage. In the integral outsourced supply chain, the final assembly process is outsourced to module contract manufacturers and thus the CEM only executes the configuration process. The modules are distributed directly from the contract manufacturer to the configuration centre and components are kept on stock at the second tier supplier and the contract manufacturer only. In the OEM supply chain the products are sourced by turnkey subcontracting. The supplier has responsibility for the execution of the entire assignment, including product development (Van Weele, 2002). The OEM supply chain is out of the scope of this project.

In addition to the above described supply chains, the CEM operates a service supply chain. This supply chain is beyond the scope of this project, since it is controlled separately from the above described supply chains. Furthermore, the service supply chain has a share of less than 5% in the supply value and supply volume of the CEM based on one year of historical data about the material requirements in the Enterprise Resource Planning (ERP) system.

To enable completion of the project within the time frame, it has been decided to select one specific supply chain as object of research for detailed analyses. It has been decided to use the supply chain of the product ‘Nero’, which has a combined partial and integral outsourced supply chain. As a result the insights can be extrapolated to other supply chains as well.

2.1.3. Purchasing processes

The purchasing function is responsible for obtaining the proper equipment, material, supplies and services of the right quality in the right quantity, at the right price and from the right source at the right time. (Aljian, 1984) From this perspective, a cross functional performance model is currently being spread throughout the organisation as part of the purchasing excellence program. This model defines four pillars that support the corporate strategy of the CEM in meeting end-customer requirements:

- Quality, reflected by low defect rates
- Logistics, reflected by short lead times, high delivery reliability and high flexibility
- Technology, reflected by short time to market and efficient development processes
- Costs, reflected by continuous reduction of costs

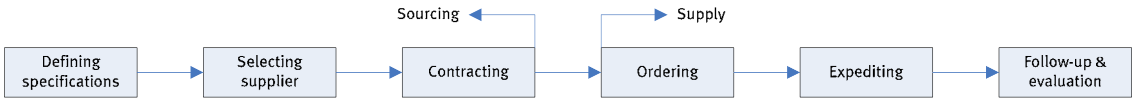


Figure 2.3: Purchasing process (Van Weele, 2002)

The purchasing process has been described by Van Weele (2002) as presented in Figure 2.3. For the scope of this project, the contracting, ordering and expediting steps are particularly relevant.

The contracting structure of the CEM consists of two hierarchical levels; the Master Purchase Agreement and the Product Supply Conditions. The Master Purchase Agreement defines the relationship between the CEM and the supplier, and exists for each supplier. On a general level it prescribes specific processes, agreements related to spare parts and tooling, and the order, delivery and payment terms. The Product Supply Conditions prescribe the conditions of supply on a detailed level for each component.

For contract manufacturers a Product Specific Agreement exists, which is positioned in-between the Master Purchase Agreement and Product Supply Conditions in the contracting hierarchy. The Product Specific Agreement describes the manufacturing and delivery conditions for a specific unit or module in detail. It deals with technical specifications, prices and quotations, sourcing procedures, quality procedures, tooling, spare parts, business resumption planning and other relevant issues. A flexibility measure is mentioned in the contract as well, though it is not a formal term. It specifies a guideline for ramping up production at the CEM. However, this guideline is not translated into a flexibility profile for the contract manufacturer.

The CEM also contracts second tier suppliers depending on their specific characteristics. Namely, each supplier is characterised based on the supply risk and supply value of the components it supplies. (see Figure 2.4) The strategic and bottleneck components are sourced from second tier suppliers that are contracted by the CEM; the contract manufacturer has an operational responsibility only. These are the prescribed components. The leverage and routine components are sourced by the contract manufacturer based on specifications provided by the CEM. These are the non-prescribed components.

		Supply risk	
		Low	High
Supply value	High	Leverage	Strategic
	Low	Routine	Bottleneck

Figure 2.4: Supplier portfolio (Kraljic, 1983)

The category of a component is determined during the engineering phase of the product development process in a discussion between R&D, quality and purchasing representatives. In general, it can be stated that prescribed components are high value, long lead time components, while non-prescribed components are low value, short lead time components. The average supply value per component is more then ten times higher and the planned lead time is more than two times longer in the case of prescribed components. This can be explained by the fact that prescribed components are in general complex components that are specifically manufactured for the CEM.

In the ordering structure of the CEM two ordering policies can be distinguished: delivery schedules and purchasing orders. In the case of purchasing orders, a single order is released each time a component has to be delivered by the supplier. In the case of delivery schedules, a forecast of the material requirements is provided weekly with a horizon of one year. (see Table 2.1 for an example) Based on this delivery schedule the supplier can source components from second tier suppliers. Since it is a forecast (and not a binding purchasing order) the CEM guarantees to cover the risk of obsolescence of these components with a commitment profile. This profile defines the percentage of the unit price that is covered by the CEM. The commitment profile is different for each component and supplier depending on supply values, minimum order quantities (MOQ) and planned lead times.

Period (week)	0-5	6-12	13-16	17-26	27-28	29-52
Level of detail of forecast (week)	1		4	12		24
Commitment (% of unit price)	100%	60%			13%	

Table 2.1: Delivery schedule of a random component

It has to be noted that the commitment profile is not completely fact based; there exists some room for negotiation between the CEM and the supplier. The relation between the delivery schedule and the planning and control structure will be discussed in section 2.2.2.

With regard to expediting, the CEM uses three different shipping terms with suppliers and contract manufacturers based on Incoterms 2000 (ICC, 2000). The shipping term defines the responsibilities among parties during transport. Free on board means that the supplier loads the goods on board the ship nominated by the CEM. Ex works means that the supplier makes the goods available at his premises. Delivered duty paid means that the supplier delivers the goods at the gate of the manufacturing facility of the CEM.

2.1.4. Demand

Demand at the CODP has been analysed, since that is the point where it penetrates the supply chain. Each configuration centre represents a single CODP, since stock at one configuration centre is only available for its own specific demand region. The common product body is the leading module in ordering. Therefore, demand is defined as the number of ordered common product bodies at each configuration centre, based on data in the ERP system.

The aggregate demand pattern of the CEM products has been analysed in order to examine cyclical effects in the business cycle of the CEM. These effects have been mentioned by the logistics professionals within the organisation. First, the bonus structure of the sales force could have an impact during the closing of the fiscal year. If the sales force has met the bonus criteria, it will try to shift orders to the next year. If the sales force has not met the bonus criteria, it will try to boost sales. Second, the two weeks company break during the summer could cause an increase in sales orders before or after this period.

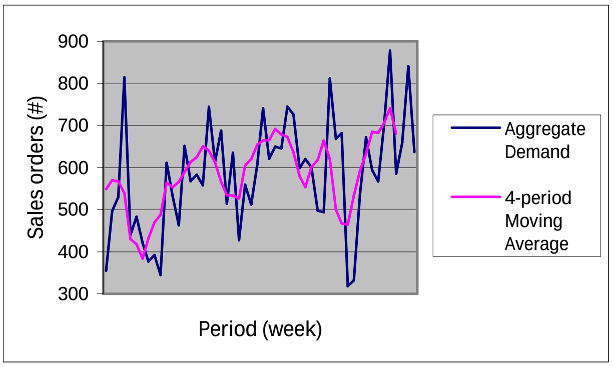


Figure 2.5: Aggregate demand pattern

Since only four products cover the complete three year data set, demand has been analysed during one year. In Figure 2.5 it can be seen that the CEM faces volatile aggregate demand (blue line) with a cyclical pattern and an upward trend (purple line). These effects have to be analysed in further detail. On a detailed level, demand can be seen as a time series consisting of a certain level, trend, seasonal pattern and irregular random fluctuations (Silver et al, 1998). Based on this definition, demand has been analysed in detail. (see Appendix A)

The seasonal pattern of a time series can be determined by constructing a correlogram (Chatfield, 2004). In a correlogram the autocorrelation coefficients of the time series are plotted against the periods. The autocorrelation coefficients determine the correlation between observations at different distances apart. If a time series is said to be seasonal, then the correlogram will show the same seasonal pattern. In the complete data set, only one product-configuration combination shows a seasonal pattern with a frequency of five months. However, the effect is not statistically significant and inexplicable. Therefore, it is assumed that demand is free from any seasonal effects.

Trend effects have been analysed with the least squares regression model that is described by Silver et al (1998). On a monthly level a trend model has been shown to be significant for all products. However, the replenishment lead time of the CODPs is defined on a weekly level, for which the trend effect is not statistically significant. Therefore, demand is assumed to be stationary.

Now, the irregular random fluctuations or standard deviation of demand can be examined. First, differences among products are analysed. For each product the mean, standard deviation and coefficient of variation (COV) have been determined. The coefficient of variation measures the relative uncertainty in demand:

$$(1)\quad COV[\chi] = \frac{\sigma[\chi]}{E[\chi]}$$

Where:
COV[χ] is the coefficient of variation of the expected demand.
E[χ] is the expected demand.
σ[χ] is the standard deviation of the expected demand.
χ is a random variable.

In the step diagram in Figure 2.6 the coefficients of variation of the CEM products are sorted from high to low distinguished into the two manufacturing organisations. It can be observed that the demand uncertainty of the CEM products is relatively low. The coefficients of variation higher than 0.7 originate from products in the introduction, growth and decline phase of the product life cycle. In addition, it has been shown that demand fits a Gamma and Normal distribution with 95% confidence. This leads to the conclusion that demand uncertainty is controllable. In section 2.2.4 it is discussed how demand uncertainty is amplified by the forecasting system of the CEM in the context of the planning and control structure of the supply chain.

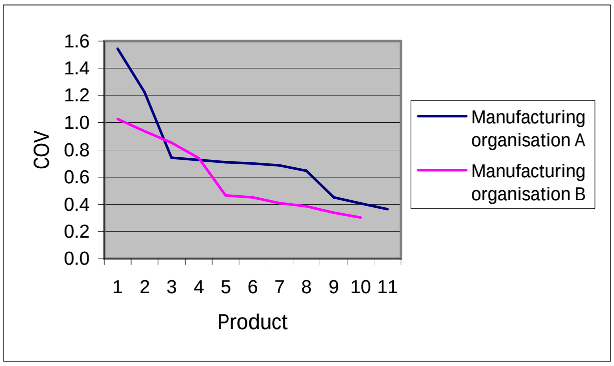


Figure 2.6: Step diagram of the coefficient of variation

2.1.5. Lead time

The BOM and BOP of the Nero supply chain have been analysed in detail in order to get insight into the cumulative lead time. The analysis is based on the concept of planned lead times (De Kok & Fransoo, 2003). This planned lead time can be decomposed into delay, waiting time and processing time according to Smits (2002). Delay represents the period between the arrival of an order and the actual release of a production order, e.g. the time for administration and order handling. Waiting time represents the period that a production order is waiting to be processed. Processing time represents the period that an order is being processed on a resource.

The cumulative lead time of the Nero has been decomposed according to the processing steps in the supply chain in Appendix B. The processing times provided are estimates of the responsible logistics professionals and are accurate in 90% of the cases based on their experience. The decomposition and figures have been verified and confirmed by all relevant employees from the logistics and purchasing departments. The planned lead times have been based on the planned lead times in the ERP system.

In the Gantt-charts of the cumulative lead time decomposition in Appendix B it can be observed that the CEM first detects a material requirement and releases an order. Based on this order, the contract manufacturer constructs a production planning and orders components at its own suppliers. This second tier supplier has a planned lead time. After the components have been received, the contract manufacturer manufactures the ordered unit or module. Then it is transported to Europe, which incurs different lead times for different transportation modes. Finally, the unit or module is processed in the final assembly stage in Europe, handled in the warehouse and forwarded to the configuration centre. In the configuration centre the product is prepared according to customer specifications. In the integral outsourced supply chain the modules are transported directly from the contract manufacturer to the configuration centre. As a result, the cumulative lead time in the integral outsourced supply chain is structurally 10 weeks shorter than in the partial outsourced supply chain.

The difference in the cumulative lead time of both supply chain structures covers the transportation lead time from the contract manufacturer to the manufacturing facilities of the CEM in Europe and the throughput time of the final assembly process (including handling). Note that the decision to operate a partial outsourced supply chain structure is often originated from the criticality of the final assembly process. Nevertheless, such a significant lead time difference and its impact on supply chain performance should be considered in the process of designing a product and its supply chain.

The cumulative lead time distribution of the Nero supply chain has been examined. In Figure 2.7 the percentage of the total supply value is shown for which the cumulative lead time is shorter than or equal to the cumulative lead time presented on the x-axis. It can be seen that the cumulative lead time is shorter than 12 weeks for 24% of the supply value, while for 64% of the supply value the cumulative lead time is between 12 and 27 weeks. For 12% of the supply value the cumulative lead time is longer than 27 weeks. It can be stated that the cumulative lead time of a common product body for the Nero is 47 weeks if there is a material requirement at the European configuration centre while the pipeline is empty, based on the longest lead time component in the second tier supply base. In case of emergency this cumulative lead time can be reduced with approximately 13 weeks by persuading suppliers to deliver in advance, giving priority to the specific order and using faster modes of transportation. Though, this quick response lead time is limited by material availability at the contract manufacturer and the CEM. In conclusion, it can be stated that the CEM supply chain faces long lead times.

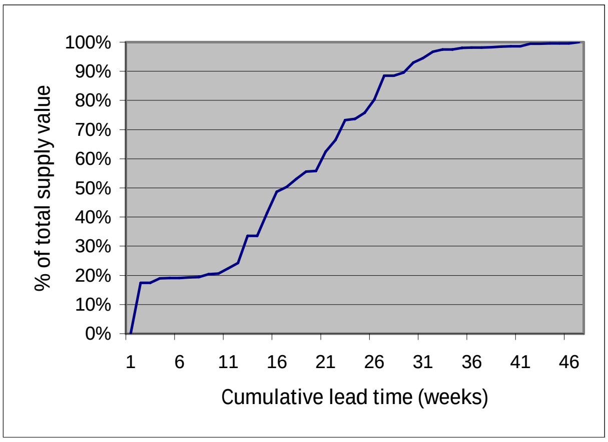


Figure 2.7: Cumulative lead time in relation to the value structure

2.1.6. Minimum order quantity

An important aspect of the CEM supply chain is the relatively large MOQs of components delivered by (second tier) suppliers. These large MOQs result in low ordering frequencies compared to those of their parents. Namely, modules and units can be ordered each week. The expected review period has been determined for the components in the supply bases of the common product body and the contract manufacturers of the Nero. (see Table 2.2) This expected review period E[R] defines the average number of weeks between two consecutive orders for a component. It is clear that the MOQ in the common product body supply base has little effect, since only 4% of the supply value has an expected review period longer than one week. For the unit contract manufacturer, the review period concentrates around 1 week, 7 weeks and 25 weeks (in total 74% of the supply value). For the module contract manufacturer the distribution of supply value among different review periods is dispersed.

Supply base	% of supply value	E[R]
Common product body	96	E[R] ≤ 1
	4	E[R] > 1
Unit contract manufacturer	35	E[R] ≤ 1
	11	1 < E[R] < 7
	7	E[R] = 7
	7	7 < E[R] < 25
	32	E[R] = 25
	9	E[R] > 25
Module contract manufacturer	9	E[R] ≤ 1
	91	E[R] > 1

Table 2.2: MOQ distribution

Several remarks have to be made with regard to this analysis. First, it is unknown whether these MOQs represent the actual MOQs correctly. They are mentioned and specified in the contract, but it is expected that the contract manufacturers arrange larger MOQs in order to get price reductions. This cannot be checked, since contract manufacturers refuse to give access to their ERP systems during supplier audits. As a result, it has to be assumed that the MOQ specified in the contract is correct. Second, for some components the contract manufacturers have arranged a call-off structure. In this structure the contract manufacturers order a quantity equal to the MOQ, but quantities are periodically released (called-off) based on the actual material requirements. The liabilities are covered with the MOQ, while the payments are based on the products released. In a call-off structure the lead times and the average review period are shorter. However, the CEM has no insight into this part of the supply chain.

2.2. Planning & control structure

In this section the planning and control structure of the inbound supply chain is described and analysed based on the framework for production control and material management as developed by Bertrand et al (1998). It is defined as the architecture of the planning and control system, which is defined by Fransoo (2004) as "the set of procedures involved in all operational decisions regarding time and quantity aspects resulting in a certain cost, service level and environmental burden, together with the relations between these procedures". The system determines what is executed, when, by whom and with what resources. A conceptual overview of the planning and control structure of the CEM is presented in Appendix C.

2.2.1. Aggregate control

The highest level of decision making with effect on goods flow control is referred to as aggregate control by Bertrand et al (1998). Within the CEM this part of the control structure is effectuated in the budget and the Manufacturing & Delivery Plan (MDP).

Annually, in September a budget is determined based on a negotiation between the heads of the manufacturing organisation and the corporate sales organisation. The corporate sales organisation has input concerning the expected sales figures, based on market information, sales targets, contracts with dealers and other relevant information. The manufacturing organisation has input concerning the availability of capacity and the status of the manufacturing operations with regard to backlogs and stock positions. From a goods flow control perspective, the budget prescribes the quantities that have to be delivered by the product creation centres for each product during the next fiscal year. From a sales and purchasing perspective, it also provides a sales and purchasing plan. The sales plan is used to set the bonus targets for the sales force and the purchasing plan provides the annual requirements based on which the purchasing professionals can negotiate prices and other contract conditions with suppliers.

The MDP is constructed quarterly based on the budget and updated information. Again this is a negotiation between the heads of the manufacturing organisation and the corporate sales organisation. It prescribes the manufacturing and delivery quantities for each product and based on the current stock levels it also states the target stock levels for the end of the period. The MDP is signed by the heads of the manufacturing organisation and the corporate sales organisation and is a formal plan regarding the planning and control of the supply chain.

The MDP can be seen as a rolling plan in which the first quarter is fixed. The fixed part of the MDP is known as the latest estimate (LE in Table 2.3). Although it is a rolling plan, the horizon is restricted by the end of the fiscal year and so this horizon is narrowed down with one quarter, each quarter.

Moment of construction	Referred to as	Horizon	Level of detail
September	Budget	Fiscal year	Year
November	LE0	Q1 – Q4	Quarter
February	LE1	Q2 – Q4	Quarter
May	LE2	Q3 – Q4	Quarter
August	LE3	Q4	Quarter

Table 2.3: Aggregate control mechanisms

2.2.2. Detailed control

Detailed control can be decomposed in capacity planning and material coordination. Within the CEM the capacity planning is known as the assembly and configuration planning, while material coordination is effectuated in the ERP system. Before detailed control is executed, the MDP is revised based on detailed forecasting information and updated stock positions. This revised MDP (rMDP) is constructed in a monthly meeting with representatives of the manufacturing organisation (logistics managers and planners) and the corporate sales organisation (controllers).

Every month an Assembly Plan (AP) is constructed that determines the planning of each assembly line on a weekly level. This AP is input to a detailed planning, based on which work orders for the assembly lines are generated. In addition, the ERP system is updated with this AP. The AP is weekly reviewed by the logistics planner to check the stock levels, actual order intake and open order status.

Every month a Sales and Operations Plan (SOP) is constructed that determines the planning of each configuration centre on a monthly level. The SOP translates the rMDP into requirements on configuration item level, based on the configuration matrix. This configuration matrix states the expected demand for configuration items in each configuration centre based on historical data. The ERP system is updated with the SOP by running a Demand Management module. This module generates part level requirements based on the BOM and the SOP. Furthermore, the SOP is input to detailed planning, which generates work orders for the configuration centres. This detailed planning is driven by the actual sales orders and is used to confirm delivery dates.

If the capacity planning deviates from the rMDP or the information in the ERP system, this can be compensated with buffer stocks on component level. In a situation that buffer stocks are insufficient, the manufacturing organisation has to pursue each supplier to accelerate lead times in order to ensure material availability. This is a time consuming task, since CEM products contain thousands of different components sourced from hundreds of different suppliers.

The ERP system is updated with planning changes by the logistics planners during the week. In the weekend the ERP system recalculates the material requirements based on the material requirements planning (MRP) algorithm. These material requirements are translated into purchasing orders and delivery schedules (DS in Figure 2.8). On Monday these are checked on inefficiencies by the MRP controllers. On Tuesday morning the purchasing orders and updated delivery schedules are sent to suppliers and contract manufacturers. Based on this delivery schedule, the contract manufacturer constructs a production planning. With this production planning the ERP system is filled and based on the MRP algorithm it calculates material requirements on part level. Based on these material requirements orders are released for second tier suppliers.

In Figure 2.8 the relations between the different elements of the planning and control structure of the CEM are presented. It has to be noted that delivery schedules have a rolling horizon of one year. Since the MDP does not have a rolling horizon, it will be insufficient to fill the delivery schedules during the year. Therefore, the logistics planner completes the expected sales figures beyond the MDP horizon based on experience and current sales trends. So Figure 2.8 is a static representation of the planning relationships at the beginning of the fiscal year.

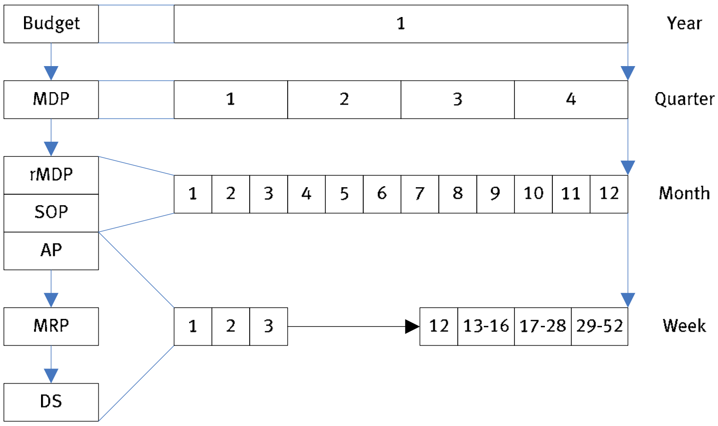


Figure 2.8: Planning relationships

2.2.3. Capacity planning vs. material coordination

In this section it is shown that material coordination is leading in the supply chain of the CEM based on a typology provided by Bertrand et al (1998). This finding is in line with those of Fransoo (2004) and more importantly, it is also endorsed by professionals within the company. Bertrand et al (1998) distinguish between three production situations based on the scope of the investments of a company. A capacity oriented company has invested in human capital, machining, space and facilities. A product oriented company has invested in product development. A process oriented company has invested in product creation process development.

The CEM is a product oriented company. Although it has invested in human capital, machining and manufacturing processes, product development is leading within the company. The human capital can easily be exchanged, as has been shown by the flexible workforce in the assembly and configuration lines. Furthermore, the machining is not leading within the CEM, since most of the machining related investments are done by specialized (second tier) suppliers. To conclude, the machining of assembly and configuration activities is relatively simple in comparison to other industries.

The product orientation is substantiated by the relatively low utilization rates of the final assembly and configuration lines of the CEM. In 2006, these figures varied between 60% and 80% on a monthly level, while the utilization rate was 75% on a yearly level. These rates exclude possible flexibilities such as overwork, introduction of extra shifts and acquiring external production capacity. Employees within the organisation claim that these flexibilities can be operational on a weekly to three-monthly notice. Furthermore, the assembly lines are in general dedicated to one product. In that perspective there are no shared resources, which simplifies capacity coordination even more.

The same line of reasoning holds for contract manufacturers. The two most important and relevant contract manufacturers have relatively low utilization rates of 70% on a yearly basis, based on current projected production output and capacity. Furthermore, the contract manufacturers experience the same flexibilities as the CEM. Overwork, introduction of extra shifts, hiring extra employees and acquiring external production capacity is relatively easy on a short notice. Furthermore, the assembly lines of the contract manufacturer are in most cases dedicated to the CEM.

With regard to capacity constraints in the second tier supply base, a distinction is made between prescribed components and non-prescribed components. Nevertheless, the following applies to both. The CEM is by nature a high-mix, low-volume manufacturer, implying that products consist of many components, but are sourced in relatively low supply volumes. As a result the commercial importance of the CEM is relatively low for individual suppliers, resulting in low priority levels. However, this also implies that the share of the CEM supply in relation to supplier capacity is relatively low; a large order from the perspective of the CEM has little impact on the capacity of a supplier. As a result, capacity restrictions in the second tier supply base have limited impact.

Nevertheless, prescribed components are in general unique and complex components with long planned lead times (see section 2.1.3). Often only one or two suppliers in the world are able to manufacture these components and it takes relatively long to find alternative supply. However, planned lead times are reliable and flexibility with regard to increasing supply chain output is relatively large following the line of reasoning in the previous paragraph.

Non-prescribed components are not specifically manufactured for the CEM. Utilization rates for these suppliers vary between 70% and 80% excluding flexibility in production capacity, e.g. introducing extra shifts and overwork. As a result, planned lead times are short (see section 2.1.3) and reliable, and flexibility with regard to increasing supply chain output is relatively large.

