MASTER

Planning and control of a petrochemical supply chain under stochastic supply

Langendoen, F.R.

Award date:
2009

Eindhoven, March 2009

Planning and control of a petrochemical supply chain under stochastic supply

by
Floris R. Langendoen

BSc Industrial Engineering and Management Science – TU/e 2006
Student identity number 0528661

in partial fulfilment of the requirements for the degree of

Master of Science
in Operations Management and Logistics

Supervisors:
Prof.dr.ir. J.C. Fransoo, TU/e, OPAC
Dr. K.H. van Donselaar, TU/e, OPAC
Drs.ir. R.H.W. van Weerdenburg, SABIC Europe, Supply Chain Management
Ing. R.G. Dreyer, SABIC Europe, Supply Chain Management

TUE. School of Industrial Engineering

Series Master Theses Operations Management and Logistics

ARW 2009 OML

Subject headings: supply chain management, inventory control, stochastic supply, global supply chain, process industry, capacitated storage, statistical process control

Abstract

This Master's thesis describes the re-design of the planning and control processes of a petrochemical supply chain under stochastic supply and capacitated storage, specific to SABIC Europe. A state-dependent base-stock policy is deployed to support the sales and replenishment planning process. Adjustments of the base-stock are based on statistical process control charts. A periodic review, base-stock model under stochastic demand and stochastic supply has been developed.

Management summary

This Master's thesis describes the planning and control of a petrochemical commodities supply chain that faces long and uncertain lead times. Companies who extend their supply chains to low-cost regions often face longer and more uncertain lead times. These long and uncertain lead times complicate the supply chain planning and control. A case study has been performed at SABIC Europe, a company that produces and markets petrochemicals.

Research area

A literature study on stochastic lead times has shown that little research is available on anticipating supply uncertainty in stochastic inventory control models and supply chain planning models. The supply chain of SABIC Europe in which products are imported from Saudi Arabia to Europe has been analysed. It has shown that the present planning and control processes do not anticipate the uncertainties in demand and supply properly. Based on a literature study and the analysis of SABIC Europe's supply chain, the following main research question has been defined:

How to plan and control a single-echelon supply chain under stochastic supply and capacitated storage, so that customer service levels are met at minimal supply chain costs?

Supply chain characteristics

The main results of the analysis of the company's supply chain of imported products are the following. The supply chain faces long and uncertain replenishment lead times. Product demand is highly dependent on a few major customers with whom long-term sales contracts are closed. Product demands tend to behave rather stationary at most of the inventory points. A stationary demand process is a demand process that is not changing with time. The addition or loss of long-term sales contracts and general market conditions could however cause non-stationary demand. As the long lead time requires to release orders well in advance, large demand uncertainty could be faced in the replenishment planning, when a long-term sales contract with a major customer is still under negotiation at the year-end. The supply chain planning and control is constrained by the storage capacity. Storage capacity is often limited in process industries, like the petrochemical industry. The tanks to store products are expensive to build and in some cases safety regulations limit the placement of storage tanks.

Re-design planning and control processes

The company's planning and control processes have been re-designed. The *budgeting activity*, which is the annual planning of sales and replenishments, has to be aligned with the tactical planning of storage capacity in the distribution planning. Alignment of these two planning processes is necessary, because the storage capacity restricts the demand that can be fulfilled for a given customer service level. In the re-design of the sales and replenishment planning, two demand situations are distinguished: (1) the regular sales and replenishment planning and (2) the sales and replenishment planning when uncertainty exists in closing a long-term sales contract.

For the *regular sales and replenishment planning*, it is proposed to control the replenishments according to an inventory control policy, which is the *periodic review, base-stock policy*. The

review period of the inventory control policy is one month, since replenishment orders are planned and released every month. In a base-stock policy, the order release quantity is determined by the difference between the base-stock and the inventory position at the review instance. When maintaining the base-stock level, this difference equals the total demand in the last month (the last review period). The inventory position reflects the amount of physical inventory and the amount on-order that is available to satisfy future demand (inventory on hand, plus outstanding orders, minus back-orders).