With regard to the second tier supply base it is concluded that capacity constraints are taken into account in the relatively long planned lead times, which are negotiated in the purchasing contracts. These planned lead times are considered reliable and include waiting time for third tier supply and high utilization rates of capacity. As a result, it is argued that capacity constraints in the second tier supply base have limited effect on the supply chain of the CEM. This leads to the conclusion that material coordination is leading in the supply chain and that capacity constraints do not have to be taken into account.

2.2.4. Forecasting system

The budget and the MDP are the leading input of the planning and control structure of the CEM, as can be seen in Figure C.3 in Appendix C. Members of the organisation expect that these plans are not functioning properly. Since material availability is dependent on the MDP, this could have a large impact on the supply chain performance. Therefore, the forecasting performance has been analysed.

Silver et al (1998) provide an overview of forecast error measures. Since the actual operations planning and control mechanisms are a derivative of the budget and the MDP, we are interested in an intuitive measure that describes the forecasting performance. Silver et al (1998) prescribe the 'Mean Absolute Percentage Error' (MAPE) in such a situation. The MAPE describes the relative deviation of the forecasted delivery quantities from the actual delivery quantities:

$$\text{(2)} \quad MAPE = \left[\frac{1}{n} \sum_{t=1}^{n} \left| \frac{x_t - \hat{x}_{t-1,t}}{x_t} \right| \right] * 100\%$$

Where:
MAPE is the mean absolute percentage error as defined in Silver et al (1998).
x_t are the actual deliveries in year t.
$x_{t-1,t}$ is the forecast at moment t-1 over period t.
n is the number of observations.

Historical data about the budget is available over a period of six years, from 2001 to 2006. The measure is planned deliveries compared to the actual deliveries. The budget deviates on average 30% from the actual deliveries with a standard deviation of 23%. So in general the budget is inaccurate and unstable.

Historical data about the MDP is available over 2006. The measure is planned deliveries compared to the actual deliveries. However, inefficiencies in the manufacturing operations are visible in the MDP, so the open order position is also taken into account. The MAPE of the MDP is relatively stable, except for LE2. However, the MDP shows a transition from underestimation to

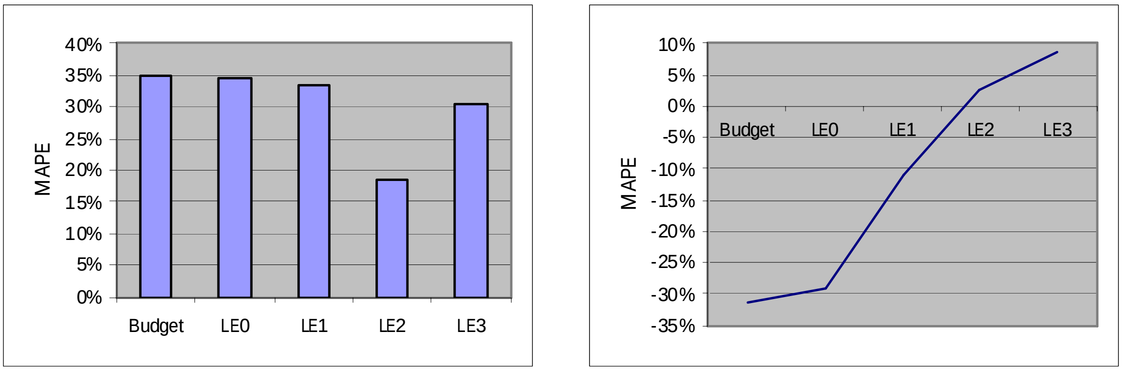
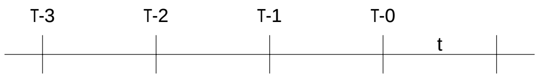


Figure 2.9: Development and direction of the MAPE of the MDP

	MAPE			
T	Average	Maximum	Minimum	Standard deviation
T-3	42%	87%	10%	21%
T-2	37%	81%	4%	19%
T-1	28%	84%	7%	19%
T-0	22%	59%	0%	18%

Table 2.4: Stability and robustness of the MAPE of the MDP

Table 2.4 shows the MAPE measure for forecast T, where T is defined as the forecast at moment T over period t:



overestimation during the year. (see Figure 2.9) Furthermore, it can be seen that the forecasting performance improves if the horizon over which the forecast is constructed is reduced. Still it is unstable. (see Table 2.4)

This analysis substantiates the belief that the forecasting system is a major source of nervousness in the supply chain. In order to determine the magnitude of this effect, it is required to quantify the current forecast error as it is perceived by the supply chain. This is complicated for two reasons. First, the supply chain faces different forecast errors for items with different cumulative lead times, while one measure for the total supply chain is preferred to be able to compare the forecast error with the raw demand uncertainty. Second, the forecast is constructed at an aggregated quarterly level, while the supply chain is controlled at a weekly level. The procedure described in Appendix D has been developed in order to circumvent these issues. The forecast error resulting from this procedure can be compared with the coefficient of variation of the expected demand. The procedure determines a forecast error of 1.49, which is much higher than the coefficient of variation of 0.3 to 0.7 as it has been determined in the demand analysis (see section 2.1.4). In conclusion, it can be stated that the forecasting system of the CEM is a source of demand uncertainty and subsequently nervousness in the supply chain, since the forecast error is a magnitude larger than the raw demand uncertainty.

2.2.5. Stock control system

The stock control systems in the supply chain of the CEM have been analysed. The stock control policy at the CODPs is based on a target stock level of two weeks of average sales orders over a month. In addition, the CODPs are controlled with an upper and lower boundary. It is argued that because the target stock levels are based on historical demand data, the stock control system is always one step behind business. For instance, if the sales figures of a certain product have an upward trend, the actual stock level –and subsequently service level– continuously lacks behind. The same applies if a product faces a declining sales trend. In conclusion, it can be stated that stock levels are either too high resulting in extra costs, or too low resulting in a poor service level performance.

The target stock levels and boundaries are based on the experience of managers and are rules of thumb rather than formal regulations. As can be seen in Figure 2.10, the stock control policy as described in the previous paragraph is violated heavily. The stock levels during the second quarter of the fiscal year are three times higher than at the end of the fiscal year (on a detailed level this can be even six times higher). As a result the CEM faces excessive stock –and related costs– during periods of high stock levels, while the service level performance is poor during periods of low stock levels.

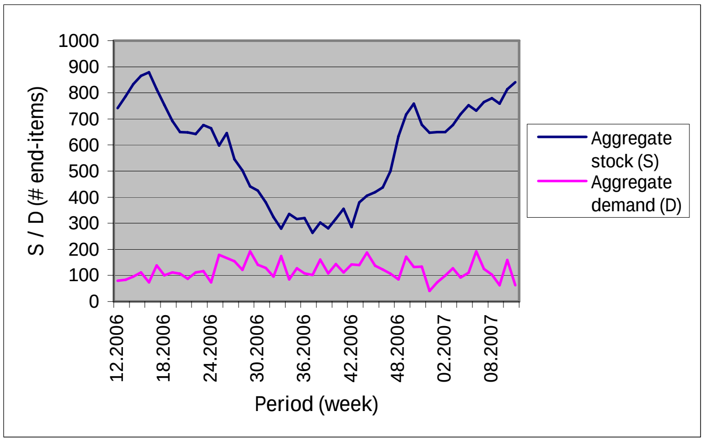


Figure 2.10: Stock vs. demand at the CODPs

In the stock distribution in the supply chain it is observed that a large part of the total stock in the CEM owned supply chain is located at the base material stock point (approximately 30% to 40% of the total capital invested by the CEM). In addition, a large share of the total stock investments in the supply chain consists of pipeline stock between the second tier suppliers and contract manufacturers. It has been shown that in the partial outsourced supply chain 5 weeks of stock and pipeline is situated at the contract manufacturer, while the pipeline towards the contract manufacturer is on average 13 weeks long. In the integral outsourced supply chain 2 weeks of stock and pipeline is situated at the contract manufacturer, while the pipeline towards the contract manufacturer is on average 18 weeks long.

2.2.6. Customer service

The CEM defines customer service as the fraction of customer demand that is met within a specified lead time without backordering. This lead time definition has three different reference points resulting in CLIP, RLIP and SLIP customer service measures; in the CLIP definition this reference point is the lead time confirmed by the manufacturing organisation, in the RLIP definition this is the lead time requested by the LSO and in the SLIP definition this is the standard LSO lead time. This standard LSO lead time specifies the standard number of working days between the moment of ordering a certain configuration and the moment that the configuration leaves the configuration centre. Because of these different definitions, each measure has its own specific dynamics. Nevertheless, the target for all measures is 95%.

The CLIP represents the accuracy of the confirmed delivery date provided by the manufacturing organisation. This service measure is therefore discounted with the flexibilities that exist in the supply chain under the assumption that the manufacturing organisation confirms 'as good as possible'. For instance, workload balance, stock positions and –to some extent– material availability are discounted in the confirmation lead time.

The RLIP represents the customer service requested by the LSO; this is the actual service level that the customer (the LSO is an internal customer) perceives. However, the requested delivery dates can be unrealistic from a supply chain perspective, since it is defined independent of the supply chain characteristics. On the other hand, the definition of the RLIP provides some flexibility that should be incorporated in the customer service measures. Namely, the requested lead time can be longer than the standard LSO lead time, which creates flexibility in the supply chain.

SLIP represents the customer service based on the standard LSO lead time that is agreed on by the manufacturing organisation and the corporate sales organisation (representing the LSOs). This lead time definition is static and thus flexibility exists in achieving this lead time. Namely, the processing time of the configuration process is a few hours to a few days, while the standard LSO lead time is one to four weeks. On the other hand, the standard LSO lead time is sometimes narrowly defined in relation to the utilization rates of the configuration centre. As a result, the longer waiting times result in a decreasing performance.

To conclude, the CLIP is an upper bound to the customer service perceived by the LSO since it incorporates flexibilities, while the SLIP is a lower bound since it ignores these flexibilities. The flexibilities are visualized in Figure 2.11, which represents different combinations of requested delivery dates by the LSO and provided delivery dates by the manufacturing organisation (MO in Figure 2.11). In the case of a match between the requested and the confirmed delivery date the service performance is high. If the LSO requests a delivery date later than the confirmation of the manufacturing organisation, then flexibility exists (F). If the LSO requests a delivery date earlier than what the manufacturing organisation can provide, then the service performance is low. In the case of a requested delivery date earlier than the standard LSO lead time, this affects the RLIP only. In the other cases, the SLIP is affected as well. It should be investigated what situations occur in the supply chain of the CEM in order to be able to determine the correct service levels. However, this is an outbound supply chain related issue and thus out of the scope of this project.

		LSO requests		
		earlier	standard	later
MO	earlier	-	F	F
	standard	RLIP	-	F
	later	SLIP	SLIP	-

Figure 2.11: Matches of requested and confirmed lead times

The customer service performance has been analysed in detail. The service levels are measured and reported by the ERP system, though the measurements are biased. Yet these service levels can be used in order to get a rough indication of the service performance over the period analogous to that of the other analyses. (see Table 2.5) The data indicates that the confirmed delivery date is quite accurate, though the CLIP is lower than the 95% target. The requested delivery date is achieved for less than 50% of the orders. With regard to the accuracy of the confirmed delivery date and the performance based on the requested delivery date, it has to be taken into account that the system only awards service to an exact match between the actual delivery date and the service level definition. This will probably improve the performance. To conclude, the performance based on the standard LSO lead time is quite poor with a SLIP of 77% and 63%. This could be explained by optimistic standard LSO lead times, high capacity utilization of the configuration lines and poor stock management and subsequently low material availability. In relation to the discussion about capacity planning versus material coordination and the analysis of the stock control system of the CEM, it can be stated that the poor customer service performance stems from low material availability caused by poor stock management.

	Man. unit	
	A	B
CLIP	93%	89%
RLIP	49%	34%
SLIP	77%	63%

Table 2.5: Service level performance

2.3. Responsibilities in the supply chain

In this section an overview is provided of the supply chain related responsibilities in the CEM organisation. The responsibilities of the contract manufacturers and the second tier suppliers have been discussed in section 2.1.3.

First, the LSOs are responsible for sales, distribution and service activities. The CEM has ownership over the LSOs, although they are managed as independent organisations. Second, the corporate sales organisations are responsible for worldwide sales and marketing and represent the LSOs in negotiations about the budget and the MDP. Third, the product creation centre is responsible for the product creation activities of the CEM. Products are ordered at the product creation centres by individual LSOs, which can be seen as internal customers.

The product creation centre is organised in a board, research and development (R&D) organisation and manufacturing organisation. The board supports R&D and manufacturing with staff departments such as human resource management and controlling. R&D is responsible for product development until the industrialisation phase. Manufacturing is responsible for manufacturing and delivery operations from the industrialisation phase onwards.

Within the CEM several cross functional teams exist in order to stimulate cooperation among organisational units. Commodity teams are responsible for developing a commodity strategy in which technology, product and sourcing roadmaps are defined. A commodity team consists of purchasing, R&D and quality representatives. Furthermore, logistics managers meet monthly in order to align business processes across the logistics organisational units.

2.4. Information systems

To support operational processes, four key information systems exist. First, SAP R/3 is the ERP system, which is used for planning and registration of operational processes and reporting of performance measures. Second, PDMS is the product data management system, which is used to manage product data such as product specifications. QMS is the quality management system, which describes and defines quality procedures. To conclude, Microsoft (MS) Office supports the above mentioned information systems in planning, reporting and monitoring operational processes.

MS Office is an important source of data for several analyses that have been conducted during this project. First, the plans that have been described in section 2.2 are all MS Excel based except for the MRP run and the delivery schedules (which are executed and reported in the ERP system). Second, the data in the ERP system is extracted monthly and stored in MS Access databases. Third, specific reports with goods flow related figures are constructed in MS Excel on a monthly and weekly level. These reports specify stock, sales order and production output levels for each product. Fourth, the BOM of a product is extracted from the ERP system into MS Excel spreadsheets. To conclude, MS Word is used to report on procedures and decisions, which are communicated in presentations that have been constructed in MS PowerPoint.

2.5. Supply chain performance

The classification framework of Bertrand et al (1998) is used to structure the synthesis of the results of the supply chain analysis. Bertrand et al (1998) suggest an evaluation of the supply chain based on the dimensions complexity, uncertainty and flexibility.

2.5.1. Complexity

Sivadasan et al (2006) define complexity in a supply chain context based on a distinction between structural and operational complexity. Structural complexity is associated with the static variety characteristics of a system as that linked to the design dimensions of the system. This class of complexity measures the complexity of the structure of the supply chain. Operational complexity is associated with the uncertainty and dynamics of the system. This class of complexity refers to the unpredictability of the supply chain. The latter one is discussed in the next section according to the classification framework of Bertrand et al (1998).

Sivadasan et al (2006) provide the following list of complexity measures, which correspond to the complexity definitions in a supply chain context provided by Choi and Hong (2002) and Choi and Krause (2006):

- number of elements or subsystems
- degree of order within the structure of elements or subsystems
- degree of interaction between the elements, subsystems and the environment
- level of variety, in terms of the different types of elements, subsystems and interactions

Complexity in the CEM supply chain is high. It has been shown that the CEM deals with a small number of products (36) that are supplied with three different conceptual supply chain structures (integral outsourced, partial outsourced and OEM). However, a typical CEM product consists of many components (in the range of thousands), sourced from many suppliers (more than 50) in many different regions around the world (more than 20 countries). Furthermore, it has been shown that cumulative lead times in the supply chain are long (30 to 50 weeks). Such a system is difficult to control.

In addition, the supply chain consists of many actors with different responsibilities; product creation centres, corporate sales organisations, LSOs, contract manufacturers, other suppliers, second tier suppliers. These different actors have to cooperate closely together on strategic, tactical and operational levels. Furthermore, cooperation is required over different functions such as product development, purchasing, supply chain planning and goods flow control. Within the CEM the different organisational units (logistics, purchasing, quality, R&D and sales) must align their business processes as well in order to synergize different knowledge areas. While cooperation is complex by nature, each different actor and organisational unit has its specific interests and needs, and pursues its own objectives. As a result, sub-optimization is unavoidable.

To conclude, the high-tech nature of the CEM products requires suppliers to have specific knowledge based on which they are able to supply components with specific characteristics. This requires specific knowledge from both the CEM and the supplier and intensified cooperation during the product development phase and the daily operation of the supply chain. These suppliers are located in many countries with different cultures, which complicates communication and cooperation even more.

In conclusion, the CEM deals with a particularly complex supply chain.

2.5.2. Uncertainty

Bertrand et al (1998) distinguish between demand and supply side uncertainty.

Demand uncertainty is controllable. At a detailed level, demand is stationary and the unpredictability is controllable for products in the maturity phase of the product life cycle. For products in the introduction, growth or decline phase of the product life cycle it has been observed that uncertainty is relatively high. Therefore, it can be concluded that during these phases a different planning and control approach is required.

The current planning and control structure creates nervousness in the supply chain, even though demand uncertainty is controllable. In the planning and control structure it can be seen that the forecasting system is the major determinant of supply chain operations planning. Since this forecasting system is performing poorly on accuracy and stability, it causes nervousness and thus uncertainty in the supply chain. An explanation of this poor performance is that the forecast is based on negotiation between organisational units with individual performance targets, rather than on joint analysis. Furthermore, the forecasting system lacks performance feedback. This prevents the system from improving.

In addition to the structural underperformance of the forecasting system, a mismatch exists between the horizon of the delivery schedules and the forecasting system. Suppliers are weekly informed about forecasts with delivery schedules with a horizon of one year, while the horizon of the forecasting system is limited to the fiscal year. As a result, the long term forecasting information received by suppliers is not based on the formal structure of the forecasting system.

Since suppliers are controlled with unreliable information, repairing operations are required to ensure material availability or to prevent high stock levels and risk of obsolescence in the supply chain. As a result it is difficult for suppliers to structurally improve their supply chain operations. Furthermore, the repairing operations are time and resource consuming. It is expected that nervousness in the supply chain of the CEM is a cause of excessive stock, long lead times, unnecessarily high commitments, inflexibility and inefficiency.

Supply side uncertainty is considered to be low. Capacity constraints are not a consideration because manufacturing operations at the CEM, contract manufacturers and second tier suppliers of non-prescribed components are dedicated and utilization rates are low. In addition, capacity constraints at the second tier suppliers of prescribed components are accounted for in the relatively long planned lead times. Planned lead times are considered to be reliable, just as quality performance.

In conclusion, demand side uncertainty is high, while supply side uncertainty is considered to be low.

2.5.3. Flexibility

Bertrand (2003) states that supply chain flexibility is a lever to react on demand uncertainty and that an imbalance between the two will result in poor supply chain performance. Flexibility can be decomposed into scope and time aspects according to Bertrand et al (1998). The scope determines the magnitude of the flexibility, while time determines the horizon within which the flexibility can be arranged. Flexibility with regard to the scope aspect has to be considered in two directions; flexibility to increase and flexibility to decrease the supply chain output in reaction to demand changes. A lack of flexibility leads to lost sales in the case of increasing demand or to writing off excess stock in the case of decreasing demand.

Flexibility with regard to the time aspect is low in the CEM supply chain. It has been shown that the actual reaction time to demand changes (defined as the cumulative lead time of a product) is 30 to 50 weeks, while the requested reaction time by the internal customer is 1 to 3 weeks. As a result the CEM is dependent on forecasts to meet customer demand. However, it has been shown that the forecasting system is performing poorly. As a result, demand changes are common and thus the flexibility required to operate the supply chain is large. On the other hand, the flexibility available to react to these changes is low, since the cumulative lead time of the inbound supply chain is much longer than the standard LSO lead time.

Flexibility to decrease the supply chain output is low, while the flexibility to increase the supply chain is high. To deal with long cumulative lead times in the inbound supply chain, the CEM provides commitments to suppliers and contract manufacturers. Based on these commitments, suppliers are able to anticipate future demand by sourcing goods in advance of actual orders. The CEM guarantees to cover the risk of obsolescence. As a result, the CEM has limited flexibility to decrease the supply chain output. This is amplified by the large MOQs in the supply base of the CEM. Flexibility to increase the supply chain output is high because of the relatively low supply volumes of the CEM and the relatively low utilization rates in the supply chain. As a result, a large order from the perspective of the CEM has little impact on capacity of a supplier. Note that the time aspect of increasing supply chain output has been mentioned as a bottleneck.

An important instrument to create flexibility in the supply chain is the use of buffer stocks. However, it has been shown that the stock control system of the CEM does not function properly. First, the target stock levels are based on experience, rather than fact based analysis. Second, the stock control system sets target stock levels based on historical demand information instead of future demand expectations. Third, these target stock levels are violated heavily and as a result the stock investments of the CEM are out of control. The results are excessive stock investments and a poor customer service performance. It has been shown that this customer service performance is structurally lower than the targets that have been established in cooperation with the internal customers. So it can be concluded that the stock control system does not provide the required flexibility to operate the supply chain efficiently.

In c0nclusion, the reaction time of the supply chain is long, while the flexibility to decrease the supply chain output is low and the flexibility to increase the supply chain output is high.

2.6. Conclusions

The supply chain structure of the CEM can be distinguished in an integral outsourced and partial outsourced supply chain. For each supply chain the BOM and BOP have been defined and relevant supply chain parameters have been determined. In addition, the planning and control structure has been charted and the performance of crucial elements has been analysed. To conclude, the responsibilities in the supply chain and key information systems have been described.

Based on a supply chain characterization it has been shown that the CEM operates a complex supply chain with low flexibility with regard to gearing down and accelerating the supply chain. Although demand uncertainty is controllable, the supply chain faces nervousness caused by a poor performing forecasting system. In combination with a large difference between the requested and the actual reaction time to demand changes, this leads to an imbalance between flexibility and uncertainty. An important lever in creating flexibility is using buffer stocks. However, the current stock control system of the CEM is not functioning properly and as a result the stock investments of the CEM are out of control, while the customer service performance is structurally lower than has been agreed on with the internal customers of the CEM.

These findings substantiate the belief of the CEM that the current supply chain strategy and corresponding planning and control models are inappropriate for operating the supply chain. They will ground the formulation of the final research assignment, which is presented in the next chapter.

CHAPTER 3, PROJECT DEFINITION

In the previous chapter the supply chain has been described and its performance has been analysed. Based on these findings, the final research assignment is defined in this chapter. First, the research areas are extracted. Second, the research scope of this project is defined. To conclude, the research approach of the design phase is presented.

3.1. Research areas

From the previous chapter it can be concluded that research areas exist with regard to complexity, uncertainty and flexibility. First, it can be investigated whether it is possible to reduce complexity by improving complexity related factors, e.g. reducing the number of components and suppliers. Second, it can be investigated whether it is possible to reduce uncertainty, e.g. by improving the performance of the forecasting system. To conclude, it can be investigated whether flexibility can be increased by improving the actual reaction time of the inbound supply chain (cumulative lead time), considering flexibility in the requested reaction time in the outbound supply chain (standard LSO lead time) and again, by improving the forecasting system. (see Figure 3.1)

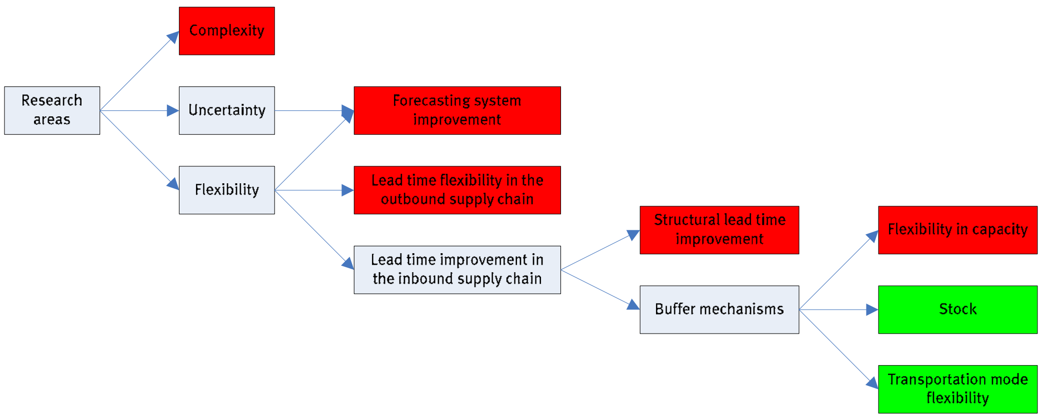


Figure 3.1: Decomposition of the research areas

The complexity and uncertainty related research areas are out of the scope of this project. First, complexity deals with the structure of the supply chain. In the initial scope it has been explicitly stated that this project concerns the planning and control structure. Second, the forecasting system is a responsibility of the senior management; this project is not situated in that part of the organisation.

With regard to the flexibility research area, the forecasting system and the outbound supply chain are out of the scope of this project. The forecasting system has already been discussed, while the outbound supply chain has been excluded in the initial scope of the project. To conclude, this project focuses on the improvement of the cumulative lead time in the inbound supply chain. This can be done by structurally shortening lead times and by using buffer mechanisms. The available buffer mechanisms are flexibility in capacity, buffer stocks and transportation mode flexibility.

Lead times can be structurally shortened with lead time reduction programs. Purchasing professionals claim that the planned lead time (or commercial lead time) is relatively long due to the fact that the commercial importance of the CEM is relatively low for a supplier. This is effectuated in unnecessary long waiting times. (see Figure 3.2) Nevertheless, the potential reduction of a lead time reduction program has a limited extent. Namely, the processing time and part of the waiting time is determined by the decision to use a certain component with certain characteristics manufactured in a production system with certain dynamics and sourced from a certain supplier on a certain location. This is a degree of freedom during product development and commodity strategy determination, but not during a lead time reduction program. Therefore, it is important to consider flexibility and other supply chain related issues during these processes. This can only be effectuated outside the borders of the CEM if the performance evaluation of the purchasing organisation is based on a broader set of indicators than only direct costs. Nevertheless, this supply chain structure related issue is out of the scope of this project.

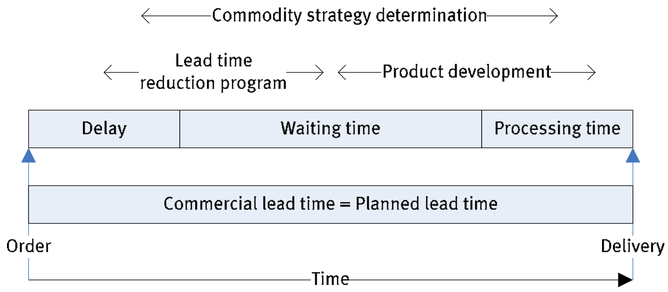


Figure 3.2: Scope of lead time reduction instruments

Flexibility in capacity is exploited in the current situation, since the production capacity of the CEM and contract manufacturers is dedicated. As a result manufacturing lead times are short. Flexibility in capacity in the second tier supply base is not considered, since the influence of the CEM is limited caused by the relatively low purchasing volumes of the CEM. In conclusion, flexibility in capacity is out of the scope of this project.

Stock buffer mechanisms have been adopted as well. However, it has been shown that the stock control system in the CEM owned supply chain is performing poorly and subsequently fails to create the required flexibility. The CEM has no notion of the impact of this misalignment on the supply chain performance. The application of buffer stock mechanisms in the commitment covered supply chain is more complicated, since it is an inter-company issue. Namely, the CEM is dependent on contract manufacturers for the supply of components in this part of the supply chain. Nevertheless, in the current contracting structure the CEM is able to force them to hold buffer stocks. In addition, the CEM has visibility over their supply chain processes and parameters. This enables planning and control of stock from a supply chain perspective. Despite this fact, such a planning and control system is not available at the moment. Even more important is that the CEM has no insight into the impact of installing stock buffers in the supply chain on supply chain performance.

To conclude, the CEM has the possibility to choose several modes of transportation in the inbound supply chain. This could increase flexibility in a situation of increased demand levels. However, fact based decision models for choosing transportation modes are not available. So the CEM has no quantitative insight into the relation between this flexibility lever and supply chain performance.

3.2. Research scope

From the previous section it is concluded that the CEM has no (quantitative) insight into the relation between the levers of flexibility and supply chain performance. As a result, the CEM is unable to leverage supply chain performance. Therefore, the objective of the research assignment is to develop an evaluation model that provides insight into the drivers of supply chain performance and their interrelations. This results in the following research assignment:

"Develop an integrated supply chain performance evaluation model
to enable the CEM to better leverage inbound supply chain performance."

On a general level, the input of the model is the set of supply chain characteristics and parameter settings, while the output is the supply chain performance. Through analyzing the output of several scenarios, the model provides insight into the behaviour of the supply chain under different supply chain strategies. These results are used to substantiate supply chain strategy and to focus on supply chain performance improvement initiatives that drive supply chain performance. For instance, purchasing professionals are enabled to leverage the different elements of the purchasing contract during contract negotiations and supplier development processes, while the senior management gains insight into the impact of a poor functioning forecasting system.

In Figure 3.3 the design model is described on a conceptual level. The supply chain performance indicators are a derivative of the performance model of the CEM (see section 2.1.3). The relevant performance aspects for this project are logistics and costs, translated into customer service and supply chain costs. The model evaluates the supply chain performance through the use of the two buffer mechanisms that have been defined in the previous chapter; planning and controlling buffer stocks from a supply chain perspective and using transportation mode flexibility. This is effectuated by applying a certain set of supply chain parameters. These supply chain parameters are the actual tuners of the supply chain operations.

The design model makes a trade-off between customer service and supply chain costs. These supply chain costs are directly related to the stock invested in the supply chain and the costs of the transportation mode. In order to circumvent a discussion about interest rates and holding costs, the costs of holding stock will be represented as the total capital invested in stocks and pipelines.

With scenario analysis the required insight is gained into the relations between the set of supply chain parameters and the supply chain performance indicators. The following scenarios have been established in close cooperation with the senior management:

- trade-off between stock investments and customer service
- improvement of the forecasting system
- improvement of lead times in the supply chain
- introduction of transportation mode flexibility
- improvement of MOQ in the second tier supply base
- evaluation of the effect of different supplier control policies

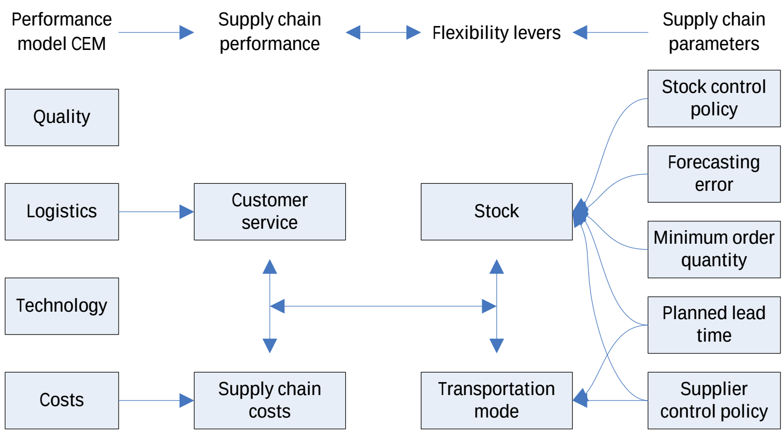


Figure 3.3: Design model

3.2.1. Demarcation of the research scope

The model focuses on material coordination in the partial and integral outsourced supply chains of the CEM from second tier suppliers until the CODP. The evaluative character of the model justifies a position within the tactical planning or medium term planning part of the planning and control structure of the CEM. This corresponds to the position between the MDP (aggregate control) and rMDP (detailed control) in Figure C.3 in Appendix C. It has to be noted that an evaluation model is developed and not a decision model.

The Nero supply chain has been selected as object of research. The Nero is a product with a combined integral and partial outsourced supply chain. As a result it incorporates subsystems with final assembly operations at both the CEM and contract manufacturers. In addition, the project is focused on supply chain operations during the maturity phase of the product life cycle. Product introduction and phase out processes are explicitly kept out of the scope, since it has been shown that these supply chains need a different approach anyway. Since the Nero is in the growth phase of the product life cycle, assumptions will be made that enable the application of the model without loss of generality.

The detailed and aggregate control parts of the planning and control structure are considered given. So, capacity planning at the CEM, the contract manufacturer and second tier suppliers is not a degree of freedom. In addition, supply side uncertainty will not be considered, resulting in the assumption that planned lead times and component quality are reliable.

3.3. Research approach

During the design phase the design model is effectuated, resulting in a supply chain performance evaluation (SCPE) model. To the best of our knowledge, the synchronised base stock (SBS) policy as described in De Kok and Fransoo (2003) is the only quantitative model available in literature that enables the evaluation of general assembly networks dealing with demand uncertainty. The policy has been tested extensively and outperforms existing quantitative models such as mathematical programming and pure base stock policies. Not only does it provide closer to optimal results, it also requires a fraction of the computational capacity of these models. Therefore, the SCPE model is based on the SBS policy.

The SCPE model development process has been tackled as follows. First, the different aspects and assumptions of the SBS policy have been defined in order to assess the applicability to the CEM situation. Second, a software tool has been developed in order to automate data processing. Third, the actual CEM supply chain has been translated into a supply network structure that can be modelled in the SBS policy. Since this results in extremely large models, an aggregation procedure has been developed in order to reduce the required computational capacity. The supply network structure has been defined, based on which the parameter settings have been determined. This exhaustively defines the SCPE model in the base case. This base case represents the actual situation at the CEM under SBS control. The base case has been tested extensively in order to determine the quality of the model and to assess the generality of the results and conclusions.

This validated SCPE model has been used to execute a scenario analysis. First, a parameter set has been defined for each scenario that has been established in the previous section. For instance, in the case of lead time reduction a set of lead times has been determined that could be applicable after the completion of a lead time reduction program with contract manufacturers. These scenarios have been calculated with the SCPE model, resulting in an enormous amount of data. The data is reported in a systematic way by the software tool. First, the supply chain investments are discussed, since the supply chain is modelled from a central objective function. Second, the ownership of these investments is assessed; the question of who has to pay for a certain scenario is answered. Third, a detailed analysis of the distribution of stock in the supply chain is discussed. To conclude, the development of stock levels at the CODP is examined. These reports provide the required insight into the functioning of the supply chain.

3.4. Conclusions

Research areas have been defined with regard to complexity, uncertainty and flexibility in the supply chain. Based on a decomposition of these research areas it has been decided to focus on buffer mechanisms that create supply chain flexibility. The CEM lacks quantitative insight into the relation between these buffer mechanisms and the supply chain performance. Therefore, a quantitative supply chain performance evaluation model is developed during the design phase of this project. The model enables the analysis of a broad range of scenarios in order to substantiate supply chain strategy and to focus on supply chain performance improvement initiatives that drive supply chain performance. The model is based on the SBS policy as it is described in De Kok and Fransoo (2003). The definitions of the model are provided in the next chapter.

CHAPTER 4, SUPPLY CHAIN PERFORMANCE EVALUATION MODEL

In the previous chapter the design model has been presented. This chapter effectuates this design model by defining the SCPE model. First, an overview is provided of the SBS policy in the context of the supply chain operations planning function. Second, the supply network structure is defined based on the actual supply chain structure. Third, an aggregation procedure is presented that has been developed for reasons of computational capacity. Fourth, the supply network parameters are determined. To conclude, the SCPE model is assessed on its validity.

4.1. Synchronised base stock policy

De Kok and Fransoo (2003) position the SBS policy within the Supply Chain Operations Planning (SCOP) function. The objective of SCOP is to coordinate the release of materials and resources in the supply network under consideration such that customer service constraints are met at minimal cost. In the SCPE model, this coordination mechanism is the so-called SBS policy. The SBS policy has been implemented at NXP and is operational since 2002 (De Kok et al, 2005). For an extensive overview of the SBS policy in the context of SCOP we refer to De Kok and Fransoo (2003).

The crux of the SBS policy lies within a smart decomposition of the supply network based on lead times. The structure of the supply network and lead time of items in the supply network determine the sequence in which orders are released for items upstream in the supply chain. Based on this sequence, a decision structure can be decomposed resulting in a divergent network. This divergent network enables the formulation of analytical expressions in the form of newsboy equations. With these expressions the SBS policy is able to synchronise order releases of items in the supply network. The decomposition procedure is described in detail in De Kok and Visschers (1999), while the analytical expressions of the newsboy equations are derived in Diks and De Kok (1998).

In the context of virtual integrating supply chains and an increasing number of organisational units involved in the SCOP function, De Kok and Fransoo (2003) assume a centralized objective function. Furthermore, they assume that information is shared across the supply chain and that each of the echelons in the supply chain accepts responsibility for maintaining a certain lead time. A centralized objective function does not violate the actual constraints in the CEM supply chain, since the responsibilities of the CEM and the contract manufacturers are intertwined in the current contracting structure with delivery schedules as a control policy (see section 5.7 for an analysis of the interwoven responsibilities of the CEM and the contract manufacturer). At the CEM this contracting structure also arranges information sharing in the supply chain, effectuated by delivery schedules communicating future demand forecasts. Furthermore, it is a basic and valid assumption in the operation of the supply chain that suppliers comply with the agreements on the parameter settings in the purchasing contract.

The supply chain is modelled as a network with activities transforming inputs into outputs using available resources. A transformation activity is a general designation of any type of relationship between two items in a supply chain, and both refers to physical transformation activities such as assembly activities and to non-physical transformation activities such as transportation of an item from one location to another. The supply network structure is represented by parent-child relationships between items, where item is the generic term for any input into and any output from transformation activities. This definition of the supply chain as part of the supply network resembles the definition as it has been presented in sections 2.1.1 and 2.1.2.

The supply network definition is effectuated by the BOM and the BOP and consists of a structure and a parameter set. The supply network structure defines the goods flows in the supply chain and their interconnections in the supply network. The supply network parameters define the specific conditions under which these goods flows are or can be operated.

First, the supply network structure is defined. The BOM structure is described by the matrix a_{ij}, where a is the number of items i required to produce one item j. The set of end-items E represents items that are not used in any other item. These items face independent demand, or external customer demand, and are stocked at the CODP. The set of intermediate items I represents items that are required for at least one other item. These intermediate items face dependent demand, which is generated from the (in)dependent demand of their successors. To conclude, the set of successors V and the set of predecessors W of an item are defined. The BOP structure is described by the set of resources and the items that are processed on these resources. The resource k processes items from the set V into an item using available capacity. The SBS policy assumes a non-capacitated supply network, which means that capacity restrictions of resources are not considered. Furthermore, it assumes that a resource can only execute one transformation process at a time. Both assumptions are valid in the CEM supply chain as has been shown in section 2.2.3.

Second, the supply network parameters are defined by subdividing them into input parameters that are external and internal to the supply network. The external parameters are the demand characteristics and the required service levels for the end-items. This independent demand is assumed to be stationary. It has a random distribution that is defined by the expected independent demand and the standard deviation of the expected independent demand. The service levels are defined in accordance with those of Silver et al (1998) in Table 4.1. P_1 represents the frequency of a stock out in a replenishment cycle. P_2 represents the magnitude of these stock outs with regard to the number of order lines that suffers from a stock out. P_3 represents the duration of a stock out.

P_i	Service level	Definition
P_1	Cycle service level	Fraction of replenishment cycles in which the on hand stock does not drop to zero.
P_2	Fill rate	Fraction of customer demand that is met routinely, without backordering or lost sales
P_3	Ready rate	Fraction of time during which the net stock is positive.

Table 4.1: Service level definitions (Silver et al, 1998)

The newsboy equations in the SBS policy are based on the P_3 service level, though a recalculation procedure enables the application of other definitions as well. P_1 is assumed to be equal to P_3. In the case of applying the P_2 service level, the SBS policy is calculated with P_3 equal to the P_2 parameter setting. After having finished the calculations, the model recalculates the obtained service levels into a P_2 service level. The empirical behaviour of these procedures is relatively smooth.

The internal supply network parameters are the lead time, added value and review period of the different processes. First, the lead time is defined as the throughput time between the moment of releasing an order for item i and the moment at which the ordered items are available for usage in other items and/or delivery to customers of the supply network. Note that this definition is different from the commonly used term lead time, which defines the amount of time that is required for processing a certain item from the set W on resource k. De Kok and Fransoo (2003) argue that the lead time is exogenous to the SCOP function, while it is assumed to be deterministic. Section 2.2.3 contains an extensive discussion on this topic in the context of the CEM supply chain. Second, the added value is defined as the value that a process adds on top of the aggregated values of the predecessors of an item. (see Table 4.2 for an overview of definitions and terminology in relation to the value structure) This added value originates from the costing structure of the process and the commercial value that is created by assembling the children into their parent. Third, the review period is defined as the period of time between subsequent release decisions in the system. This parameter originates from the fact that the SBS policy belongs to the class of periodic review systems. This review period can be different for each item in the supply network. In the CEM supply chain the review period is determined by the MOQ of an item, since this parameter implicitly determines how often an item can be ordered. To conclude, the BOM quantity ‘a’ is defined as an internal supply network parameter, though the matrix structure of a_{ij} defines the supply network structure (as well as the BOM structure).

Concept	Symbol	Definition
Supply value	sv	The aggregated values of the items required to manufacture one item i.
Added value	v	The value that is added to an item during the transformation process that creates the item.
Value	h	The value of an item (sv+v).

Table 4.2: Value structure definitions

4.1.1. Software tool

The SBS policy is implemented in the software tool 'SCOPE', which is available at the Eindhoven University of Technology (De Kok, 2007). SCOPE is proprietary software that has been put at the disposal of this project. The tool is used to build the SCPE model as described in the introduction and to calculate the scenarios as established in the previous section. SCOPE is designed on an MS Windows platform enabling the use of the software on standard personal computers. The tool consists of an input interface, a computing centre and an output interface. In the input interface the supply network structure and supply network parameters are entered. In addition, the program has a cockpit in which the general computational settings of the SBS policy are set.

In the computing centre of SCOPE, the SBS policy calculations are executed in an analysis and simulation section. In the analysis section the results are calculated analytically assuming SBS control. This way the user is enabled to evaluate a given set of decisions or to optimize decisions given a set of supply network parameters. In the simulation section the decisions (whether based on the evaluation or optimization mode) are simulated by discrete event simulation. The simulation period is set at 50,000, which is known to be large enough to reach the steady state of the system.

In the output interface the calculation results are presented in a semicolon delimited file, which enables the user to edit the data in a spreadsheet or database. The output consists of auxiliary variables that have been used in the calculations, decision variables that have been set by the SBS policy and output variables that are determined by the decisions made by the SBS policy. The auxiliary variables are the expected dependent demand, the standard deviation of the expected dependent demand, value, recalculated review period and average batch size for each item. The decision variables are the P_1 service level and order-up-to-level for each item. The output variables are the average stock level, P_2 service level and backlog for each item. In the evaluation mode SCOPE also calculates dead and remnant stock.

Since the SCPE model deals with a large number of items, a data processing tool has been developed in order to automate the processing and presentation of data. This prevents the outcomes of the model being biased by human error. Furthermore, it enables quick and structured reporting of the scenario analysis. The tool is referred to as the data engine, and has been developed in MS Office, using MS Excel and MS Access. It is described in Appendix E.

4.2. Supply network structure

In this section the actual supply chain structure of the Nero is discussed, based on which the supply network structure of the SCPE model is defined.

4.2.1. Supply chain structure

An important aspect of the supply chain of the CEM is commonality between items in different products. Commonality exists in the supply bases of the common product body and contract manufacturers, and at the CODP.

The common product body supply base has common parts with other CEM products. The stock of these parts is controlled and physically located at the same location. Therefore, commonality should be taken into account. Nevertheless, this would increase the modelling complexity disproportional and as a result, it has been decided not to incorporate it in the model. Besides, this project focuses on the supply bases of the contract manufacturers as has been mentioned in the introduction. Therefore, it is argued that this does not affect the applicability of the model, though in the operational planning and control structure it has to be taken into account. Namely, by not incorporating this commonality, pooling effects are neglected. As a result, the total average stock level as calculated by the model compared to reality is smaller, since demand rates for individual parts are higher. On the other hand, the fraction of the stock allocated to the Nero is larger, since synergetic effects in safety stock settings are not taken into account.

Commonality in the supply base of the unit contract manufacturer originates from the fact that it also manufactures a module for another CEM product. There is little to no commonality between these items except for some cheap, standard parts. The parts in the units do have some commonality with those in other Nero modules and CEM products. However, the contract manufacturer operates its own physical manufacturing location and therefore these parts cannot be pooled. As a result, only commonality between parts within the contract manufacturer supply base is taken into account.

Commonality in the supply base of the module contract manufacturer is more relevant, since it manufactures several modules for the CEM. The Nero modules are unique, though similar modules in the Caligula configuration are also manufactured by this contract manufacturer. Module A and module B match with module AB of the Caligula for approximately 50% of the parts, while module C of the Nero matches with module C of the Caligula for 98% of the parts. Commonality with parts in other items manufactured by this contract manufacturer is negligible.

The high level of commonality between module C of the Nero and module C of the Caligula indicates that pooling effects on the module level are feasible. Nevertheless, the nature of the product specific parts is such that it prevents pooling, as well as postponement. Namely, these parts are crucial in the assembly operations of the module. In an emergency situation, the allocation decision can at most be postponed until the start of the manufacturing operations at the contract manufacturer. This is approximately in the fourth week of the lead time of twelve weeks and as a result the effect of postponement is limited even in an emergency situation. In conclusion, the modules C are considered to be unique from a supply chain perspective, while they are equal from a supply base perspective.

At the CODP of the Nero supply chain, commonality exists for module D and module E. Namely; these modules are also configured in other products. With regard to module D the main part of demand originates from other products, while with regard to module E the main part of demand is Nero related. Furthermore, module D is only delivered in 20% of the Nero configurations, while module E is always delivered once with a Nero configuration. As a result, module E is planned as a Nero module, while module D is planned separately from the Nero. Therefore, module D is not taken into account during this project, while module E is. An implicit assumption that follows from this decision is the 100% availability of module D for the Nero or the willingness of customers to wait for backlogging module D separately from the ordered configuration. Both assumptions are valid, since the Nero is awarded priority over the other products and module D is easily backlogged separately.

An issue in the demand model of module E is that it has two demand sources of which the Caligula demand rate is different from the demand rate for the above described Caligula modules with commonality with the Nero. The Caligula demand cannot be neglected, since it represents 50% of the total demand for module E. Furthermore, it has to be noted that the Nero has priority regarding module E, resulting in maximum availability for the Nero. This is due to the fact that module E is easily backlogged with the Caligula, in addition to the larger commercial importance of the Nero. In conclusion, module E should not be modelled as an item in the Nero supply chain and so module E is modelled with an external independent demand source.

4.2.2. Supply network structure

The SBS policy is applicable to assemble-to-order (ATO) and make-to-stock (MTS) supply network structures. In the ATO structure, the end-item is created in a final assembly step that is initiated by customer orders. The service level is based on the delivery of the item within the lead time specified. In the MTS structure, end-items represent the CODP for which independent demand and service level are modelled. This means that each module is modelled as an end-item for which independent demand has to be determined, including dependencies between different end-items. These dependencies can be modelled with a correlation matrix specifying the statistical relation between two independent demand distributions. The differences are visualized in Figure 4.1.

Neither case represents the situation of the CEM exactly. The MTS model defines modules as end-items, while this is not true. This prevents the synchronisation of stock allocation decisions on the module level. The ATO model defines the modules as children of end-items in a static BOM. In reality, the BOM is dynamic, since several modules are optional or semi-optional. (see section 2.1.1)

Since one of the most important drivers of this project is the allocation of stock in the supply chain, it has been decided to use the ATO model. As a result, a discrepancy exists with the actual situation. Namely, the ATO model differs with regard to the dependent demand model of optional and semi-

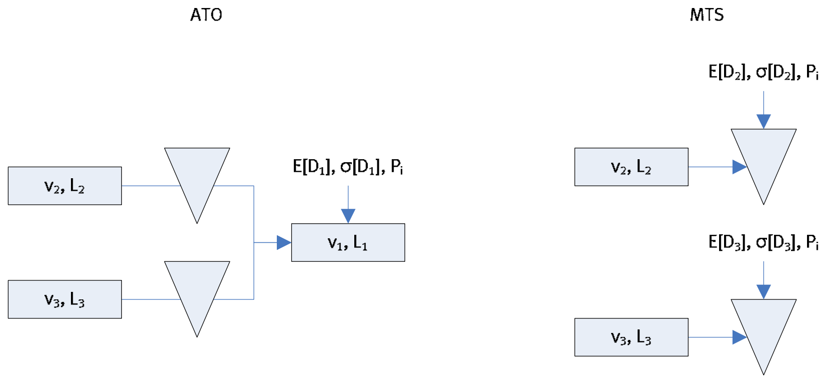


Figure 4.1: ATO vs. MTS supply network structure in the SBS policy

optional items. These modules are considered as being required in a configuration in a fixed quantity, while in reality the amount of modules per configuration differs. As a result the demand uncertainty for these items is lower in the model than in the actual situation, since uncertainty exists with regard to the required quantity per configuration in addition to the uncertainty in the amount of configurations.