The inventory control policy is based on a stationary demand situation. To prevent build up of excessive inventory or an increase in back-orders, the reorder level of the inventory control policy has to be adjusted when non-stationary demand behaviour is expected to occur. The inventory control policy is then dependent on the state of the demand process. Statistical process control charts are used to support decision making on whether to adjust the reorder level. Using statistical process control charts in adjusting the base-stock has two potential advantages. First, it might reduce the variability of replenishment orders. Frequent adjustments of the reorder level to the latest demand forecasts can induce more variability in the supply chain when the demand process behaves stationary. Second, it can lead to a better understanding of the demand behaviour among the organisational members. Since the validity of applying statistical process control methods in inventory control is not supported by literature, this approach is explorative.

For the sales and replenishment planning under *uncertainty in the conclusion of a long-term sales contract*, the replenishment planning activity should decide on which part of the potential demand to make internally (source from the mother company in Saudi Arabia) and which part to source externally. The decision can be supported by evaluating the relevant costs of the make and source options, under the expected probability of whether the sales contract is closed. This is an optimization problem wherein available storage capacity constrains the feasible solutions.

Inventory control tool

An inventory control tool has been developed to support the decisions in the sales and replenishment planning. The inventory control tool calculates the optimal reorder levels to meet customer service levels at minimal costs for a given demand and supply process. Therefore, the periodic review, base-stock model for *stochastic supply* has been developed. Two demand situations are considered: demand is occurring every day (period demand) and demand is occurring less frequently, for instance every two weeks (intermittent demand). The formulas to calculate the standard *customer service levels* (the cycle service level and the fill rate) for a given base-stock level, have been derived. A procedure is developed to determine the probability distribution of the *customer order waiting time*, when the base-stock levels are sufficiently large. The customer order waiting time distribution is used to calculate the optimal base-stock for service objectives specified as time windows. Within these time windows a given percentage of all customer orders should be delivered. Since the storage capacity constrains the supply chain planning and control, the quantitative relation between the base-stock level and the probability distribution of the maximum physical inventory has been obtained. The *storage capacity requirements* can be determined by evaluating the distribution of the physical inventory. The inventory control model has been implemented as a tool in MS Excel.

Recommendations

The performance measurement system of the company has been re-designed, so that it reflects supply chain performance more accurately and provides better support to the planning and control processes. Validation tests were performed on the re-designed regular sales and replenishment planning process to assess whether it performs as intended. An analysis of lead time scenarios has provided insights into improvement opportunities in the supply chain. The following recommendations to the company have been formulated:

1. Improve the **performance measurement** system (key performance indicators) so that it supports the planning and control processes better. Make modifications to the ERP-system to register requested delivery dates, first promised dates and the demand forecasts used in the sales and replenishment planning.

2. **Align the budget with the capacity plan**, as the distribution planning restricts the demand that can be fulfilled for a given customer service level. Discuss and decide on the desired customer service performance in the tactical planning. The customer service performance at the terminal that faces intermittent demand is of special interest, since the project results indicate that the present order fulfilment has been made dependent on the timing of the replenishments.

3. Invest in improving **demand forecasting**. Register the demand forecasts used in the replenishment planning and discuss the demand forecast accuracy regularly.

4. For the sales and replenishment planning, **construct control charts** of the demand. These control charts might lead to a better understanding of the demand behaviour and could support decision making whether to adjust the reorder levels of the inventory control policy.

5. Support the sales and replenishment planning (for the terminals that face period demand) by **calculating optimal replenishment quantities** with the inventory control tool.

6. Study how facing **uncertainty in the conclusion of sales contracts** in the operational replenishment planning can best be avoided. When uncertainty in the conclusion of sales contracts does arise, discuss it explicitly in the sales and replenishment planning. Decide on which part of the potential demand to make internally (source from the mother company in Saudi Arabia) and which part to source externally.

7. Research how the **replenishment scheduling** can be organised in such a way that the total supply chain performance increases.

Preface

This thesis is the result of my graduation project for the MSc program in Operations Management and Logistics at the Eindhoven University of Technology. The graduation project was performed at SABIC Europe.

I would like to use this opportunity to express my gratitude to my supervisors. First of all, I would like to thank Jan Fransoo. It was a pleasure to work with him during this project and on many other occassions throughout my studies. His directions and enthousiasm has truly motivated me in performing this project and other activities. Furthermore, my gratitude goes out to Karel van Donselaar, my second supervisor. During our meetings he asked me valuable questions that encouraged me to reflect on my work.

I would like to thank my colleagues at SABIC. I am especially grateful to my supervisors Ralph van Weerdenburg and Roelie Dreyer. They provided me the opportunity to work in a nice and dynamic environment, and challenged me to stay focused on the practical implications of my project.