It is argued that the difference between the actual supply chain and the ATO model can be neglected. Namely, in the planning and control structure the configuration items are also planned in a static quantity per configuration, based on the configuration matrix that is updated regularly. This artificial grouping of items is referred to as the planning BOM. Since the supply chain is controlled with this planning BOM, it can be assumed that the ATO model correctly represents the actual supply chain. This is under the assumption that the quantities in the BOM of the SCPE model are updated with the same frequency as the planning BOM. Furthermore, it has to be mentioned that in the operational safety stock settings of the (semi)optional modules, a surcharge should be awarded in order to cover for uncertainty in the number of modules per configuration.

Although the assumptions of the ATO supply network structure are valid in the CEM situation, the integration of optionals in the ATO supply network structure is an important area of further research in the context of supply chain operations planning. Namely, it is common in complex equipment supply chains that products have a modular structure (Salvador et al, 2002). This modular structure enables product differentiation among different customers without investing heavily in new product development. As a result, one base product results in a complete product family by swapping modules on a common product body. The common product body follows customer demand, while the modules (or options) face increased uncertainty with regard to their dependent demand. Industries where these issues will arise are the automotive, computer, and machinery and equipment industry. For instance, in the automotive industry a product family (the car model) typically has a fixed chassis (the common product body), with a broad set of engine types (the modules).

4.3. Aggregation procedure

The Nero supply chain as it proposed to be modelled consists of 2,588 individual items, while the computing centre of SCOPE is able to handle 350 items. Therefore, an aggregation procedure has been developed resulting in an aggregated model that provides the required insight into the supply chain without loss of generality. This aggregation procedure is based on the fact that the decisions made by the SBS policy are equal for items with similar BOM structures and lead times. The following description is generic for SBS controlled supply networks.

With regard to the BOM structure it can be stated that if two items have similar parents, than one item is redundant if the other is not available. After all, if not all children are available, the parent item cannot be assembled. So increasing the availability of one item without increasing the availability of its brothers and sisters (items with the same position in the BOM structure), does not increase the availability of the parent item. In conclusion, the BOM structure is one factor in the aggregation procedure. Note that the BOM structure in the SBS policy exhaustively defines the supply network structure due to the assumptions that the supply network is non-capacitated and that a resource can execute only one transformation process at a time.

A more thorough understanding of the divergent decision structure is required to understand the validity of the aggregation procedure with regard to similar lead times. The SBS policy creates a divergent decision structure in which the items with longer cumulative lead times are seen as input of items with shorter cumulative lead times. This causes the material availability of long lead time items to be the input of the material availability of the short lead time items. Another important observation is that the items with similar BOM structures and lead times face the same amount of demand uncertainty. As a result, it does not make sense to decide on different material availabilities for items with similar lead times. In conclusion, items with similar BOM structures and lead times can be aggregated without loss of generality.

When applying these rules, an interesting difference occurs between pure assembly and general assembly subsystems in the supply network. In a pure assembly subsystem an item has only one parent. As a result the coefficients of variation of demand of all children are equal. On the contrary, in a general assembly subsystem an item has multiple parents. As a result the coefficients of variation of demand of the children are different. This difference can be explained by the fact that demand uncertainty in the analytical expressions of the SBS policy is represented by the coefficient of variation of the expected demand. If demand uncertainty is enumerated, the squared standard deviation of the expected demand is used.

In conclusion, items with similar BOM structures and lead times are aggregated, while different aggregation rules are applied to pure assembly and general assembly subsystems. This results in the aggregation procedure as described in Appendix F, which has been implemented in the earlier mentioned automated data processing tool in Appendix E. This results in 154 items in the aggregated model representing 2,094 items in the supply network model.

4.4. Supply network parameters

In this section the input parameter settings are discussed.

4.4.1. Demand

The SBS policy assumes stationary demand with a random distribution represented by the parameters expected independent demand and standard deviation of the expected independent demand. An extensive demand analysis can be found in section 2.1.4, where it has been shown that the demand for products in the maturity phase of the product life cycle is stationary and fits both Gamma and Normal probability distributions. However, the Nero is a product in the growth phase of the product life cycle and thus the demand data has to be selected carefully. In Figure 4.2 it can be seen that the introduction phase ends around week 48 of 2006. After week 48 of 2006 the demand levels sink and in the subsequent period the growth phase starts. From week 50 of 2006 onwards, demand tends to have a moderate upward trend.

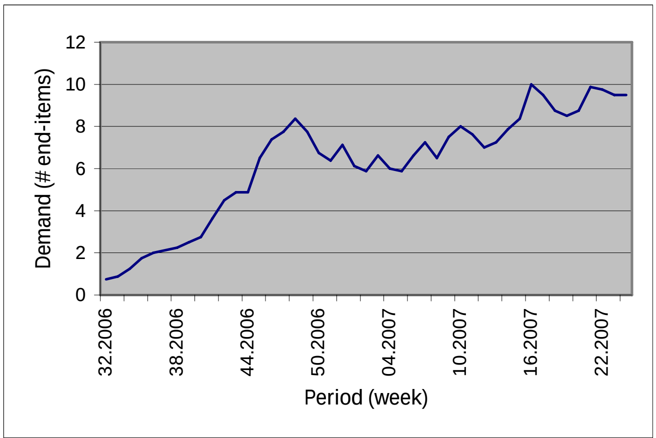


Figure 4.2: Demand of the Nero

It has been decided to use the growth phase as reference demand data set. In this phase the supply chain has stabilized to a certain extent and the main product introduction issues have been solved. This data set covers a period of 30 weeks, which is sufficient for the SCPE model in relation to the cumulative lead times in the supply chain. Analogous to the Nero data set, the demand for module E and the Caligula modules has been modelled over the same period. The three data sets fit both a Normal and Gamma distribution.

Silver et al (1998) prescribe the forecast error as input parameter of the standard deviation of the expected demand. However, this is only relevant under the assumption that the forecast error of the forecasted demand is smaller than the standard deviation of the raw demand. As has been shown in section 2.2.4, this is not the case for the CEM. Another option is to use a trend model for the Nero demand, which has been shown to be statistically significant at the 95% confidence level with a simple regression analysis. The demand uncertainty of this trend model is lower than the demand uncertainty in the raw dataset. However, setting the standard deviation based on this trend model implicitly assumes that the CEM uses such a model to forecast demand. This is not the case and therefore it is more appropriate to use the raw demand data for determining the standard deviations. Hereby we assume stationary demand, since the focus is on products in the maturity phase of the product life cycle for which this has been shown to be a valid assumption.

The assumptions of the demand model require a careful interpretation of the results of the SCPE model. A certain demand level is assumed based on the most recent demand data, although it is expected that the demand levels will increase. Higher demand levels require increased stock levels and thus have impact on the output of the SCPE model. Nevertheless, the outcomes of the scenarios develop proportional with the increasing demand levels. Namely, there is no reason whatsoever to assume that the coefficient of variation of demand will significantly change. So this assumption does not violate the objective of the project to provide insight into the relation between the different supply chain parameters and supply chain performance.

Another remark has to be made with regard to the exclusion of the outbound supply chain. During the period of consideration the Nero demand has only been satisfied from the European configuration centre due to the fact that the Nero was still in the introduction phase. In the future, the Asian and USA configuration centres will be used to satisfy demand in their own specific demand region. First, this results in two extra demand penetration points. Second, modules sourced from contract manufacturers are shipped directly to the configuration centres leading to a different lead time structure. Third, demand is satisfied closer to the market, leading to smaller demand rates per configuration centre, but more flexibility with regard to distribution lead times in the outbound supply chain. In conclusion, such a different supply chain structure asks for different modelling decisions.

4.4.2. Customer service

In the SBS policy customer service is defined with P_1, P_2 and P_3 service levels, while within the CEM the SLIP, CLIP and RLIP measures are used. The SLIP, CLIP and RLIP define the fraction of orders that is delivered within a certain lead time. So these service level measures describe the magnitude of the cases of non-service. This definition resembles P_2, which defines the fraction of customer demand that is met routinely without backordering or lost sales. Since for SLIP, CLIP and RLIP a performance of 95% is pursued, it is argued that it is appropriate to use a P_2 service level setting of 95%.

4.4.3. Value structure

The added value of items and subsequently the value structure of the supply network are based on the information in the ERP system and purchasing contracts. With regard to the information in the ERP system a discrepancy exists with the actual value of the items at the CODP. Namely, in the supply chain the standard price of modules surcharged with the transportation costs resembles the value of the modules at the CODP. The costs of preparing the modules for distribution to LSOs are taken into account in the added value of the configuration process. However, in the ERP system the modules are awarded these costs already at the CODP.

An interesting discussion unfolds, since both situations have their own rationale. First, current accounting principles in decision making prescribe that the actual physical processes (the supply chain) are the best representation of the value structure (Zimmerman, 2000). In such a case, activity-based costing (ABC) prescribes the allocation of costs to the item that has triggered the activity on a certain resource causing these costs. Nevertheless, the CEM is assessed on its financial position by shareholders, and therefore it is in the interest of the CEM to increase shareholder value. Shareholders assess the performance of the CEM based on the financial reporting system in the ERP system.

A sensitivity analysis has been executed with regard to the distribution of the added value in the downstream part of the supply chain in order to examine the effect on the decision making process. With the value structure of the costing system of the CEM, the supply chain stock investments increase with 1.6%. This is due to the fact that the modules under consideration are assigned a higher value at the CODP and as a result their stock investments increase (with 6.6%). However, the average stock levels (in weeks of supply) of these modules decrease with 1%, while average stock levels in the supply bases of these modules increase. So the model pushes stock back in the supply chain because it is less economical to hold stock at the CODP due to the increased added value.

To conclude, the sensitivity of the model with regard to the discrepancy in added value is relevant and it has been shown that the SBS policy adapts the stock allocation decision under different value structures. Taking into account the nature of the project it is more appropriate to use the ABC approach as prescribed by Zimmerman (2000).

4.4.4. Lead time

The lead time parameter settings are distinguished by the ordering strategy. The lead time of items ordered with purchasing orders is straightforwardly defined by the planned lead time in the purchasing contract. In the case of delivery schedules this definition is more complicated.

The lead time of items ordered with delivery schedules is defined by the fixed fence. Namely, the fixed fence defines the period over which the CEM cannot change the delivery quantities anymore. So the quantities in the periods outside the fixed fence can be changed unlimitedly. Therefore, these quantities cannot be seen as releases, but merely as forecasts enabling anticipation of capacity and material requirements further upstream in the supply chain. At the moment that a quantity in the delivery schedule shifts from outside to within the fixed fence, this can be seen as the release of an order for an item. As a result, the lead time for items with a delivery schedule ordering strategy is defined as the fixed fence.

In Figure 4.3 it can be observed that the lead time in this definition is shorter than the lead time as it exists in reality for this particular item. As a result, 100% availability of children items is assumed if these are not incorporated in the model. So in the case of delivery schedules, it is required to model these children items as well. However, it is impossible to model the children of all items that are controlled with a delivery schedule policy, since this would lead to an explosion of the number of modelled items.

The question arises which lead time to use in the case of a delivery schedule control policy, while the supply base of the item is not included in the model. First, the lead time of the item can be modelled based on the fixed fence. The outcome then represents the impact of scenarios on the CEM stock levels, assuming that the supplier has sufficiently buffered for uncertainties. Second, the lead time can be modelled based on the planned lead time of the item (which is the cumulative lead time of the longest lead time item). The outcome then represents the impact of scenarios on the total supply

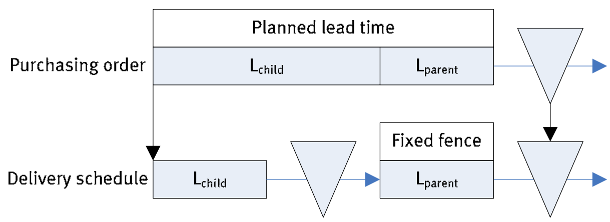


Figure 4.3: Lead time definition in the delivery schedule and purchasing order control structure

chain stock, since it also includes buffering for uncertainties over the lead time that is covered by the supplier. It has been decided to use the planned lead times. Although in theory the CEM commits to certain stock levels to enable buffering for uncertainties by suppliers, it is assumed that suppliers are reluctant to holding stock. As a result, the CEM has to buffer for these uncertainties in supply in its own stock control system anyway. The effect on the outcomes of the SCPE model will be limited, since a large share of the supply value of items controlled with a delivery schedule policy is represented by the modules of which the supply bases have been included (the modules sourced from contract manufacturers).

According to this line of reasoning about the lead time definition, we argue that the SBS policy does not add any value to synchronising the stock allocation decisions of parent and children items, for those parent items that are sourced company specific, though not controlled with delivery schedules or similar supplier control policies. Namely, if the parent is sourced with purchasing orders, the replenishment lead time is equal to the planned lead time, which is then the cumulative lead time of the longest lead time item in the supply base of the parent. (see Figure 4.3) So one has to buffer for demand uncertainty over this entire cumulative lead time anyway, which includes the lead time of children items. As a result, the stock levels of these children items have become irrelevant, since their material availability is already incorporated in the stock levels of the parent item.

4.4.5. Review period vs. Minimum order quantity

An important aspect of the supply chain of the CEM is the MOQ of items in the supply bases of the common product body and the contract manufacturers. (see section 2.1.6) In the SBS policy the effect of MOQ can be taken into account with the review period; the MOQ implicitly determines how often an item can be ordered. Based on the MOQ and the demand per period, an expected review period can be defined (which is the inverse of the ordering frequency of the item):

$$(3) \quad R_i \approx E\left[R_i\right] = \frac{MOQ_i}{E\left[G_i\right]}$$

Where:
R_i is the review period for item i in weeks.
$E[R_i]$ is the expected review period for item i in weeks.
MOQ_i is the minimum order quantity for item i in number of items.
$E[G_i]$ is the expected dependent demand for item i in number of items per week

The decomposition approach of the SBS policy forces the review period of an item to be the lowest common multiple of the review period of items with a shorter cumulative lead time in the same divergent network:

$$(4) \quad R_i' = LCM(R_i, \left\{R_{j \in C_i}\right\})$$
$$C_i \left\{ j \mid L_{c,j} < L_{c,i} \right\}$$

Where:
R' is the recalculated review period that is used in the SBS policy in unit of time.
C_i is the set of items j with a cumulative lead time shorter than that of item i.
L_c is the cumulative lead time in unit of time.

As a result, the review period definition in the SBS policy does not represent the behaviour of MOQ items in the CEM supply chain. MOQ items are items with a review period longer than one week.

It can be considered to exclude the MOQ items from the model. This is in fact the question whether to take into account the availability of these items. If the MOQ items are not included, the SBS policy assumes 100% availability of these items. As a result the SBS policy does not synchronise the rest of the supply network with the possible unavailability of the MOQ items. A sensitivity analysis has shown that the exclusion of MOQ items results in lower CODP stock levels. If these calculated stock levels are evaluated with the MOQ items included, an implosion of service levels results. So one way or the other, a procedure is required to incorporate MOQ items.

Fransoo et al (2001) have shown that the service levels determined with multi-echelon stock control models (such as the SBS policy) can be used as constraints for classical stock control models. These classical stock control models enable the inclusion of lot sizing restrictions such as MOQs. The context of their paper is different –Fransoo et al (2001) deal with the fact that information cannot be shared across the supply chain–, but still the procedure can be applied to the SCPE model without loss of generality. Based on this procedure, classical stock control models have been applied to the MOQ items. In the case of excluding the MOQ items from the SBS policy the service levels for these items are set at 99%, implying high material availability. As a result, extra stock investments are required of approximately €471,000 in the second tier, while resulting in a stock investment savings for the CEM of €56,000. This is an unrealistic trade-off from a supply chain costs point of view. In fact the model including the MOQ items also represents reality more accurately from a practical perspective. Namely, complete material availability in the supply bases is not achievable in reality, since the contract manufacturers pursue a lean manufacturing strategy; stock levels are as low as possible and purchasing orders are released as late as possible.

So in the SCPE model the SBS policy is applied including the MOQ items with a review period set equal to the review period of the system (one week). After completion of the SBS calculations, the output parameters are replaced with classical stock control model calculations. These calculations are based on the service levels provided by the SBS policy. The classical stock control model definitions are presented in Appendix G.1.

A sensitivity analysis has been executed with regard to the service level settings of the classical stock control models. (see Appendix G.2) The first important observation is that for almost two third of the stock investments proposed by the model, the review period is longer than one week and subsequently the stock allocation is modified with the above described procedure. The impact of MOQ is therefore considered to be significant. The second observation is that a considerable amount of extra stock is allocated with the procedure of Fransoo et al (2001). This mainly originates from cycle stock, which is directly related to the MOQ of the items. The impact of cycle stock on the total stock investments is therefore considered to be large. The third observation is that if classical stock control models are used, the amount of safety stock is low in the case of using the SBS policy proposed service level. The safety stocks of the P_1 setting are responsible for 0.1% of the total stock investment in the supply bases. Therefore, the impact of safety stock is considered to be negligible. The fourth observation is that if classical stock control models are used that pursue a 95% service level as proposed at the CODP, the safety stocks increase dramatically. In that case 25% of the stock investments in the supply bases are safety stock originated. This demonstrates the power of the SBS policy, since it shows that pursuing a 95% service level in this part of the supply chain creates an enormous amount of dead stock.

So the SCPE model prescribes low levels of safety stock at the contract manufacturers. As a result the contract manufacturers mainly invest in cycle stock. This reflects a lean manufacturing strategy using Just-In-Time (JIT) delivery from second tier suppliers. Items are ordered just before their availability is required, resulting in minimal safety stocks. This is in line with the current strategy of the contract manufacturers and thus the supply chain of the CEM is aligned correctly in that sense.

4.5. Validity

An important aspect of the design phase is the assessment of the quality of the proposed model. Van Aken et al (2007) define three quality criteria in relation to business problem-solving projects; controllability, reliability and validity. Controllability is a prerequisite for the evaluation of reliability and validity. Reliability refers to the independency of the results of the particular characteristics of the study, such as the researcher, instrument and respondents. Controllability and reliability are inherent to the research model as discussed in section 1.2. Validity refers to the adequacy of the research results and can be decomposed into construct validity, internal validity and external validity. Assessment of the validity of the research results is crucial in order to be able to generalize conclusions to the CEM supply chain.

Construct validity is the extent to which a measuring instrument measures what it is intended to measure (De Groot, 1969). Construct validity thus refers to the quality of the operationalisation of the SCPE model. This process has been described extensively in this chapter. It has been argued which structure and parameter settings to use, based on the actual supply chain and the availability of data in the organisation. Therefore, it can be concluded that the model is valid in terms of construct validity.

Internal validity refers to the adequacy of the internal causal relationships as defined in the model. In the simulation section of SCOPE the analytical results are simulated and verified. In all cases the simulation results were close to the analytical results, indicating that the model is internally valid.

External validity refers to the generality of the research results with regard to the actual situation. Therefore, it is a crucial element in this project. In multi-echelon stock control models like the SBS policy it is common to determine the external validity by comparing the balance between stock and service levels at the CODP.

The average stock levels and corresponding service levels during the period over which the input parameters of the SCPE model have been determined are compared with the service levels that the SBS policy calculates in the evaluation mode provided a certain average stock level. Due to product introduction issues only the service levels from April 2007 onwards are appropriate for validation. In addition service levels have not been reported over May 2007. As a result, three months are available for comparison.

In Figure 4.4 it can be seen that the magnitude of the service levels provided by the SCPE model are similar to the actual service levels. As can be seen, the service levels within the model behave as expected. The P_2 service level is structurally higher than the P_1 service level. In addition the shape of the graph is similar. Also the development of the actual service level is similar. As has been stated earlier, the P_2 service level is the equivalent service level of the customer service measures of the CEM. The P_2 is approximately 20% lower than the actual service level during April and June. It is approximately 30% higher than the actual service level in July. These deviations have been determined over $1\text{-}P_2$.

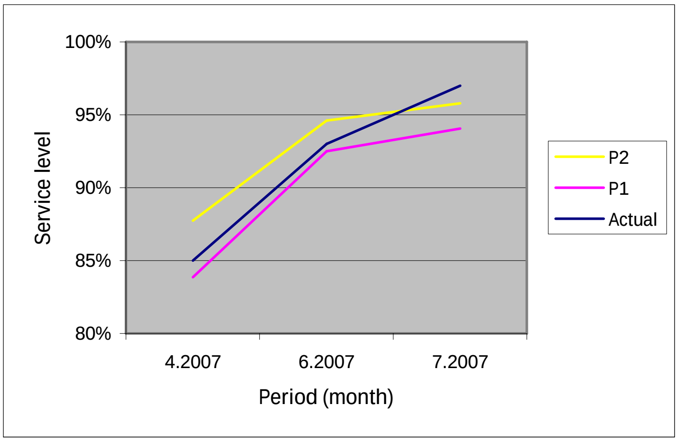


Figure 4.4: Comparison of actual and modelled service levels

These differences can be explained from different perspectives. First, unreliability in the supply of the CODP stock locations has not been taken into account. Second, uncertainty in the configuration process has not been included. These are quality issues, but also the flexibilities in the service level definitions that have been discussed in section 2.2.6. To conclude, the evaluation mode of SCOPE assumes the application of the SBS policy, while in reality MRP is the control system. The SBS policy outperforms the MRP system, although planners can overrule MRP in the actual situation by accelerating the supply chain.

The last criterion of validity is the recognition of the results by the professionals in the organisation. This criterion is less prominent in the methodological literature, though it is a very important instrument in business problem-solving projects (Van Dijk et al, 1991). The model results have been presented to members of the logistics, purchasing and sales departments with responsibilities in the Nero supply chain. The members agree that the model represents the actual situation accurately and accept the results.

In conclusion, the SCPE model is considered to be valid, though it is important to acknowledge the fact that the supply chain of the CEM is controlled by human decision making. This means that such a complex and subjectively controlled system can never be completely represented by an explicit model as has been used in this project. Still, the SCPE model does provide the required insight into the behaviour of the supply chain as a system with a certain structure and parameter set facing demand uncertainty.

4.6. Conclusions

The modelling structure and parameter settings of the SCPE model have been defined based on the actual supply chain structure. An important aspect of this structure is commonality in some modules at the CODP and in the supply bases of the contract manufacturers. This commonality has been taken into account. The SCPE model is effectuated in a software tool that applies the SBS policy in an ATO supply network structure.

The results from the SBS policy are decomposed based on an aggregation procedure that enables the aggregation of items with similar BOM structures and lead times. As a result, the 2,588 items in the actual supply chain are represented by 154 items in the aggregated model without loss of generality. The procedure significantly reduces the required computational complexity.

Furthermore, a procedure has been applied in order to deal with lot sizing restrictions. Namely, the average stock levels of MOQ items are replaced with the average stock levels obtained with classical stock control models.

The SCPE model has been validated in terms of construct, internal and external validity. It behaves as expected and provides adequate results in relation to the actual situation. This is acknowledged by the members of the CEM organisation with responsibilities in the supply chain.

CHAPTER 5, SCENARIO ANALYSIS

In the previous section the SCPE model has been defined. This model has been applied to the scenarios that have been established in section 3.2. In this chapter the results of the scenario analysis are discussed. For each scenario, the supply chain investments and the distribution of these investments among the CEM and other actors in the supply chain are discussed. Furthermore, the stock distribution at the CODP is analysed. In the final section of this chapter a synthesis is presented of the results from the scenario analysis and the findings of the supply chain analysis.

5.1. Base Case

The base case is the reference scenario of the SCPE model. It defines the close-to-optimal supply chain strategy for the Nero given the supply network structure and parameter settings as they exist at this moment. This does not imply that the decisions in the base case represent the actual decisions of the CEM. In section 4.5 a comparison of the SCPE model and the actual situation is presented.

In the base case approximately €3 million of stock is invested in the supply chain of which 50% is located in the CEM owned supply chain. The remaining 50% is situated at the contract manufacturers; 34% at the module contract manufacturer (MCM) and 16% at the unit contract manufacturer (UCM). The fact that more stock is allocated to the module contract manufacturer originates from the inclusion of Caligula modules for reasons of commonality. As a result, the allocated stock is not entirely Nero originated.

In Figure 5.1 the stock distribution in the supply chain is presented. It can be observed that a large share of the stock investments is allocated to the CODP and the contract manufacturers. In Table 5.1 it can be seen that 21% of the stock is invested in Nero modules, which are located at the CODP. This large stock investment downstream in the supply chain can be explained by the fact that in general customer service is provided and perceived at the CODP. As a result, it is important to maintain high service levels and subsequently high levels of stock at that point in the supply chain.

Another large share of stock investments is cycle stock located at the contract manufacturers (almost 50% of the total stock investments). The large share of cycle stock reflects a lean manufacturing strategy using JIT; components are ordered just before the stock positions drop to zero, resulting in minimal safety stocks. This is in line with the current strategy of the contract manufacturers. In that sense, the supply chain is aligned correctly. It has to be noted that although this stock is not CEM owned, it is covered by the CEM with commitments. Thus the CEM is liable for these investments.

It is interesting to note that logistics and purchasing professionals of the CEM have judged the lean manufacturing strategy of the contract manufacturers as a problem area. The SCPE model concludes the opposite; from an integral supply chain performance perspective the contract manufacturers should be lean and stock should be allocated downstream in the supply chain.

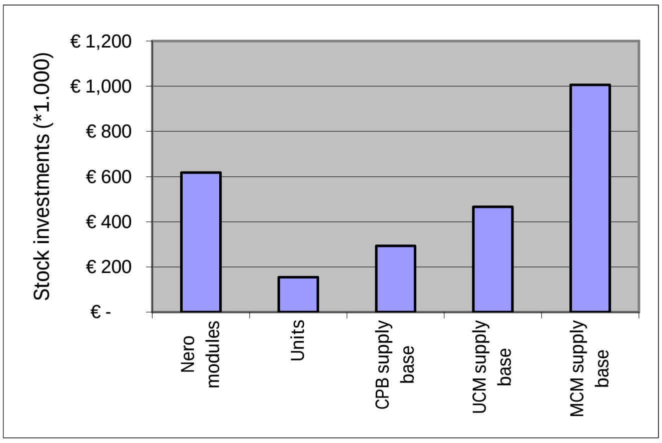


Figure 5.1: Stock distribution in the supply chain in the base case

b	SS_c	CS_c	S_c	S (%)
Nero modules	-	-	618,129	21%
Caligula modules	-	-	293,899	10%
Module E	-	-	86,546	3%
Units	-	-	154,625	5%
CPB supply base	55	206,602	293,478	10%
UCM supply base	1,505	432,955	466,715	16%
MCM supply base	54,278	944,433	1,005,198	34%
Total	55,838	1,583,990	2,918,590	100%

Table 5.1: Stock distribution in the supply chain in the base case

If the stock distribution at the CODP is examined in detail, it can be observed that different service levels and subsequently different stock levels are required for different items at the CODP. (see Table 5.2) Material availability is relatively high for products with short lead times. This enables relatively lower stock levels for long lead time items. The economic rationale behind this allocation decision is the fact that demand uncertainty develops disproportional with increasing lead times. Currently, the target stock levels are equal for all modules. This results in dead stock in the supply chain. Dead stock is stock that does not contribute to the customer service performance in anyway.

In Table 5.2 it can be seen that the CODP stock investments are concentrated at the common product body (CPB) and module A. The common product body is an expensive module and thus it requires a relatively large stock investment. Module A has a long lead time and thus it requires high stock levels in order to buffer for uncertainties. These high stock levels in weeks of supply can be observed for all modules originated from the Far East.

Module	S_c	S	S_t	h	L	P_1	P_2
CPB	276,290	39%	1.48	23,005	2	91%	95%
Module A	202,744	29%	3.50	3,577	12	9%	38%
Module B + C	91,255	13%	3.50	3,220	12	9%	38%
Module F	17,994	3%	3.71	598	14	0%	37%
Module G	17,727	3%	1.48	1,476	2	91%	95%
Module H	12,119	2%	2.32	646	3	76%	80%

Table 5.2: Stock distribution at the CODP in the base case

So the SCPE model shows that a decoupling is required of the inbound goods flow originated from the Far East. This is counterintuitive for the CEM, since these modules are expensive (they cover 50% of the total supply value) and thus result in large stock investments. However, these modules are also responsible for 12 of the 30 to 50 weeks cumulative lead time. Therefore, it is unavoidable to buffer for uncertainties during this long transportation lead time between the Far East and Europe.

An important observation is that the SCPE allocates stock downstream in the supply chain. This can be explained by the specific value structure of CEM products. The added value of the manufacturing operations of the contract manufacturers and the CEM is relatively low and thus the value in the supply chain increases only moderately. As a result it requires only a small extra investment to allocate items more downstream in the supply chain, while the extra service obtained by doing so is relatively large. Namely, customer service is provided and perceived at the CODP and thus it is important to allocate stock as close to the CODP as possible. De Kok and Fransoo (2003) observe similar patterns in the stock allocation decisions in the supply network. They intuitively explain that, apparently, the pull of stock towards the CODP to ensure high customer service is stronger than the pull of stock upstream in the supply chain to reap the benefits of lower item values.

This nicely illustrates the power of the SBS policy; it enables the synchronisation of items over the value structure, while incorporating the complex relations between demand uncertainty and other parameters in the supply network. These complex relations between the input parameters (demand uncertainty, lead time and value structure), decision parameters (material availability and stock levels) and output parameters (service level and stock investments) are crucial in effectively managing the supply network. This further emphasizes the necessity of using quantitative models in order to gain insight into the performance of supply chains dealing with demand uncertainty.

5.2. Customer service

The SBS policy allocates stock in the supply network in order to buffer for demand uncertainty. Demand uncertainty originates from the fact that demand is unknown at the moment of releasing the order that satisfies the demand. As a result it is required to predict future demand. Since demand is uncertain by nature, it has to be decided which part of the possible future demand to cover. Covering all demand will result in an infinite amount of stock, since the maximum demand in a period is unknown (and thus infinite). On the other hand, holding no stock at all results in zero sales. The service level represents the trade-off between these two extremes. It specifies the risk that the CEM is willing to take by investing in stock and by not being able to cover all demand.

The trade-off between customer service and stock investments is elementary in the supply chain. By increasing the stock levels in the supply chain, the material availability is increased. As a result the probability of being able to deliver the right quantity at the right moment increases, and subsequently customer service improves. In order to correctly interpret the results in this section, it is recommended to study sections 2.2.6 and 4.1, where the customer service measures of the CEM and the service level definitions of the SBS policy are discussed. Furthermore, it has to be noted that it has been shown in section 4.4.2 that the customer service measures of the CEM are directly related to the fill rate (P_2) service level as it is defined in the SBS policy.

In Figure 5.2 it can be seen that the supply chain stock investments increase exponentially under increasing service levels. This is a commonly known effect in operations research. It is interesting to note that the slope of the graph is moderate until the 95% service level and steep afterwards. This indicates that the agreed target service level is relatively efficient. Namely, a small increase of the target service level requires a relatively large investment in stock, while lowering the stock investments results in a relatively large reduction of customer service. So it is probably not within the interest of the CEM to pursue a service level higher than 95%. Still, the decision to pursue a certain service level is in fact a trade-off between the costs of delaying or losing sales (penalty costs) and the costs of holding stock (holding costs). We refer to section 5.3 for an analysis of the penalty costs structure of the Nero supply chain under different service level restrictions.

An important aspect of the scenario analysis is the behaviour of the stock distribution under different service level restrictions. In Figure 5.2 it can be observed that the stock investments of the contract manufacturers remain relatively stable under increasing service levels, while the stock investments of the CEM increase exponentially. This means that the CEM is the actor in the supply chain that absorbs the effect of increasing service levels. If the ownership is expressed as a percentage of the total supply chain investments, it can be seen that the investments are leveraged from the non-CEM to the CEM owned supply chain; the model pushes stock downstream in the supply chain. This is in line with the earlier mentioned fact that customer service is provided and perceived at the CODP.

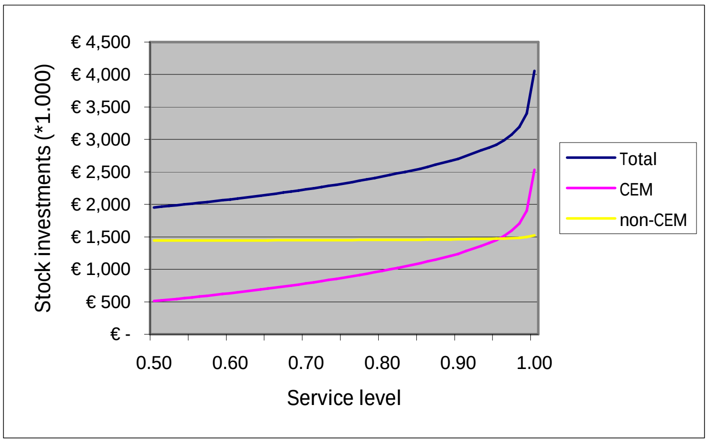


Figure 5.2: Stock investments in the service level scenarios

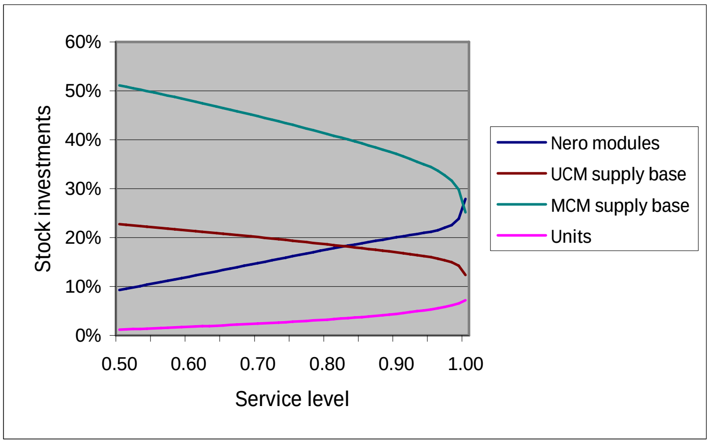


Figure 5.3: Stock distribution in the supply chain in the service level scenarios

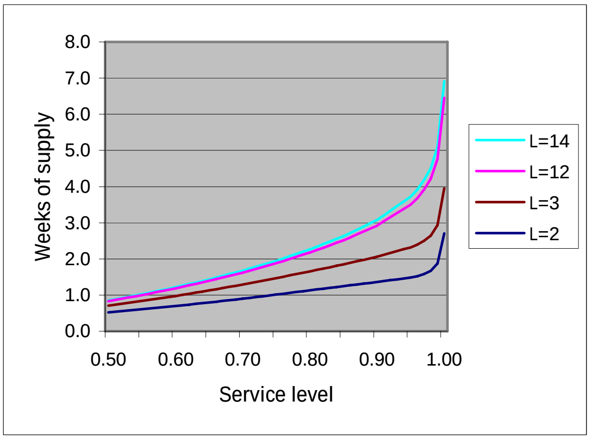


Figure 5.4: Stock levels in weeks of supply at the CODP in the service level scenarios

This effect is also observed in the stock distribution among the different supply chain nodes. (see Figure 5.3) The share in the total stock investments of the contract manufacturers decreases exponentially, while the investments of the CEM increase exponentially. The unit stock investments –which are positioned in-between these two nodes– increase as well, though more or less proportional. This further stipulates the fact that higher service levels can only be obtained by increasing stock levels more downstream in the supply chain. Since the value per item increases further downstream in the supply chain, the effect on the stock investment distribution is hyper-exponential.

The stock levels at the CODP are also reallocated as can be seen in Figure 5.4. It can be observed that the increase in stock level is stronger for modules with longer lead times. So under increasing service levels, the availability of longer lead time modules becomes relatively more important. Because the shortest lead time module (the common product body) also represents 60% of the total supply value, this effect is even stronger in terms of stock investments per module.

5.3. Penalty costs

Although this project focuses on holding costs, it is interesting to further analyse the penalty costs structure behind the SCPE model. It is impossible to unambiguously define an accurate measure of penalty costs, since many uncertain factors are related to such an event (will the sale be lost, does it have impact on service contracts, etc.). Nevertheless, it is possible to calculate penalty costs as an output parameter, based on the newsboy equations that are used in the SBS policy. This enables the assignment of a certain amount of penalty costs to a certain service level scenario. These penalty costs can be shared with the sales professionals responsible for the specific product, in order to create intuition with regard to optimal service level settings.

The penalty costs per period are obtained by multiplying the number of configurations that is backlogged per period and the costs of backlogging one configuration for one period. The costs of backlogging are based on the specific service level setting and the supply value of the end-item:

(5) $p_{Cicero} = B_{Cicero} * pen_{Cicero}$

(6) $pen_{Cicero} = \left(\frac{P_2 \sum_{i|b=2} h_i - v_{i|b=1}}{1 - P_2} \right)_{Cicero}$

Where:
p are the periodic penalty costs in euro per week.
B is the average backlog per week, which is an output variable of the SCPE model.
pen are the item penalty costs; the penalty costs in euro for backlogging one item for one week.
P_2 is the fill rate service level (1/1).
h is the value of an item in euro.
v is the added value of an item in euro.
b is the BOM level.

The penalty costs have been determined for the Nero. As can be seen in Figure 5.5, the periodic penalty costs graph has a parabolic shape, which can be explained by the convexity of formula (6). Nevertheless, it is a mixture of the item penalty costs and the backlog per period. To correctly interpret the cost structure, the item penalty costs have been examined. In Figure 5.6 it can be observed that the item penalty costs increase exponentially under increasing service levels. From 95% onwards, the item penalty costs explode; though the backlog over the service level interval (0.75, 1.00) decreases such that the periodic penalty costs decrease as well.

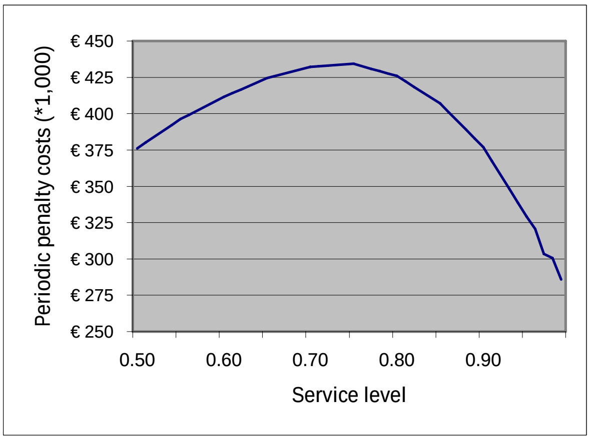


Figure 5.5: Periodic penalty costs

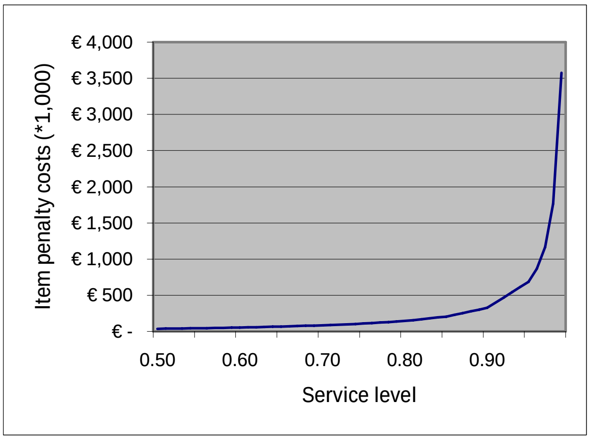


Figure 5.6: Item penalty costs

The above described model seems to accurately represent the actual penalty costs that are incurred by not being able to deliver on time. The Nero is sold in roughly two markets. In the first market products are sold with tenders that prescribe a strict delivery profile. In the second market the availability of the complex system is crucial, since it is part of the operational process of the customer. As a result, contracts for both markets contain a strict and firm penalty clausal, resulting in large penalty costs or lost sales for the CEM. The average revenues of a Nero contract amount approximately €600,000 of which 45% is profit margin. This amount roughly complies with the €685,000 that is proposed in the penalty costs model under a service level restriction of 95%. So the current target service level seems to accurately describe the actual item penalty costs. In conclusion, it can be stated that the 95% target service level is also a relatively efficient measure from a penalty costs perspective.

5.4. Forecasting

The demand uncertainty determines the magnitude of the required stock investments for maintaining a certain service level. The demand has a level of uncertainty by nature, which is defined as the standard deviation of the expected demand or the coefficient of variation of the expected demand. This is an upper limit to the forecast error. A forecasting system would normally result in a forecast error that is lower than this upper bound, since trend and seasonal effects are predicted, while commercial information is anticipated. As a result, the demand uncertainty perceived by the supply chain is reduced, or in other words, the forecast error is smaller. However, it has been shown in section 2.2.4 that the forecast error in the CEM supply chain is larger than the raw demand uncertainty. As a result, the forecasting system of the CEM is a source of demand uncertainty in the supply chain.

In order to determine the effect of improving the forecasting system, it is required to quantify the current forecast error perceived by the supply chain. This is complicated because the supply chain faces different forecast errors for different items, while multi-echelon stock control models assume one forecast error for the entire supply chain.

This is a fundamental error in multi-echelon stock control models, including the SBS policy. As can be seen in the cumulative lead time distribution of the components in the Nero supply chain, different components are controlled with different forecasts. (see section 2.1.5 and 2.2.4) This is due to the fact that demand information is updated in the period between two release decisions for items that are assembled into the same unique parent. For instance, item A in the end-item X has a cumulative lead time of 13 weeks and is released in the last week of the third quarter. Therefore, the forecast error originates from the forecast T-1. The end-item X will also contain an item B, which has a cumulative lead time of 39 weeks. Item B for end-item X has already been released in the last week of the first quarter. So the forecast error faced by item B originates from the forecast T-3. In multi-echelon stock control models it is assumed that both items face the same forecast error, while the forecast error perceived by item A is smaller than for item B. This is an area of further research.

The problem can be circumvented if the forecast error is set equal to the standard deviation of the raw expected demand. In that situation the forecast error is equal for all items under the assumption that demand is stationary. Nevertheless, this situation is not applicable to the CEM, since it has been shown that different forecast errors exist for different forecasts, used for different items in the same unique end-item. Therefore, a two-step procedure has been developed to determine the current forecast error perceived by the supply chain. (see Appendix D) First, the weighted average forecast error for each cumulative lead time is determined based on cumulative lead time intervals over which a forecast is used. This assumes equally divided demand over the periods within the interval, which is valid under the assumption of stationary demand. With these forecast errors per cumulative lead time, the expected forecast error as faced by the supply chain is determined. By applying Pareto logic, an average forecast error is determined weighted with the added value that is injected in the supply chain by a release decision for each cumulative lead time. This procedure results in a forecast error of 1.49 compared to a coefficient of variation of expected demand of 0.3 to 0.7 for products in the maturity phase of the product life cycle.

To provide insight into the effect of improving the forecasting system, scenarios have been calculated for forecast errors between zero and 1.5. (see Figure 5.7) As has been mentioned earlier, a forecasting system will only have impact if its forecast error outperforms the raw demand uncertainty. Therefore,

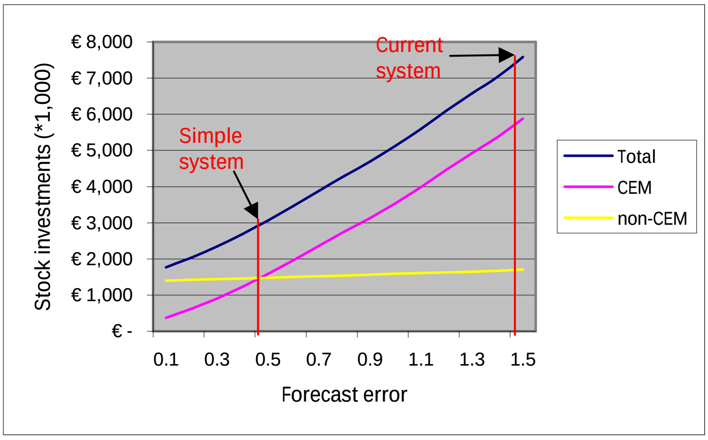


Figure 5.7: Stock investments in the forecast error scenarios

it would already be beneficial for the CEM to stop using the current forecasting system for products in the maturity phase of the product life cycle and to introduce a basic forecasting system that is based on raw demand uncertainty only. This will result in a savings of approximately €4.4 million in supply chain stock investments, which resembles 59% of the total investments. Further improving the forecasting system by introducing advanced forecasting tools will likely reduce the stock investments even further. If the advanced forecasting system halves the forecast error, a supply chain stock investment saving of €950,000 is achieved. This resembles 30% of the stock investments in the situation of a simple forecasting system. An almost linear relationship exists between the forecast error and the stock investments. A simple linear model prescribes that each 0.1 reduction in forecast error results in €415,000 supply chain stock investment savings.

It has to be noted that an improved forecasting system has effect on all products in the product portfolio of the CEM. Namely, the forecasting system is easily implemented company wide. As a result, the above presented savings will be in the range of tens of millions of euros, while an advanced forecasting system will likely increase this amount even further.

In Figure 5.7 it can also be observed that the improvement in stock investments is almost completely achieved in the CEM owned supply chain. This is caused by the fact that uncertainty further upstream in the supply chain has to be buffered for anyway because of the long lead times between the contract manufacturers and the CEM. Another factor is the large MOQ in the supply bases of the contract manufacturers, resulting in a relatively small impact of safety stocks. The safety stock is the part of the stock investment that is used to buffer demand uncertainties.

So stock is pulled downstream in the supply chain under increasing demand uncertainty. In Figure 5.8 it can be observed that the relative share of the modules at the CODP (the Nero modules) in the total supply chain stock investments increases. Furthermore it can be seen that the share of the units

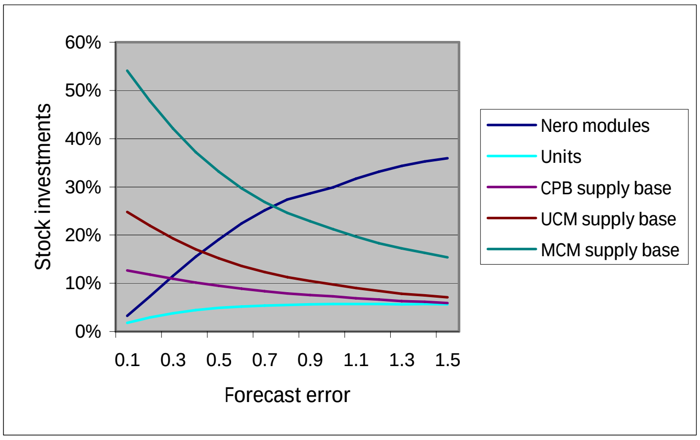


Figure 5.8: Stock distribution in the supply chain in the forecast error scenarios

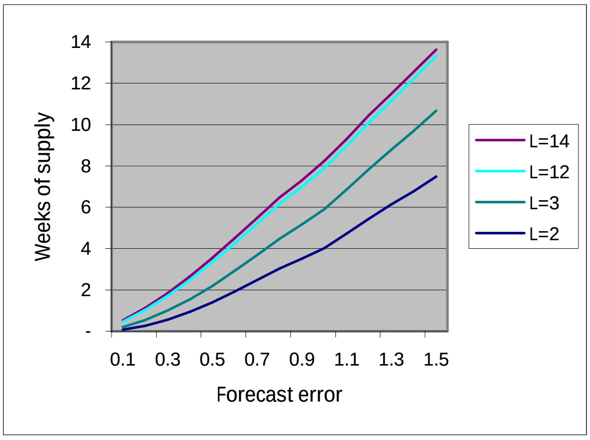


Figure 5.9: Stock levels in weeks of supply at the CODP in the forecast error scenarios

–which are positioned in-between the contract manufacturers and the CODP– increases as well, though moderately compared to the CODP. So increasing demand uncertainty is caught up with extra stock close to the CODP, where customer service is provided and perceived. At the CODP the same effects are observed as in the customer service scenarios; the relative impact of long lead time modules increases, while the share of the common product body in the stock investments increases due to its high supply value. (see Figure 5.9)

5.5. Lead time reduction

A distinction can be made with regard to lead time reduction in the first tier and in the second tier. Lead time reduction in the first tier refers to the lead times of the contract manufacturers, while lead time reduction in the second tier refers to the lead times of the suppliers of these contract manufacturers. Lead time reduction has a two-sided impact. First, the period over which demand uncertainty has to be covered decreases because the release decision can be taken closer to the demand effectuation moment. This results in lower stock investments. Second, the pipeline length decreases for some cases of lead time reduction. As a result, the pipeline investments are reduced.

It has already been shown that lead time is not a lever in improving supply chain performance in the supply bases of the contract manufacturers; due to the large MOQs only cycle stock is allocated. Cycle stock can only be influenced by reducing the MOQ.

The impact of a reduction of the lead time of the contract manufacturer is in fact a reduction of the fixed fence. This does not necessarily result in a reduction of the pipeline length, since the fixed fence also comprises planning time. In the scenarios established in this section only the impact on stock levels is considered. If the pipeline length is reduced by the lead time reduction program, than each week of pipeline length results in €287,000 of investment savings. This reduction is significant.