I owe many thanks to my my parents for their continuing support that allowed me to become who I am. Thanks to all my friends who have made more than six years of studying at the university so enjoyable. Finally, thanks to my girlfriend. It is good to have someone who reminds you of what is really important.

Floris Langendoen

March 2009

Table of contents

1 Introduction

This Master’s thesis project studies the planning and control of a petrochemical commodities supply chain under stochastic supply.

1.1 Research scope

Stochastic supply in global supply chains

To remain competitive in a globalizing marketplace companies are extending their supply chains to other regions. Production is outsourced to low-cost regions to reduce costs. Products with a low value density are transported between continents by deep sea shipping. The planning and control of these globalizing supply chains is more complex, as lead times often increase and become more uncertain. Consequently, the demand uncertainty increases, since the demand has to be forecasted over a longer time period. These uncertainties in supply and demand have to be anticipated in the planning and control processes. The supply chain of importing products from Saudi Arabia to Europe at SABIC Europe is investigated. This supply chain represents the complexity in the planning and control of a supply chain under long and uncertain lead times. A literature study on stochastic lead times shows that little research is available on anticipating supply uncertainty in stochastic inventory control models and supply chain planning models.

This project will contribute to the existing literature as a periodic review, base-stock model for stationary stochastic demand and supply is developed. The demand distribution over the lead time and review period is modelled by splitting the lead time in a deterministic part, the minimum lead time, and a stochastic part, the additional lead time; and by discretizing the continuous distributions of the demand and additional lead time. Both period demand as well as intermittent demand is considered. Tempelmeier (2000) studied the order waiting time distribution for a periodic review, base-stock system with deterministic lead times. In this project, his procedure is extended to determine the customer order waiting time distribution under stochastic lead times.

Capacitated storage in the process industry

The project is conducted within the petrochemical industry. The production of petrochemicals can be classified as a continuous flow process. Process manufacturing is defined by APICS as: “production that adds value by mixing, separating, forming and/or chemical reactions by either batch or continuous mode” (Wallace 1992; in: Dennis and Meredith, 2000). In some process industries, like the petrochemical industry, storage capacity is constrained. The tanks to store products are expensive to build and in some cases safety regulations limit the placement of storage tanks. Since the storage capacity constrains the supply chain planning and control, this project studies the quantitative relation between the reorder level and the distribution of the maximum physical inventory. The customer order waiting time distribution is used to calculate the optimal base-stock for service objectives specified as time windows. Within these time windows a given percentage of all customer orders should be delivered.

Non-stationary demand behaviour

While the demand tends to behave stationary in this supply chain, the addition or loss of sales contracts and general market conditions could cause non-stationary demand behaviour. Adjusting the base-stock level each review period to the latest demand forecasts, might induce more variability in the supply chain under stationary demand conditions. This project explores the use of a state-dependent base-stock model in which statistical process control charts are used to determine when the base-stock levels should be adjusted. Since the validity of applying statistical process control methods in inventory control is not supported by literature, this approach is explorative.

Large binomial demand uncertainty

The supply chain analysis also shows how long lead times could contribute to additional supply chain uncertainty. Long-term sales contracts with major customers are closed for one or more calendar years. It could be that potential sales contracts with major customers are still under negotiation at the year-end, when the supply to fulfil the potential demand already has to be ordered. Thus large binomial demand uncertainty can occur at the year-end. This project provides a case study on how to manage such large binomial demand uncertainty by identifying the decision options to acquire the potentially required supply.

1.2 Company description

The project is performed at SABIC Europe, an organisation that produces and markets petrochemicals. It is a subsidiary of Saudi Basics Industries Corporation (SABIC), one of the top 10 diversified chemical companies in the world. The European subsidiary employs 3,200 people and is headquartered in Sittard (The Netherlands). It operates production sites in Geleen (The Netherlands), Teesside (United Kingdom) and Gelsenkirchen (Germany); and has sales offices and logistical terminals throughout Europe. In 2007, SABIC Europe sold 10.9 million metric tonnes of petrochemicals which generated a total turnover of 8.5 billion euro.