Three scenarios have been established. First, the lead time of the module contract manufacturer has been reduced. Second, the lead time of the unit contract manufacturer has been reduced. To conclude, the lead times of both contract manufacturers have been reduced. It is interesting to note that the savings obtained by lead time reduction fully benefit the CEM. Figure 5.10 shows the development of the investments in the CEM owned supply chain. It is even more interesting to note that the contract manufacturers encounter extra investments in order to comply with shorter lead times. (see Figure 5.11) So as a result of the short lead times towards the CEM, the contract manufacturers have to invest in inbound stock in order to keep up with service levels.

If the effect of the three scenarios on the stock distribution in the supply chain and at the CODP is examined, it can be observed that the results of the separate contract manufacturer lead time reduction scenarios are also visible in the total lead time reduction scenario. Therefore, only the details of the total scenario are presented.

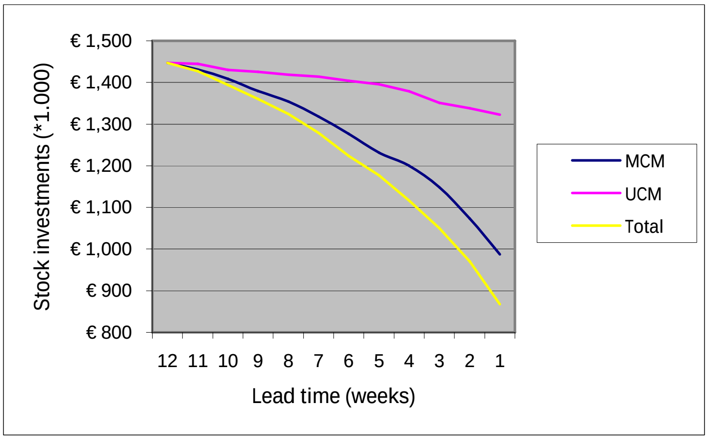


Figure 5.10: CEM owned stock investments in the lead time reduction scenarios

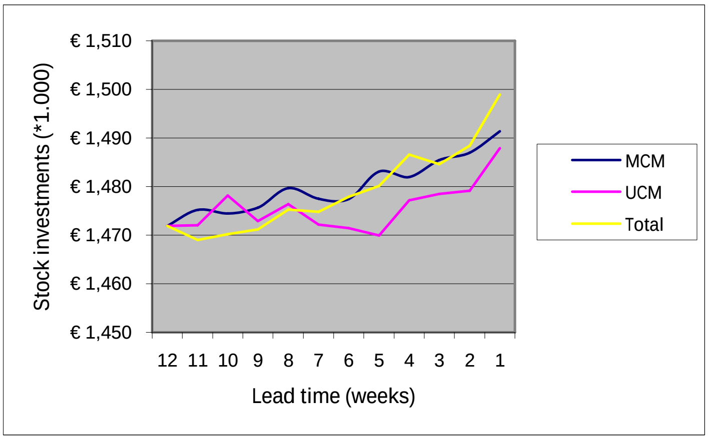


Figure 5.11: non-CEM owned stock investments in the lead time reduction scenarios

As expected, the stock investments of the contract manufacturers increase, while the share of the inbound stock investments of the modules for which the lead time has been reduced decreases. (see Figure 5.12) The effect of the unit contract manufacturer lead time reduction is completely absorbed by a reduction in the inbound stock of units. In the module contract manufacturer scenario the effect of reducing lead time also has impact on the rest of the supply chain. This can be explained by the fact that the reduced lead times are those of the pipelines towards the CODP. At the CODP the lead time reduction has a direct effect on the modules. As a result the synchronization of the other modules at the CODP changes as well. These changes also affect the rest of the supply chain. It is interesting to note that the investments in the common product body supply base increases. This is the result of a shift in bottlenecks in the supply chain.

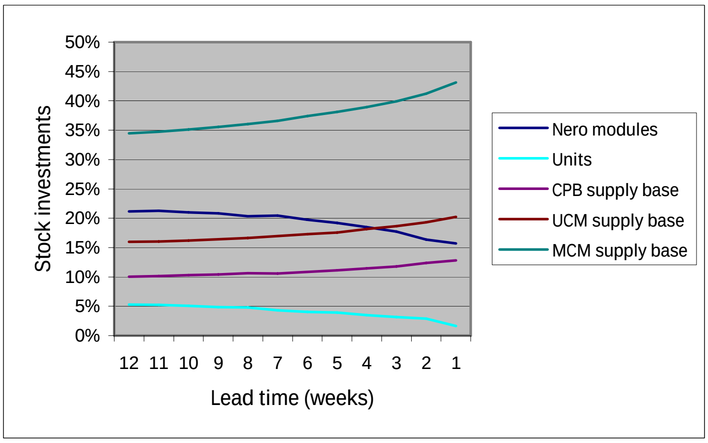


Figure 5.12: Stock distribution in the supply chain in the total lead time reduction scenarios

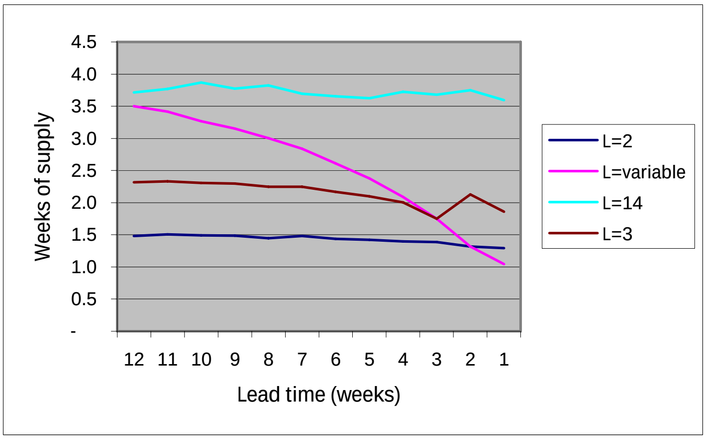


Figure 5.13: Stock levels in weeks of supply at the CODP in the total lead time reduction scenarios

If the effect on the distribution of stock at the CODP is examined, it can be seen that the share of the modules sourced from the contract manufacturer in the total CODP stock investments reduces. The common product body is awarded a larger share of the stock investments. In weeks of supply this effect is also visible. (see Figure 5.13) It is clear that the stock levels of modules sourced from the contract manufacturer decrease, while the stock levels of the other modules are more or less maintained. The crack in the stock level of the module with a lead time of three weeks can be explained by the fact that at that point the lead times of the modules cross. As a result the bottlenecks shift, which leads to this behaviour.

5.6. Transportation mode flexibility

In Chapter 3 it has been argued that this project should consider two flexibility levers; buffer stock and transportation mode flexibility. In the previous scenarios the buffer stock mechanism has been analysed extensively by applying different scenarios to the SCPE model. In this section it is examined whether transportation mode flexibility in the pipelines between the Far East and Europe is an economical flexibility lever as well.

The SCPE enables the modelling of two extreme transportation scenarios; every shipment of a certain item by air or by sea. Air transportation reduces the lead time with five weeks and this will have a positive effect on the stock investment in the supply chain. It is expected that the service level has an impact on this decision as well, since high service levels increase the stock investment exponentially, while the transportation costs remain the same (the demand volume does not change). Therefore, the decision to use air transportation will be more economical in a situation with high service levels.

Although two extreme scenarios are calculated, it is probably more economical to use a hybrid transportation model with combined air and sea shipments (Kiesmüller et al, 2005). The line of reasoning is that a relatively large amount of stock is required to cover the relatively small demand in the tail of the demand distribution. So the stock invested per item delivered (or sold) increases exponentially, while the transportation costs per item remain the same (an item is transported only once). Therefore, it is more lucrative to accelerate the items that serve demand in the tail of the demand distribution by using faster, but more expensive transportation modes. In practice this results in a constant stream of items transported by sea, while in the case of peaks in demand a part of the items is accelerated with air shipments. Such a model requires the SBS policy to make an additional allocation decision, which is currently not possible.

Three scenarios have been established for which air transportation has been modelled. In the unit contract manufacturer scenario approximately €379,000 of savings are obtained, while in the module contract manufacturer scenario €1,2 million of savings is achieved. The total scenario results in an investment reduction of €1,6 million. A large share of the investment savings is assigned to pipeline length reduction. (see Appendix H)

For each scenario a cost price saving indicates the break-even costs of switching to air transportation. These cost price savings are approximately €92 per set of units. Given the fact that the differential cost price of air shipments is €2,000 to €3,400 per set of units, it is not economically feasible to use air transportation. In fact, the other sets of modules are larger and weigh more, which would result in increasing differential costs for using air transportation for these modules. In addition, the cost price savings for these modules are lower. To conclude, transportation mode flexibility is not a lever for creating flexibility in the supply chain.

5.7. Supplier control policy

In this section we elaborate on the different aspects of responsibility and ownership in the supply chain in relation to the supplier control policy. The supplier control policy has been defined in the contracting hierarchy as it is presented in section 2.1.3.

5.7.1. Responsibilities in the supply chain

The contract with suppliers defines the responsibilities in the supply chain. In this contract, two types of order policies are distinguished; purchasing orders and delivery schedules. The purchasing order policy defines a traditional buyer-supplier relationship, while the delivery schedule defines a policy from a supply chain management perspective (Schönsleben, 2000). Namely, in the delivery schedule policy the individual objectives of the CEM and the supplier are intertwined. This supports the assumption of the SCPE model that a centralized objective function exists for the entire supply chain.

First, the contract manufacturer is awarded responsibility over the CEM stock. This refers to the inbound stock of the contract manufacturer that is covered with part commitment (this is the commitment outside the fixed fence). In the case of a purchasing order control structure, this stock is CEM owned in the sense that the CEM has ordered the item in which this part will be used. After completion of the order, the ownership of the item is transferred automatically to the CEM. From the moment of ordering, this process has become irreversible. On the contrary, in the case of delivery schedules the CEM only commits to purchasing this part (integrated in a module or unit) somewhere in the future, without specifying a moment of transfer. As a result, the responsibility and ownership of the item is transferred to the contract manufacturer. It enables the CEM to more or less control the stock position of the contract manufacturer. However, the contract manufacturer can neglect the delivery schedule information by not exploding it into its own planning and control structure. As a result, the contract manufacturer controls the inbound supply of the CEM.

Second, a part of the 'CEM owned' lead time is transferred to the contract manufacturer. (see Figure 4.3) Namely, the CEM orders a company specific item and therefore faces a lead time equal to the cumulative lead time of the longest lead time item in the supply base of that item. The delivery schedule squeezes this cumulative lead time as far as the actual processing time of the contract manufacturer (often including some slack). The remaining part of the lead time has become the responsibility of the contract manufacturer. By doing so the delivery schedule implicates the contract manufacturer in the long lead time issues of the CEM.

So the delivery schedules result in lower stock investments for the CEM due to a reduction in lead time, in addition to a reduction of the impact of obsolescence. First, the lead time is reduced by enabling the CEM to change orders from the fixed fence onwards. In the case of a purchasing order control structure, the orders from the fixed fence onwards are fixed as well. As a result, the CEM has to cover demand uncertainty over a shorter period, resulting in lower inbound stock investments. Second, the impact of obsolescence is reduced, since the CEM only commits to the supply value of the items ordered beyond the fixed fence. In a purchasing order control structure the CEM is liable for the added value of the contract manufacturer as well.

Although a delivery schedule policy reduces the impact of obsolescence, we argue that it increases the risk of obsolescence. The delivery schedules arrange that the CEM is liable for stock investments within the boundaries of a company with its own specific objectives. It is not unthinkable that this company (the contract manufacturer) assigns less priority to managing the risk of obsolescence of these stocks, since it is not affected by this risk. This is not an issue during the regular operation of the supply network, since stock is owned by the contract manufacturer in that situation. However, if the product enters the decline phase of the product life cycle, the CEM is confronted with the mismanagement of the contract manufacturer. Namely, the CEM is liable for the stock investments from that moment on.

The risk of obsolescence is significant due to the long cumulative lead times and large MOQs in the supply bases of the contract manufacturers. The long cumulative lead time demands a long horizon over which the CEM has to foresee a structural decline in sales. The large MOQ results in a large impact of not foreseeing such a decline. One way or the other, it is important to reduce MOQ and lead times and to accurately manage the phase out process during the decline phase of the product life cycle. The detection of a sales decline is in our opinion a crucial element in this process. Namely, it has been shown that the forecasting system of the CEM is performing poorly, while the sales organisation has a significant vote in the planning and control structure. The first issue results in a late detection. The second issue amplifies this effect because in general sales professionals are focussed on sales targets instead of cost targets.

In conclusion, it is recommendable for the CEM to extend the delivery schedule control policy, though only if the CEM is capable of managing the phase out processes effectively. In such a situation the delivery schedule policy reduces risk and costs in the supply chain. Note that it is more time consuming to construct purchasing contracts with delivery schedules than with purchasing orders. So the resource investment should be leveraged with the risk and cost improvements (including those of the other party). To start with, the CEM should apply the policy to all contract manufacturers and to suppliers of expensive components with long lead times. Specifically for components that have relatively short processing times in the first tier supply base, the improvement potential is large.

5.7.2. Ownership in the supply chain

Ownership in the supply chain is defined by the shipping term in the contract. Currently, the CEM is supplied free on board by contract manufacturers, which means that the ownership is transferred to the CEM at the moment of loading the items on the ship in the harbour in the Far East. As a result, the pipeline and stock investments from thereon are CEM owned. It could be considered to implement a Vendor Managed Inventory (VMI) concept in which the ownership is transferred to the CEM at the moment of delivery to the assembly or configuration lines of the CEM. This results in an investment reduction of approximately €4.5 million including stock and pipeline investments for Caligula and Nero modules sourced from contract manufacturers. Even so, the contract manufacturers will demand a compensation for the extra investments they incur.

From a business process perspective, two important arguments exist for introducing VMI concepts. First, demand uncertainty can be pooled. This is not the case in the inbound supply chain of the CEM, since the components are the CEM or even product specific. Second, VMI enables the alignment of business processes in the supply chain. Obviously, it is less complicated to align the business processes within the boundaries of one company than over the boundaries of multiple companies. For instance, it would be easier to reduce the fixed fence by annihilating several planning and transferring steps in the current lead time decomposition. (see Appendix B) A significant side effect is that the advantages of business process alignment are completely consumed by the contract manufacturer in a VMI concept. As a result, it receives a direct incentive to improve processes and thereby the integral supply chain performance. In the free on board concept the incentives for the contract manufacturer are limited.

The downside of a VMI concept is that supply chain operations planning in the inbound supply chain falls almost completely within the responsibility of the contract manufacturer. It is questionable whether this is desirable, since several professionals in the purchasing and logistics departments have expressed their worries about the supply chain management competences of the contract manufacturers.

5.8. Conclusions & Synthesis

From the scenario analysis it can be concluded that the most important driver of increasing supply chain performance is the reduction of demand uncertainty. The CEM should urgently improve its current forecasting system in order to stabilize supply chain operations. The current system of negotiation between the corporate sales organisation and the manufacturing organisation as effectuated in the MDP is outdated and underperforms heavily in terms of forecast error. Introducing a simple forecasting system based on raw demand uncertainty would already result in stock investment savings in the range of 59%, while maintaining current service levels. An advanced forecasting system will further improve supply chain performance. Even more important is the fact that these savings are achieved almost completely in the CEM owned supply chain. An improved forecasting system thus directly impacts the financial performance of the CEM.

The introduction of an up-to-date forecasting system has more impact on the planning and control structure than solely the introduction of a system. We argue that such an implementation requires a completely different mindset in planning supply chain operations. In the current planning and control structure the MDP is a crucial element, since it directly controls the capacity and material coordination mechanisms. We conclude that the MDP should only be used for capacity planning on an aggregate level. Namely, the MDP is a high level (quarterly) system for balancing demand and supply. As a result, the MDP incorporates the politics of different departments within the CEM. Directly coupling this plan to the detailed planning and control mechanisms will thus introduce these politics to supply chain operations planning. Furthermore, the MDP enables the sales organisation to directly influence the supply chain operations planning decisions, which is unwanted due to their specific business environment and subsequently unique performance targets. In our opinion, the MDP should only be used as an aggregate planning mechanism for balancing *aggregate* demand and supply, while ensuring capacity availability.

The delivery oriented control mechanism (MDP) is replaced with a service oriented control mechanism. For each product-market combination a target service level is assigned. The manufacturing organisation is responsible and accountable for maintaining this service level. The service level should be based on a solid customer service measure. As has been argued earlier, the CLIP, RLIP and SLIP require some redefinition in order to fairly describe and measure the customer service performance of the manufacturing organisation. However, the fundamentals of these service levels remain, since their fill rate oriented approach is appropriate in the business environment of the CEM.

The SCPE model has shown that a fill rate service level of 95% is efficient from both a holding and penalty costs perspective. Furthermore, the penalty costs corresponding to this target service level correctly represent the actual penalty costs incurred by not being able to deliver the right product in the right quantity at the right time. Although the current service level setting is correct, it is important to increase the organisation wide notion of the impact of service levels. It has been shown in section 5.2 and 5.3 that the SBS policy enables a quantitative approach of trading-off penalty costs and holding costs as effectuated in the service level restriction. This helps creating awareness about the costs and risks involved in maintaining a certain service level. A deeper understanding of this trade-off would lead to insight and acceptance within the different departments of the CEM organisation about the fact that supply chain performance can only be maintained with a certain stock investment and subsequently a certain cost level.

It has to be mentioned that the SCPE model has not incorporated the outbound supply chain of the CEM. As a result, the service and stock level decisions have been balanced over a restricted part of the supply chain. Still, we think that the 95% target service level is correct, since the CODP concept has been applied correctly by the CEM. The part of the supply chain that has not been included in the SCPE model is officially customer order driven. On the other hand, the current service performance is structurally lower than the 95% target. This has not been indicated as a problem area, while the sales organisation is not even aware of customer service performance measures. So it could be argued that a lower service level than 95% is sufficient as well.

So we propagate a fundamental change in the approach of supply chain operations planning from a delivery oriented to a customer service oriented model. This requires that the current stock control models are adapted accordingly. We argue that a more fact based decision structure with regard to these stock levels will result in increased supply chain performance. It has been shown in the supply chain analysis that stock levels are out of control. Furthermore, the SCPE model has shown that a rigid target stock level of two to three weeks of supply for all modules results in dead stock in the supply chain. It is disputable what cause is and what is effect; a bad performing target stock level or the uncomfortable feeling of dependency on a supply chain operations planning system.

In addition, the SCPE model has illustrated how the different target stock levels in the supply chain should be aligned. Relatively large stock investments are located at the CODP because of the specific value structure of the CEM supply chain and the fact that customer service is provided and perceived at the CODP. The CODP target stock levels should be determined according to the specific lead time and value structure of a module, resulting in different service and target stock levels for different modules; this is currently not the case since target stock levels are two to three weeks of supply for all modules. Furthermore, the supply chain of the CEM should be decoupled at the inbound stock points for modules originated from the Far East. These are not necessarily the CODP stock locations.

Further upstream in the supply chain, the SCPE model has provided insight into the most important performance levers of the supply chain. First, it has been shown that the contract manufacturers should pursue a lean manufacturing strategy with JIT delivery from their suppliers. This is currently the case and thus the CEM supply chain is aligned correctly in that sense. Second, performance improvement in this part of the supply chain should be focused on lead time reduction of the pipelines between the Far East and the configuration centres. The fixed fence in the contract with contract manufacturers should be reduced. In addition, the business processes of all parties should be further aligned in order to reduce pipeline length. Third, performance improvement in the second tier supply base should be focused on MOQ reduction. The current MOQ structure annihilates the effect of other performance levers and is a root cause of the large impact of obsolescence. Another important lever in reducing risk of obsolescence is the extension of the delivery schedule control policy to suppliers of expensive modules with long lead times. This will also result in an improvement of the stock investments in the CEM owned supply chain. Despite this all, the most important driver of the reduction of risk and impact of obsolescence is a solid system for detecting declining sales and managing phase out processes in the supply chain.

To conclude, the SCPE model has shown that transportation mode flexibility is not an economical lever for creating flexibility in the supply chain.

CHAPTER 6, CONCLUSIONS & RECOMMENDATIONS

In the previous chapter the results of the scenario analysis have been presented. In this chapter, the conclusions and recommendations are formulated based on these results. First, the most important conclusions from the supply chain analysis are summarized. Second, the recommendations resulting from the scenario analysis are presented. To conclude, areas for further research are defined.

6.1. Conclusions

This project has been initiated because a complex equipment manufacturer (CEM) expects that its current supply chain strategy is inappropriate to control the supply chain at operational, tactical and strategic levels. A structured supply chain analysis has been executed in order to gain the required detailed insight into the operational processes and corresponding planning and control structure. The conclusions from this analysis confirm the expectation of the CEM:

- The CEM operates a highly complex supply chain that can be distinguished in partial and integral outsourced structures. The complexity originates from the large number of components that is sourced from many suppliers in different geographical regions around the world. In addition, both supply chain structures face long cumulative lead times in the range of 30 to 50 weeks, while the minimum order quantities are also relatively large.

- Demand and supply side uncertainty in the supply chain of the CEM are controllable. Demand is stationary for products in the maturity phase of the product life cycle and the relative uncertainty in demand is controllable. Supply is relatively stable because capacity constraints are not an issue, while lead times are reliable.

- The forecasting system of the CEM is a source of nervousness in the supply chain because of a structurally poor performance in terms of forecast error. In addition, it lacks a rolling horizon and a performance feedback loop. The nervousness created by the forecasting system is a root cause of excessive stock, long lead times, unnecessarily high commitments, inflexibility and inefficiency.

- Flexibility in the supply chain with regard to demand changes is low because of the large difference between the requested and available reaction time in the supply chain: the standard delivery lead time to local sales organisations is 1 to 4 weeks, while the reaction time of the supply chain (or cumulative lead time) is 30 to 50 weeks. In addition, the flexibility to decrease the supply chain output is low as well, due to these same long lead times and large minimum order quantities.

- The stock control system of the CEM is not functioning properly. First, the target stock levels are based on experience, rather than fact based analysis. Second, the stock control system determines stock levels based on historical demand information instead of future demand expectations. Third, the target stock levels are violated heavily and as a result the stock investments of the CEM are out of control. This results in excessive stock investments in the supply chain and a poor customer service performance. This customer service performance is structurally lower than the targets that have been established in cooperation with the internal customers of the CEM.

Based on these observations it has been concluded that the CEM should redefine its supply chain strategy in order to increase supply chain performance. However, the CEM has no quantitative insight into the relations between the supply chain parameters and supply chain performance. Therefore the following research assignment has been defined:

"Develop an integrated supply chain performance evaluation model
to enable the CEM to better leverage inbound supply chain performance."

6.2. Recommendations

A design model has been developed in order to define the appropriate supply chain performance indicators and supply chain parameters. The design model is accompanied with a set of scenarios enabling the evaluation of different supply chain strategies. The analysis of these scenarios has resulted in the following recommendations.

The CEM should focus its supply chain strategy on:

- Improving the forecasting system

  The CEM should urgently improve its current forecasting system in order to stabilize supply chain operations. The current system is outdated and underperforms heavily in terms of forecast error. Introducing a simple forecasting system based on raw demand uncertainty would result in stock investment savings in the CEM owned supply chain in the range of 60%.

- Decoupling the MDP from the supply chain operations planning

  The MDP should only be used as an aggregate planning and control mechanism for balancing *aggregate* demand, supply and capacity. Namely, it incorporates the politics of different departments within the CEM. Furthermore, it enables the sales organisation to directly influence the supply chain operations planning decisions. This is unwanted due to the specific business environments and subsequently unique performance targets of these different organisational units.

- Transforming from a delivery oriented to a service oriented supply chain

  The delivery oriented control mechanism (MDP) should be replaced with a service oriented control mechanism. For each product-market combination a target service level has to be determined, for which the manufacturing organisation is responsible and accountable. As a result, the manufacturing organisation pursues a long term objective, instead of chasing individual orders. The fundamentals of the current service level definitions are correct and the SCPE model has shown that the target of 95% is efficient from both a holding and penalty costs perspective.

- Formalizing and updating the current stock control system

  The above mentioned fundamental change in the approach of supply chain operations planning requires that the current stock control system is updated accordingly. A fact based decision structure for setting stock levels should be implemented in the ERP system resulting in increased supply chain performance. The target stock levels of different items at the CODP should be synchronised according to their specific value and lead time structure. The SCPE model has shown that the CODP target stock levels are crucial in the supply chain performance.

- Reducing lead times of contract manufacturers

  Performance improvement in the upstream supply chain should be focused on lead time reduction of the pipelines between the Far East and the CODPs. The fixed fence in the contract with contract manufacturers should be reduced, in addition to business process alignment in order to realize pipeline length reduction. The contract manufacturers should pursue a lean manufacturing strategy with Just-In-Time delivery from their suppliers.

6.3. Areas for further research

During this empirical case study some issues have evolved with regard to the SBS policy that are not mentioned by De Kok and Fransoo (2003) as an area for further research. First, the integration of optionals in the ATO supply network structure is an important issue in the context of increasingly modular structured supply chains. Second, the application of different forecast errors to items with different cumulative lead times in the same supply network structure is impossible. This is a fundamental error in multi-echelon stock control models. To conclude, this project has shown that lot sizing decisions (or MOQ settings) are relevant in the supply chain operations planning function. Although a relatively smooth procedure has been developed to circumvent this issue, it would add significant value to the applicability of the SBS policy if lot sizes would be incorporated.

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READING GUIDES

From this page onwards, the table of figures is presented and the abbreviations, definitions and symbols used throughout the report are defined.

Table of figures

Abbreviations

Concept	Definition
ABC	Activity Based Costing
AP	Assembly Plan
ATO	Assemble-To-Order
BOM	Bill Of Materials
BOP	Bill Of Processes
CEM	Complex Equipment Manufacturer
CODP	Customer Order Decoupling Point
COV	Coefficient Of Variation
CPB	Common Product Body
ERP	Enterprise Resource Planning
JIT	Just-In-Time
MAPE	Mean Absolute Percentage Error
MCM	Module Contract Manufacturer
MDP	Manufacturing & Delivery Plan
MOQ	Minimum Order Quantity
MRP	Material Requirements Planning
MS	Microsoft
MTS	Make-To-Stock
OEM	Original Equipment Manufacturer
LSO	Local Sales Organisation
R&D	Research and Development
rMDP	Revised MDP
SBS	Synchronized Base Stock
SCOP	Supply Chain Operations Planning
SCPE	Supply Chain Performance Evaluation
SOP	Sales and Operations Plan
UCM	Unit Contract Manufacturer
USA	United States of America
VMI	Vendor Managed Inventory

Definitions

Terminology	Definition
Added value	The value that is added to item i during the transformation process that creates item i.
BOM quantity	Number of items I required to produce one item j.
BOM structure	The matrix a_{ij}, where a is the number of items i required to produce one item j.
BOP structure	The set of resources and the items they process.
Component	The set of elements consisting of parts, subassemblies, units and modules as defined by the BOM.
Contract manufacturer	A company that supplies components based on buyer specifications; the component is integrated in the buyers' own products or services.
Cumulative lead time	The throughput time between the moment of release of an order for item i and the moment at which the ordered items are available for delivery to customers as part of a product.
Customer service	Service perceived by the customer with regard to the availability of the right product in the right quantity, in the right time.
Cycle service level	Fraction of cycles in which the on hand stock does not drop to zero.
Dependent demand	Demand that is generated from the (in)dependent demand of items in the supply network.
End-item	An item that is not used in any other item and is stocked at the CODP.
Fill rate	Fraction of customer demand that is met routinely, without backordering or lost sales.
Inbound supply chain	The upstream supply chain from the configuration centres onwards.
Independent demand	The external customer demand, which is exogenous to the supply network.
Integral outsourced supply chain	Supply chain in which the final assembly process is outsourced to contract manufacturers.
Intermediate item	Item that is required for at least one other item.
Stock point	Point in the supply chain at which products or components are kept on stock.
Item	The generic term for any input into and any output from transformation activities; an item is a unique instance of a component.
Lead time	The throughput time between the moment of release of an order for item i and the moment at which the ordered items are available for usage in other items and/or delivery to customers.
MOQ item	Item with an expected review period longer than one week.
OEM supply chain	Supply chain in which the product is sourced by turnkey subcontracting.
Outbound supply chain	The downstream supply chain from the configuration centre onwards.
Partial outsourced supply chain	Supply chain in which the final assembly process is executed by the CEM.
Penalty costs	The costs incurred by delaying or loosing a customer order.
Planned lead time	The lead time of a supplier as defined in the purchasing contract.
Predecessor (item i of item j)	The item i that is required to manufacture item j.
Processing step	Point in the supply chain at which value is added to a set of components during a process executed on a certain resource.
Processing time	The period in number of weeks during which an order is being processed.
Product	The complex system that is sold to the customer, representing the highest level of the BOM.
Ready rate	Fraction of time during which the net stock is positive.
Replenishment lead time	The lead time required to deliver a module to a specific configuration centre.
Resource	The system that creates an item by executing a transformation activity.
Review period	Period between subsequent release decisions for an item in the supply network.
SBS policy	A coordination mechanism for executing the supply chain operations planning function.
Supply chain operations planning	The function that coordinates activities in the supply chain by making decisions on the quantities and timing of material and resource releases.
Second tier supplier	A supplier of the contract manufacturer.
Service level	Measure of customer service.
Shipping term	A term that defines the responsibilities among parties during transport.

Terminology	Definition
Standard LSO lead time	The agreed lead time of the configuration centre for delivery to the LSO, where the moment of delivery is defined as the moment that the configuration is booked into the processes of the distributor.
Standard price	Purchasing price in euro of one item i as defined in the purchasing contract.
Successor (item j of item i)	The item j that contains item i.
Supplier	A single company in the supply base.
Supply chain	The chain of processes that purchases raw materials, transforms them into semi-finished and ultimately marketable products and distributes these to the customer.
Supply network	A network of activities transforming inputs into outputs using available resources, defined by parent-child relationships between items.
Supply network parameters	The specific conditions under which the supply network structure is/can be operated.
Supply network structure	The goods flows through the supply chain and their interconnections in the supply network.
Supply value	The aggregated values of the predecessors of item j.
Transformation activity	A general designation of any type of relationship between two items in a supply chain, both referring to physical transformation activities such as assembly activities and to non-physical transformation activities such as transportation from one location to another.
Unit price	Purchasing price in a random currency of one item as defined in the purchasing contract.
Value	The monetary value of an item.
Vertical integrated supply chain	A supply chain that is completely owned by one company.
Virtual integrated supply chain	A series of companies that cooperate in order to be able to develop, produce and distribute products.

Symbols

Symbol	Definition	Unit of measurement
a_{ij}	Number of items i required to manufacture one item j, i = 1,2,...,N, j = 1,2,...,N	1/1
b	BOM level	-
B	Average backlog per period	1/week
c	Subscript defining the unit of measurement as value	-
C_i	Set of items j with a cumulative lead time shorter than that of item i	-
COC	Cost of capital	year/year
COV[χ]	Coefficient of variation of the expected demand	1/1
CPS	Cost price savings	euro
CS_q	Average cycle stock level	1/1
d	Dummy item	-
D	Set of items in the aggregated model	-
E	Set of end-items	-
$E[D_j]$	Expected independent demand for item j	1/week
$E[D_{set}]$	Expected demand for a set of units and/or modules	set/week
$E[G_i]$	Expected dependent demand for item i	1/week
$E[R_i]$	Expected review period for item i	weeks
E[χ]	Expected demand	1/unit of time
e_{ij}	Number of intermediate items i that occurs in end-item j, I ϵ I, j ϵ E	1/1
F	Weighted average forecast error faced by the supply chain	1/1
F_1	Forecast error over a lead time of duration L_T	1/1
F_2	Forecast error over one forecast update period	1/1
F_{Lc}	Weighted average of the forecast error faced by items with cumulative lead time L_c	1/1
F_T	Forecast error of forecast T	1/1
$F_{T,Lc}$	Forecast error of the most recent forecast used for the item with cumulative lead time L_c	1/1
F_{T-1}	Forecast error of the forecast that has been updated by forecast T	1/1
h	Value	euro
i	Item	-
I	Set of intermediary items	-
k	Resource	-
k_α	Safety factor	1/1
L	Lead time	weeks
L*	Length of the pipeline	weeks
$L_{0,T}$	Shortest cumulative lead time for which forecast T is used	weeks
$L_{1,T}$	Longest cumulative lead time for which forecast T is used	weeks
L_c	Cumulative lead time	weeks
L_T	Lead time in number of forecast update periods	1/1
L_x	Longest planned lead time of an item in the second tier supply base	weeks
L_y	Transportation mode dependent transportation lead time according to Table B.3	weeks
L_z	Transportation lead time according to Table B.4	weeks
MAPE	Mean absolute percentage error as defined in Silver et al (1998)	%
MOQ	Minimum order quantity	1/1
n	Number of observations	1/1
p	Periodic penalty costs	euro/week
P_1	Cycle service level	1/1
P_2	Fill rate	1/1
P_3	Ready rate	1/1
pen	Item penalty costs; penalty costs for backlogging one item for one period	euro/week*item

Symbol	Definition	Unit of measurement
PL_c	Average pipeline level in value	euro
PL_q	Average pipeline level in number of items	1/1
q	Subscript defining the unit of measurement as number of items	-
R	Review period	weeks
R'	Recalculated review period that is used in the SBS policy	1/1
S_c	Average stock level in value	euro
S_q	Average stock level in number of items	1/1
S_t	Average stock level in unit of time	weeks
SS_q	Safety stock level	1/1
ST	Set of MOQ items in the supply bases	-
sv	Supply value	euro
t	Subscript defining the unit of measurement as time	-
T	Forecast	-
v	Added value	euro
V	Set of predecessors of an item	-
v_{Lc}	Added value injected in supply chain by releasing items with cumulative lead time L_c	euro
W	Set of successors of an item	-
x_t	Actual deliveries in period t	1/1
$x_{t-1,t}$	Forecast at moment t-1 over period t	1/1
β	Coefficient that is estimated empirically	1/1
$\sigma[D_j]$	Standard deviation of the expected independent demand for item j	1/week
$\sigma[G_i]$	Standard deviation of the expected dependent demand for item i	1/week
$\sigma[\chi]$	Standard deviation of the expected demand	1/unit of time
χ	Random variable	-

TABLE OF APPENDICES

APPENDIX A, DEMAND ANALYSIS

In this appendix the demand analysis is presented. The data that has been used is based on the sales order figures in the ERP system.

Demand can be seen as a time series that consists of a certain level, trend, seasonal effect and irregular random fluctuations. (Silver et al, 1998) The seasonal effect of a time series can be determined by constructing a correlogram (Chatfield, 2004). In a correlogram the autocorrelation coefficients of the time series are plotted against the periods. The autocorrelation coefficients determine the correlation between observations at different distances apart. If a time series is said to be seasonal, then the correlogram will show the same seasonal pattern. By adding an upper and lower boundary to the correlogram, it can be shown that a seasonal effect is significant. In common practice this boundary is set at $1/\sqrt{N}$, where N is the number of observations. It is advised to use at least three complete seasons of data, while trend effects have to be removed.

Three years of demand data is available for four products on a monthly level. All other products have started or ended their product life cycle in the past three years and can therefore not be analyzed on seasonal effects. A monthly level is an appropriate level, since the seasonal effects described by employees can be observed at this level.

The trend effect is removed with the exponential smoothing procedure described by Silver et al (1998). First the seasonal pattern is removed by determining the centred moving averages with a number of periods that equals the season. In our case the season is one year, or 12 months. With this centred moving average a least squares regression model is applied in order to determine the level and trend. The difference between the trend model and the real demand data shows the pure seasonal pattern.

This data is plotted in a correlogram by using Matlab R2006b. Only the demand for one product at the Asian configuration centre shows a seasonal pattern with a frequency of five months. However, the effect is not significant, since there are no values outside the significance boundaries. Furthermore, the effect cannot be explained. Therefore, it is reasonable to assume that demand is free from seasonal effects.

Since the replenishment lead time of the CODPs is between 1 and 6 weeks, demand has to be modelled on a weekly level. This replenishment lead time is defined as the period in number of weeks between ordering a module and receiving the order at the configuration centre. On a weekly level demand figures are available over a one year horizon.

The trend effect, which has been shown to be significant on a monthly level, is not significant on a weekly level. This is shown by applying the least squares regression model that is described by Silver et al (1998). Therefore, it is reasonable to assume that demand is stationary.

To conclude, the random fluctuations have been examined, expressed in the standard deviation of the expected demand. The mean, standard deviation and coefficient of variation have been determined for each product. In addition, the demand of three products has been fitted with Exponential, Gamma, Normal and Poisson probability distributions (see De Kok, 2002). This is done by importing the demand data in Statgraphics Centurion XV software and applying the ‘distribution fitting’ function. It is shown that Gamma and Normal distribution fit with 95% confidence.

APPENDIX B, CUMULATIVE LEAD TIME ANALYSIS

In this appendix the cumulative lead time in both the integral and partial outsourced supply chain is analysed based on a decomposition of the different processing steps in the supply chain.

In Table B.1 and Table B.2 the processes are decomposed in the order of their appearance. The lead time of each processing step has been determined, based on estimates of logistics professionals. The process itself is considered as a black box. The decomposition reaches as far as the processes of the second tier suppliers. Their processing steps have been analysed, although the second tier supplier is seen as a black box for which the planned lead time concept applies (see De Kok & Fransoo, 2003). In Figure B.1 and Figure B.2 the decomposition is visualized in a Gantt-chart that also presents the relation with the supply chain definition in Figure 2.2.

Based on this decomposition, the cumulative lead time in the inbound supply chain is defined:

(7) $L_{c,partial} = 12 + L_x + L_y + L_z$

(8) $L_{c,integral} = 9 + L_x + L_z$

Where:
L_c is the cumulative lead time in weeks.
L_x is the longest planned lead time of an item in the second tier supply base in weeks.
L_y is the transportation mode dependent transportation lead time in weeks according to Table B.3.
L_z is the transportation lead time in weeks according to Table B.4.

This cumulative lead time defines the reaction time of the inbound supply chain. In the outbound supply chain a required reaction time is defined by the standard LSO lead time. This standard LSO lead time is the number of weeks between the moment of ordering a certain configuration and the moment that the configuration leaves the configuration centre. It is established at 1, 2, 3 or 4 weeks depending on the product and configuration centre combination. Since the starting moment is defined as the moment of ordering, and the configuration process is customer order driven, the available reaction time is 0 to 3 weeks.

	Process	Lead time (weeks)
	Process owner: CEM	
1	Order detection	1
	Process owner: Contract manufacturer	
2	Order generation	1
3a	Production planning	1
	Process owner: Second tier supplier	
3b	Planned lead time	L_x
	Process owner: Contract manufacturer	
4	Goods receiving	1
5a	Manufacturing	2
5b	Transportation planning	1
	Process owner: Contract manufacturer / CEM	
6	Transportation	L_y
	Process owner: CEM	
7	Final assembly	2
8	Handling	1
9	Transportation to configuration centre	L_z
10	Goods receiving	1
11	Configuration	1

Table B.1: Cumulative lead time decomposition of the partial outsourced supply chain

	Process	Lead time (weeks)
	Process owner: CEM	
1	Order detection	1
	Process owner: Contract manufacturer	
2	Order generation	1
3a	Production planning	1
	Process owner: Second tier supplier	
3b	Planned lead time	L_x
	Process owner: Contract manufacturer	
4	Goods receiving	1
5a	Manufacturing	2
5b	Transportation planning	1
	Process owner: Contract manufacturer / CEM	
6	Transportation to configuration centre	L_z
	Process owner: CEM	
7	Goods receiving	1
8	Configuration	1

Table B.2: Cumulative lead time decomposition of the integral outsourced supply chain

The transportation lead times are defined in Table B.4 under the assumption that components are transported over sea. In Table B.3 the transportation lead times between the Far East and Europe are defined for different transportation modes.

Process	Lead time (weeks)
Sea	
Transport	6
Handling	1
Air	
Transport	2
Express	
Transport	1

Table B.3: Transportation lead times for different transportation modes

From \ to (weeks)	Asia	Europe	USA
Europe	6	0	5
Contract manufacturer	1	6	4

Table B.4: Standard transportation lead times

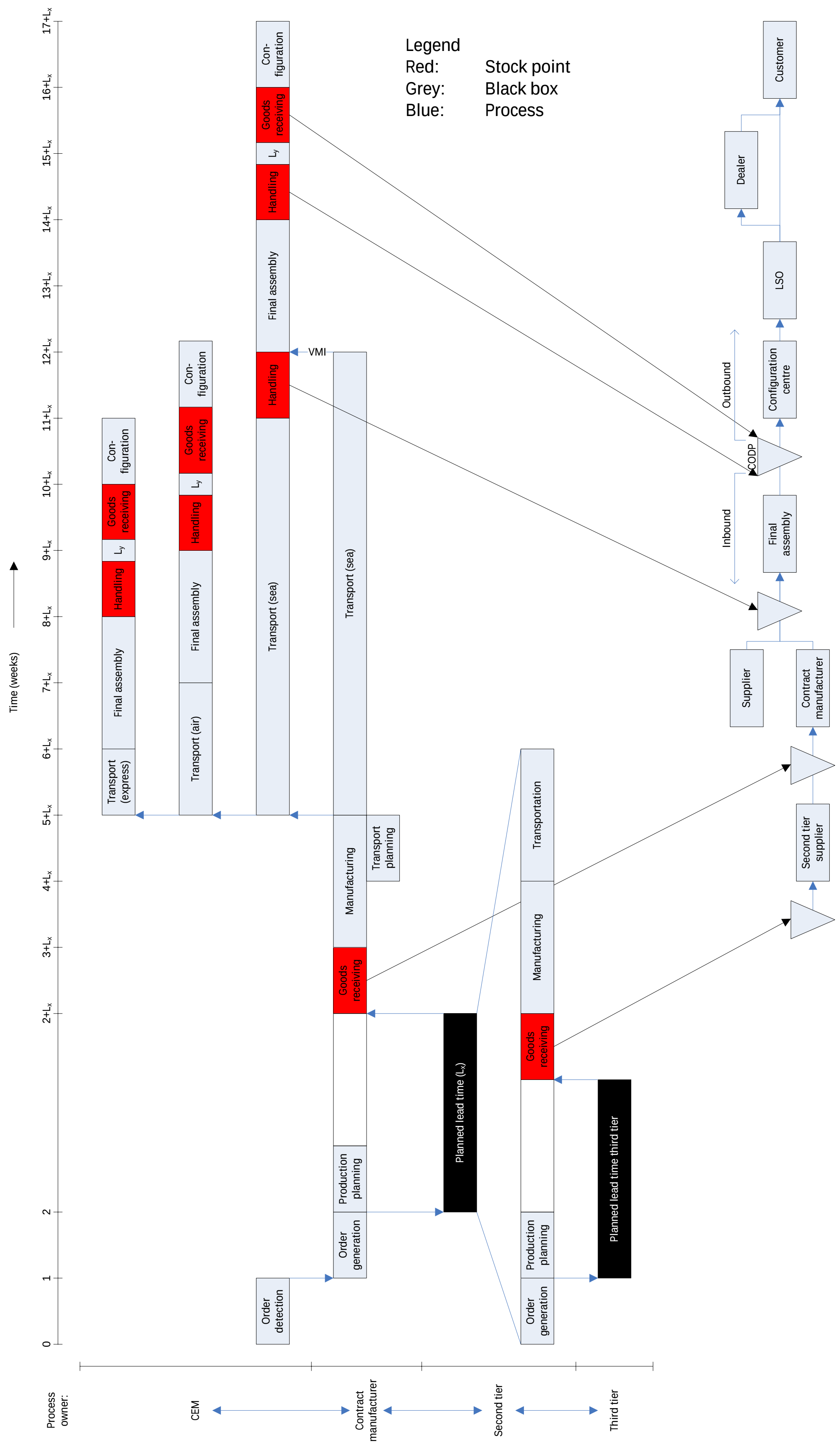

Figure B.1: Gantt-chart of the cumulative lead time decomposition of the partial outsourced supply chain

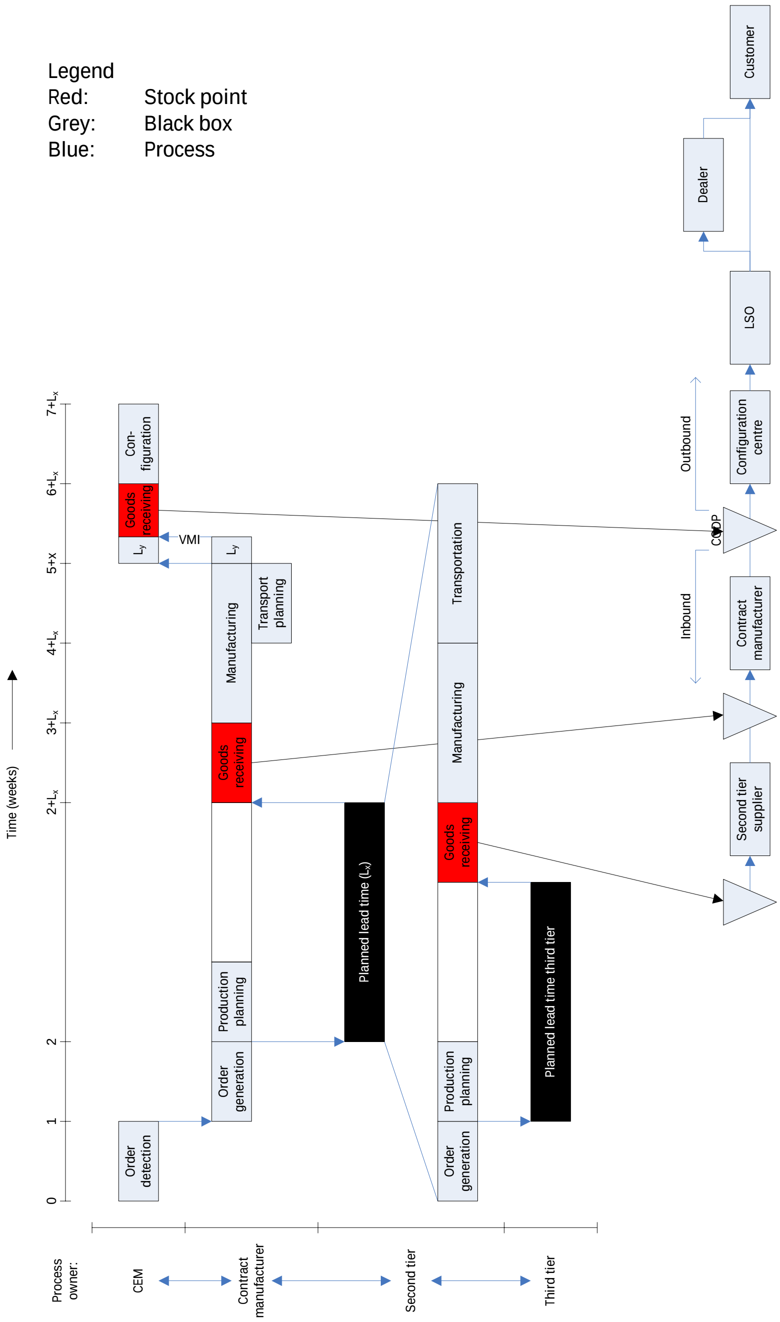

Figure B.2: Gantt-chart of the cumulative lead time decomposition of the integral outsourced supply chain

APPENDIX C, PLANNING AND CONTROL STRUCTURE

In this appendix the planning and control structure of the CEM is presented based on the BWW framework (Bertrand et al, 1998).

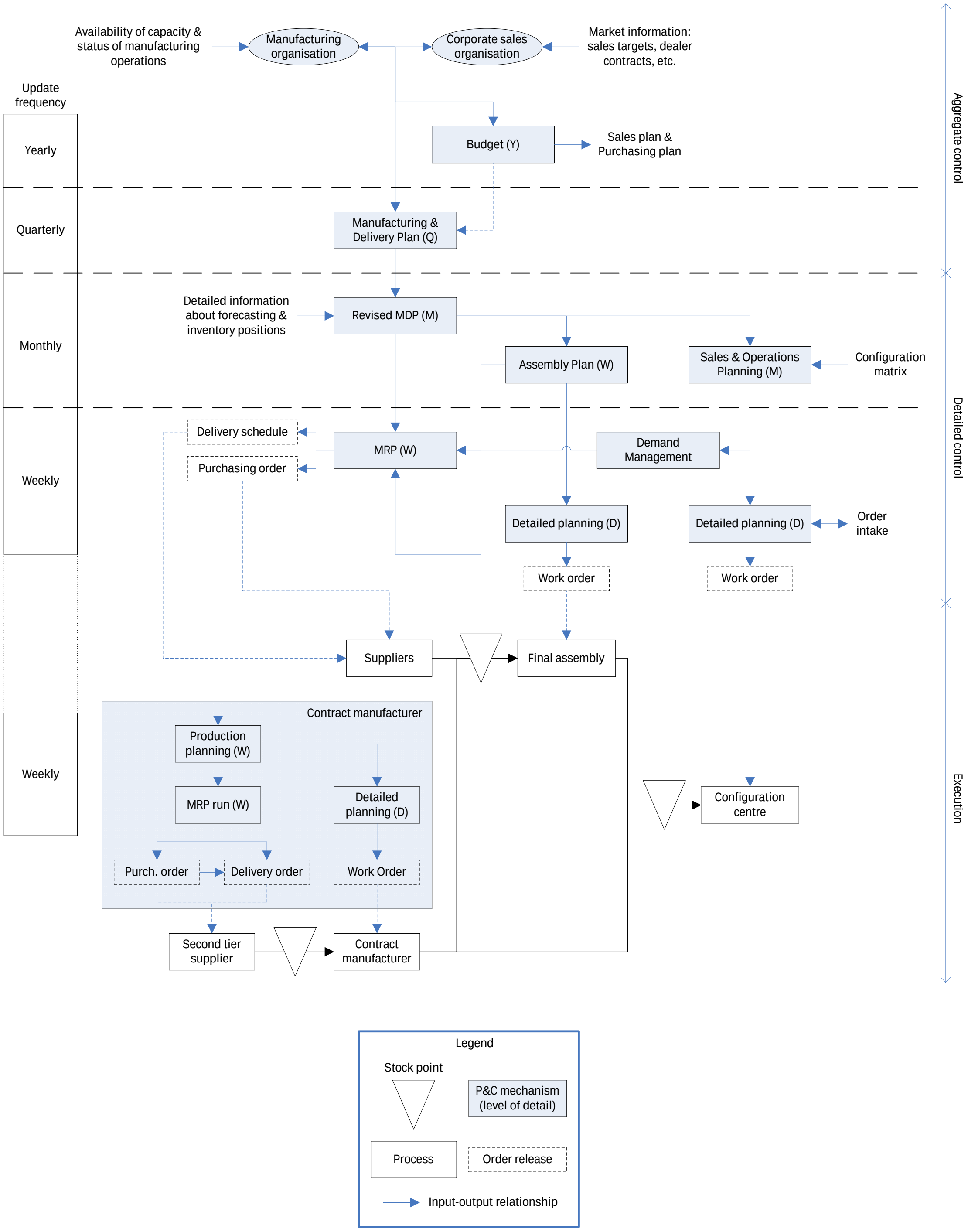

Figure C.3: Planning and control structure of the CEM

APPENDIX D, PROCEDURE TO DETERMINE THE FORECAST ERROR

In this appendix a procedure is described to determine the current forecast error faced by the supply chain in order to assess the current performance of the forecasting system and to determine the effect of improving this system.

It is required to quantify the current forecast error perceived by the supply chain. This is complicated for two reasons. First, the supply chain faces different forecast errors for different items, while we are interested in a single measure that can be compared with the raw demand uncertainty. This would indicate the current performance of the forecasting system. Analogous to this requirement, multi-echelon stock control models also assume a single forecast error for the entire supply chain. So in order to determine the current impact of the forecast error it is required to define the forecast error as it is perceived by the entire supply chain. Second, the forecast is constructed at an aggregated quarterly level, while the supply chain is controlled at a weekly level.

In the cumulative lead time distribution of the items in the Nero supply chain it can be seen that different items are controlled with different forecasts. (see section 5.4) The relation between the cumulative lead time and the forecasts is described in Table D.5.

T	L_0	L_1	F
T-0	0	13	0.31
T-1	13	26	0.39
T-2	26	39	0.47
T-3	39	52	0.61

Table D.5: Relation between forecast and cumulative lead time

L_0 represents the shortest cumulative lead time, while L_1 represents the longest cumulative lead time, for which the forecast T with forecaster error F is used. Forecast error F_T is defined according to the definition of the mean square error or MSE of Silver et al (1998):

$$(9)\quad F_T = \frac{\sum_{t=1}^{n}\left(x_t - \hat{x}_{t-1,t}\right)^2}{\sum_{t=1}^{n} x_t}$$

F_T is the forecast error of forecast T.
x_t are the actual deliveries in period t.
$x_{t-1,t}$ is the forecast at moment t-1 over period t.
n is the number of observations.

If it is assumed that demand is equally divided over the weeks within a quarter (which is true under the assumption of stationary demand), a weighted average forecast error can be determined for each specific cumulative lead time:

$$(10)\quad F_{L_c} = \left(1 - \frac{L_c - L_{0,T}}{L_{1,T} - L_{0,T}}\right) F_{T,L_c} + \frac{L_c - L_{0,T}}{L_{1,T} - L_{0,T}} F_{T-1}$$

Where:
F_{Lc} is the weighted average of the forecast error faced by items with cumulative lead time L_c.
L_c is the cumulative lead time in weeks.
$L_{0,T}$ is the shortest cumulative lead time for which forecast T is used in weeks.
$L_{1,T}$ is the longest cumulative lead time for which forecast T is used in weeks.
$F_{T,Lc}$ is the forecast error of the most recent forecast used for the item with cumulative lead time L_c.
F_{T-1} is the forecast error of the forecast that has been updated by forecast T.

Now orders are released each review period for all items and thus for all cumulative lead times present in the supply chain. This release decision is in fact a decision to inject a certain amount of value into the supply chain, represented by the added value of the items for which the release decision is made. Based on the Pareto logic (Silver et al, 1998), it is determined that the forecast error faced by the supply chain is the average of the forecast errors for each cumulative lead time for which a release decision has to be made, weighted with the added value injected in the supply chain with each release decision. For the Nero supply chain the estimated forecast error is 0.41 at a quarterly level:

$$(11)\quad F = \frac{\sum_{L_c} F_{L_c} v_{L_c}}{\sum_{L_c} v_{L_c}}$$

$$(12)\quad v_{L_c} = \sum_{i|L_c=L_c} v_i$$

Where:
F is the weighted average forecast error faced by the supply chain.
v_{Lc} is the added value injected in the supply chain by releasing items with cumulative lead time L_c.
v_i is the added value of item i.

Silver et al (1998) present a procedure to translate this aggregated forecast error into a forecast error at the level at which the supply chain is controlled. The following formula is applied, which translates the aggregated forecast error (F_1) into a forecast error over the lead time considered in the stock control model (F_2):

$$(13)\quad F_1 = L_T^{\beta} F_2 = L_T^{\beta} F$$

Where:
F_1 is the forecast error over a lead time of duration L_T.
L_T is the lead time in number of forecast update periods.
F_2 is the forecast error over one forecast update period, which equals the estimate F.
β is a coefficient that is estimated empirically.

At least three years of historical data is required for estimating the coefficient β. Since the data is unavailable, it is impossible to determine the coefficient. Nevertheless, Silver et al (1998) state that setting β at 0.5 results in quite reasonable empirical behaviour. This setting implicitly assumes independent demand between the weeks within a quarter. In practice, this is almost never true, although the demand analysis (see Appendix A) has not been able to reject the idea that demand is independent. Therefore, it is appropriate to apply this procedure, which results in a forecast error of 1.49.

APPENDIX E, DATA ENGINE

In this appendix the data engine is described.

Since the SCPE model deals with a large number of items, an automated data processing tool has been developed. This prevents the outcomes of the model being biased by human error. Furthermore, it enables quick and structured reporting of the scenario analysis. The tool is referred to as the data engine, and has been developed in MS Office, using MS Excel and MS Access.

The data engine basically processes the input data and output data from the interfaces of SCOPE and the actual data of the CEM. The input data is reported in a database that has been created based on the aggregation procedure described in Appendix F. The output data is reported in a database that has been generated based on the output interface of SCOPE. The actual data of the CEM is reported in a database that has been created with the data from the original sources.

The data engine is described with an UML diagram (Alter, 2002) in Figure E.4. The input and output databases from SCOPE are linked by a unique identifier, the item number i. The input data from SCOPE is linked to the actual data by the merging rules that have been developed in the merging model. The unique identifiers are the supply network structure (b and a_{ij}) and lead times (L). The output of the data engine is a spreadsheet with for each item defined in the actual dataset the relevant parameters and decisions.

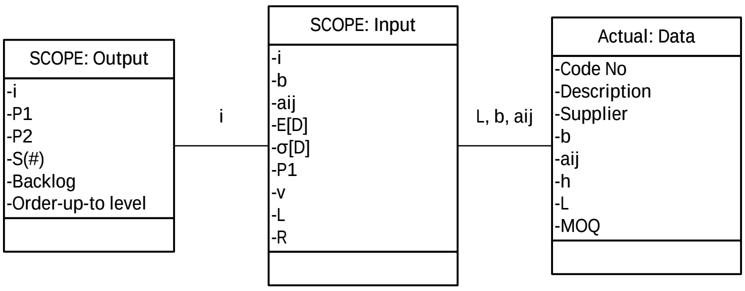

Figure E.4: UML diagram of the data engine

APPENDIX F, AGGREGATION PROCEDURE

In this appendix the aggregation procedure that has been applied to the SCPE model is described.

F.1. Demand model

First the demand model is defined, which assumes the availability of an exogenous independent demand distribution for end-items. The formulas below describe the expected dependent demand and the standard deviation of the expected dependent demand:

$$(14)\quad E\left[G_i\right] = \sum_{j=1}^{N} e_{ij} E\left[D_j\right]$$

$$(15)\quad \sigma\left[G_i\right] = \sqrt{\sum_{j=1}^{N} \left(e_{ij}\sigma\left[D_j\right]\right)^2}$$

$$I\left\{i \mid \exists 1 \le j \le N, a_{ij} > 0, i = 1,2,\ldots,N\right\}$$

$$E\left\{i \mid a_{ij} = 0, i = 1,2,\ldots,N, j = 1,2,\ldots,N\right\}$$

Where:
$E[D_j]$ is the expected independent demand per unit of time for item j.
$E[G_i]$ is the expected dependent demand per unit of time for item i.
$\sigma[D_j]$ is the standard deviation of the expected independent demand per unit of time for item j.
$\sigma[G_i]$ is the standard deviation of the expected dependent demand per unit of time for item i.
a_{ij} is the number of items i required to manufacture one item j, i = 1,2,...,N, j = 1,2,...,N.
e_{ij} is the number of intermediate items i that occurs in end-item j, i є I, j є E.
I is the set of intermediary items.
E is the set of end-items.

F.2. Relation between the aggregated model and the SCPE model

Second, the relation between the actual item and the item in the aggregated model –the dummy item– is defined. Actual item i is represented by dummy item d if the lead time, review period and BOM level are equal:

$$(16)\quad i \equiv d$$

$$d \in D$$

$$(17)\quad L_i = L_d$$

$$(18)\quad R_i = R_d$$

$$(19)\quad b_i = b_d$$

This BOM level is assigned based on the supply network structure. It groups items based on isolated parent-child relations, regardless of the BOP and BOM structure in the supply network upstream or downstream of this specific parent-child relation. The BOM level is assigned according to the following definition:

“All predecessor items of an item are assigned the same BOM level,
as well as all predecessor items of a brother of the item, where the brother item
is defined as an item that consists of one or more similar predecessor items.”

In Figure F.5 an example is given of the assignment of BOM levels in a typical BOM structure with end-items e, modules m, units u and parts i. Item i_1 and i_2 are assigned the same BOM level, since

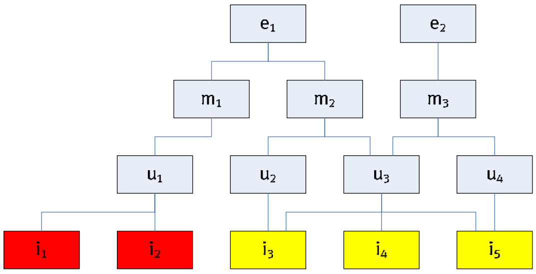

Figure F.5: Example BOM structure

they have a single and similar parent. Item i_3, i_4 and i_5 are assigned the same BOM level, since their parents are brother items. Namely, item i_3 is a child of item u_2 and item u_3, so item u_2 and u_3 are brother items. Furthermore, item i_5 is a child of item u_3 and item u_4, so item u_3 and u_4 are also brother items. So item u_2, u_3 and u_4 are brother items and thus all children items (i_3, i_4 and i_5) are assigned the same BOM level.

The BOM level creates the subsystems that are mentioned in section 4.3. A general assembly subsystem is defined as a certain BOM level for which the items have more than one parent, while a pure assembly subsystem is defined as a certain BOM level for which all items have the same unique parent. In the example, the BOM level of item i_1 and i_2 is defined as a pure assembly subsystem, since it has one unique parent (item u_1). The BOM level of item i_3, i_4 and i_5 is defined as a general assembly subsystem, since it has multiple parents (item u_2, u_3 and u_4).

The different structure of the pure assembly and general assembly subsystem result in a different impact of the demand model on the SBS policy. Namely, in a pure assembly subsystem items have only one parent. As a result, the coefficients of variation (and thus demand uncertainty) of all items in that subsystem are equal. On the contrary, in a general assembly subsystem items have multiple parents. As a result the coefficients of variation (and thus demand uncertainty) of the items in that subsystem are different. This originates from the fact that demand uncertainty in the analytical expressions of the SBS policy is represented by the coefficient of variation of the expected demand. If demand uncertainty is enumerated, the squared standard deviation (also referred to as variability) of the expected demand is used. Therefore, the coefficient of variation of the expected dependent demand of items in a general assembly subsystem differs for items with different parents or for items with different ratios between the BOM quantities in which they occur in these parents (also referred to as multiplicity). An exceptional instance of this case is when the coefficients of variation of the expected independent demand of the parents are equal.

F.3. Aggregation procedure

Third, the aggregation procedure is defined. Since the demand model has a different impact on both types of subsystems, the aggregation procedure is different as well.

In a general assembly subsystem the BOM quantities are left intact in the dummy items, since the SBS policy has to be able to take into account multiplicity. So items are aggregated if constraints (17), (18) and (19) hold and the items have similar multiplicity. In that case, the added value of the actual items is summed in order to ensure that the value structure of the aggregated model represents the actual value structure correctly:

$$(20)\quad a_{ij} = a_{id}$$

$$(21)\quad v_d = \sum_{i \equiv d} v_i$$

In a pure assembly subsystem multiplicity can be ignored, since the subsystem has only one parent. As a result, the BOM quantity of actual items does not influence the aggregation procedure. This is convenient, since it enables the aggregation of items with different BOM quantities. Namely, items are aggregated according to constraints (17), (18) and (19), while the BOM quantity of the dummy item is set equal to one. In order to ensure that the value structure of the aggregated model represents the actual value structure correctly, the supply values of the original items are summed:

(22) $a_{id} = 1$

(23) $v_d = \sum_{i \equiv d} a_{ij} v_i$

Now the parameter setting of the dummy items has been defined exhaustively and so the SBS policy can be applied. Subsequently, the output of the model is decomposed.

The service levels of the dummy items are equal to those of the actual items they represent:

(24) $P_{1,d} = P_{1,i}$

(25) $P_{2,d} = P_{2,i}$

(26) $P_{3,d} = P_{3,i}$

For general assembly subsystems the average stock levels in number of items are equal as well, since the BOM quantities have been left intact:

(27) $S_{d,q} = S_{i,q}$

For pure assembly subsystems the BOM quantities have been set to one. Therefore, the average stock level of the dummy item in number of items has to be multiplied with the BOM quantities of the actual item in order to obtain the actual stock level:

(28) $\sum_{j=1}^{N} a_{ij} S_{d,q} = S_{i,q}$

To conclude the following general relations are formulated to determine the average stock and pipeline levels in number of items, time and value:

(29) $S_{i,t} = \frac{S_{i,q}}{E\left[G_i\right]}$

(30) $S_{i,c} = S_{i,q} h_i$

(31) $PL_{i,q} = E\left[G_i\right] L_i^*$

(32) $PL_{i,c} = PL_{i,q} h_i$

Where:
Item i is an item represented by dummy item d.
D is the set of items in the aggregated model.
L is the lead time in unit of time.
R is the review period in unit of time.
b is the BOM level.
v is the added value of an item.
P_1 is the cycle service level (1/1).
P_2 is the fill rate (1/1).
P_3 is the ready rate (1/1).
S is the average stock level.
h is the value an item.
PL is the average pipeline level.
L* is the length of the pipeline in unit of time.
The subscripts q, t and c define the unit of measurement as number of items, unit of time and value.

For both aggregation procedures an example has been constructed based on Figure F.5.

Example A: aggregation procedure in a general assembly subsystem
Item i_5 in Figure F.5 and item i_6 both have a lead time of six weeks and a review period of one week, while they occur once in item u_3 and twice in item u_4. Dummy item d_1 represents these items in the aggregated model as presented in Table F.6.

Item	L	R	$a_{i,u3}$	$a_{i,u4}$	v		P_1	S_q
i5	6	1	1	2	1		0.62	5
i6	6	1	1	2	2		0.62	5
d1	6	1	1	2	3	→	0.62	5

Table F.6: Example of the aggregation procedure in a general assembly subsystem

Example B: aggregation procedure in a pure assembly subsystem
Item i_1 and i_2 in Figure F.5 both have a lead time of six weeks and a review period of one week. Dummy item d_2 represents these items in the aggregated model as presented in Table F.7.

Item	L	R	$a_{i,u2}$	v		P_1	S_q
i_1	6	1	2	1		0.62	10
i_2	6	1	3	2		0.62	15
d_2	6	1	1	8	→	0.62	5

Table F.7: Example of the aggregation procedure in a pure assembly subsystem

F.4. Application to the CEM situation

To conclude, the aggregation procedure has been applied to the CEM situation, resulting in the aggregated model that represents the supply network structure. The aggregation procedure results in a significant reduction of the number of items that has to be modelled with the SBS policy. (see Table F.8)

	Number of items	
b	SCOPE	SCPE
1	3	2
2	5	7
3	1	2
4	1	1
5	1	13
6	23	390
7	26	921
8	94*	758
Total	154	2094

Table F.8: Results of the aggregation procedure

* The aggregation procedure still results in 371 BOM level 8 items and therefore the Pareto rule has to be applied in order to achieve a feasible number of items. If 90% of the BOM level 8 supply value is taken into account, it is required to model 94 items in SCOPE. This is within the capacity of the computing centre. For the items that are not taken into account, the supply value is added to the added value of their parents. This ensures that the value of the parent is defined correctly, though it implies that the material availability of these items is 100%. Therefore, classical stock control models have been applied with a service level of 99%. (see Appendix G.1 for the definitions of these models)

APPENDIX G, MOQ PROCEDURE

In this appendix the detailed analyses and procedures with regard to the treatment of MOQ items are presented.

G.1. Definitions of the classical stock control models

In this section the classical stock control models are defined that have been used to modify the average stock levels of MOQ items in the supply bases of the common product body and the contract manufacturers. First, the appropriate classical stock control model is chosen. Second, the assumptions underlying these models are discussed. To conclude, the formal classical stock control model is presented.

The stock control systems of contract manufacturers resemble the (s,Q) model as described in Silver et al (1998) and De Kok (2002). The system has a review period of one week, after which a fixed quantity is ordered equal to the MOQ, provided that the stock level drops below a certain level. This complies with the (R,s,Q) model as described by Silver et al (1998) and De Kok (2002). However, it is known that the contract manufacturers monitor their stock positions multiple times a day in order to be able to execute a JIT supply chain strategy. Therefore, it is reasonable to assume an (s,Q) model.

According to De Kok (2002) classical stock control models inhibit several assumptions. First, demand follows a normal distribution. The demand for MOQ items is the dependent demand in the SCPE model. Since it has been shown that the independent demand from which this dependent demand is generated fits a normal distribution, it is reasonable to assume the dependent demand fits a Normal distribution as well. Second, the stock position at the moment of ordering is exactly equal to the reorder level. This assumption refers to concept of undershoot. Undershoot is the difference between the reorder level and the actual stock position at the moment of ordering. This difference is caused by the fact that the system only orders when the stock position drops to the reorder level. However, customers (the manufacturing system of the contract manufacturer in this case) do not necessarily order a quantity of which the MOQ is a multiple (because it appears multiple times in the BOM of a parent item). So a difference can exist between the stock position at the moment of reordering and the reorder level. Undershoot tends to deteriorate the service levels and results in lower average stock levels. In the SCPE model it is assumed that the contract manufacturers adapt the stock control system to this undershoot by increasing the reorder levels. As a result, undershoot can be neglected in this model. Third, orders cannot overtake each other. This is a valid assumption, since there is no reason whatsoever for suppliers to change the sequence in which the deliveries of the same item for the same contract manufacturer are carried out. Fourth, lead times are constant. This is a fundamental assumption of the SBS policy and its validity has been discussed in section 2.2.3. To conclude, the net stock after arrival of an order is positive. This assumption only regards the P_2 measure, while the P_1 measure is used in this model.

The assumptions hold and thus the classical stock control model is defined as follows:

(33) $S_{i,q} = CS_{i,q} + SS_{i,q}$

(34) $CS_{i,q} = \frac{1}{2} MOQ_i$

(35) $SS_{i,q} = \max\left(0, k_{\alpha_i} \sigma\left[G_i\right]\sqrt{L_i}\right)$

(36) $k_{\alpha,i} = \Phi^{-1}\left(P_{1,i}\right)$

$i \in ST$

$ST\left\{i \,|\, b \in \left\{6,7,8\right\} \vee E\left[R_i\right] > 1\right\}$

Where:
$S_{i,q}$ is the average stock level for item i in number of items.
$CS_{i,q}$ is the average cycle stock level for item i in number of items.
$SS_{i,q}$ is the safety stock level for item i in number of items.
MOQ_i is the minimum order quantity of item i in number of items.
$k_{\alpha,i}$ is the safety factor for item i (1/1).
$\sigma[G_i]$ is the standard deviation of the expected dependent demand for item i.
L_i is the lead time of item i in weeks.
$P_{1,i}$ is the cycle service level of item i (1/1).
ST is the set of MOQ items in the supply bases.
b is the BOM level.
$E[R_i]$ is the expected review period for item i.

To conclude, the general relations between average stock levels in number of items, time and value are described as in formula (29) and (30).

G.2. Sensitivity of the SCPE model to service level settings for MOQ items

A sensitivity analysis has been executed with regard to the service level settings for MOQ items. Three options have been defined. First, MOQ can be ignored; SBS policy determined stock levels are used, which are based on a review period of one week. Second, MOQ item stock levels can be replaced with cycle stock only, implicitly assuming that the effect of safety stock is negligible. Third, MOQ item stock levels can be replaced with classical stock control model based stock levels; takes into account safety stock based on the service level constraint provided by the SBS policy (representing the procedure of Fransoo et al, 2001).

In Table G.9 the proposed average stock levels are presented for a service level based on the P_1 level of the SBS policy and a service level set based on the target service level at the CODP.

Description	$S_{IMOQ,c}$	$S_{P1=P1,c}$	$S_{P1=95,c}$
Total	1,598,803	2,766,950	3,302,853
Δ_{IMOQ}	-	1,168,147	1,704,050
SBS	446,839	131,428	131,428
SS	-	2,285	538,188
CS	-	1,481,273	1,481,273
Supply bases	446,839	1,614,986	2,150,889

Table G.9: Sensitivity analysis of the impact of classical stock control models

Where:
Total represents the total average stock investment in the supply chain in euro.
Δ_{IMOQ} represents the difference between the total average stock investment with a certain service level setting for MOQ items and the total average stock investment when ignoring MOQ in euro.
SBS represents the average stock allocated by the SBS policy to non-MOQ items in euro.
SS and CS are defined according to formula (34) and (35) respectively.
Supply bases represents the total average stock allocated to the supply bases of the common product body and the contract manufacturers in euro.

The proposed settings are defined as follows:
IMOQ is the model ignoring MOQ.
P_1=P_1 is the model that sets the service level for MOQ items at the P_1 level proposed by the SBS policy.
P_1=95 is the model that sets the service level for MOQ items at 95%.

APPENDIX H, TRANSPORTATION MODE FLEXIBILITY

In this appendix the calculations are presented for the transportation mode flexibility scenario.

In Table H.10 the stock, pipeline and total investments are presented for the four scenarios that have been established. The lead time for units and modules has been altered between 12 and 7 weeks, representing sea and air shipments respectively. It can be observed that a significant reduction in investments is achieved by using air transportation. A large share of the savings can be assigned to pipeline investment reduction. Furthermore, it can be observed that the modules sourced from the contract manufacturer have a large absolute impact. This can be explained by the higher demand rate of the Caligula modules.

	S_c (CEM owned)	Stock savings	Pipeline savings	TS	CPS
All by sea	1,446,675	-	-	-	-
Units by air	1,414,221	32,455	346,366	378,821	90
Modules by air	1,317,776	128,899	1,092,822	1,221,721	72
All by air	1,278,577	168,099	1,439,188	1,607,287	76

Table H.10: Effect of transportation mode flexibility

$$(37)\quad CPS = \frac{TS * COC}{52 * E[D_{set}]}$$

Where:
TS are the total savings in euro.
CPS is the cost price saving per end-item in euro.
COC are the costs of capital per year set at 10%.
$E[D_{set}]$ is the expected demand for a set of units and/or modules in sets per week.