This project focuses on the planning and control of the supply chain of imported petrochemicals. SABIC Europe imports more than 1.9 million metric tonnes (MT) of chemicals per year from production sites located in the Kingdom of Saudi Arabia (SABIC KSA). Marketing and distributing these imported chemicals is one of the key activities of SABIC Europe. SABIC Europe can compete with producers in Europe, because the additional costs of shipping chemicals to Europe are offset by feedstock advantages in Saudi Arabia. The imported products are distributed to customers in Europe directly or via logistical terminals. The products that are sourced from SABIC KSA are depicted in Table 1.1.

Product group	Product
Glycols	Monoethylene glycol (MEG) Diethylene glycol (DEG) Triethylene glycol (TEG)
Aromatics	Methyl tert-butyl ether (MTBE) Methanol (MEOH) Styrene Monomer (SM)

Table 1.1 *Products sourced from SABIC KSA*

1.3 Project approach

This project is executed according to the following project approach. The project starts with an extensive analysis of the company's supply chain of petrochemical products that are imported from Saudi Arabia. Part of the analysis follows the PCI framework (Bemelmans, 1986); a reference framework for describing the supply chain's primary processes, control processes, organisation and information systems. The analysis is based on interviews with employees of the company and data analysis. From the analysis, several main problems are identified. Subsequently, a literature review is carried out to address the general problem of stochastic supply and the more specific problems found in the supply chain of the company. Based on the identified problems and the conclusions of the literature review, research questions are formulated.

The research questions are addressed by making a re-design for the planning and control processes of the company's supply chain. To support the re-design, an inventory model under stochastic supply is developed. The inventory model is implemented as a tool in MS Excel. Validation tests are performed to study whether the re-designed supply and operations planning processes perform as intended. Additionally, activities are started to implement the re-designed processes within the organisation. The inventory tool is used to analyse several lead time scenarios. The project is evaluated by drawing conclusions and recommendations.

The report structure follows the project approach. Chapter 2 describes the supply chain analysis. Chapter 3 presents the research plan which is based on the identified supply chain problems and a literature review. In Chapter 4 the re-design of the planning and control processes is presented. The inventory model and tool to support the planning and control are worked out in Chapter 5. Chapter 6 gives the results of validation tests and a lead time scenario analysis. The conclusions and recommendations are presented in Chapter 7.

2 Supply chain analysis

In this chapter the company's supply chain is analysed. In Section 2.1, the primary supply chain processes are described and analysed. In Section 2.2, the planning and control processes are studied. The information systems and organisation are described in Section 2.3 and Section 2.4, respectively. The supply chain performance is analysed in Section 2.5. This chapter concludes with a supply chain evaluation in Section 2.6.

2.1 Process

Products are produced at plants in Al-Jubail, Bahrain (near the Persian Gulf), and Yanbu (near the Red Sea) in Saudi Arabia, and are shipped on vessels to customers in Europe, directly or via terminals. Vessels are chartered to ship products from Saudi Arabia to Europe. A vessel is fully loaded with products of the company and discharged at several ports in Europe. Vessel loads range from about 10,000 to 40,000 MT. After lifting the products in Saudi Arabia it takes 2 to 3 weeks until the vessel reaches the first discharge port in Europe. At the ports, the products are discharged and stored into shore tanks (terminals) or delivered to customers directly.

Most of the imported products are stored in terminals from where these are delivered to customers. Terminals are located in Rotterdam (The Netherlands), Antwerp (Belgium), Barcelona (Spain), Livorno, Ravenna (Italy) and Malta. Table 2.1 provides an overview of the products stored in each terminal. Depending on the customer order sizes and customer location, products are delivered from the terminals to the customers by vessel, barge, rail tank car, truck or pipeline.

Terminal	Product(s) stored
Rotterdam	MTBE, MEOH
Antwerp	DEG, MEG
Barcelona	MEG, DEG, MEOH
Livorno	MEG, DEG, SM
Ravenna	MEG, DEG, MEOH
Malta	MTBE

Table 2.1 *Products stored in terminals*

The supply chain structure is shown in Figure 2.1. The goods flow is decoupled at two points: (1) before the shipment from Saudi Arabia to the terminals and the customers that are supplied directly, and (2) between goods storage at terminals and delivery to customers that are supplied from the terminals. The decoupling after terminal storage is a customer order decoupling point (CODP), because the goods flows become driven by customer orders instead of demand planning and forecasts from this point on. The point where production and storage at SABIC KSA is decoupled from shipment to Europe is only a quasi-feasible CODP, because the goods flow at this point is driven by both demand planning and forecast as well as orders from customers that are delivered directly.

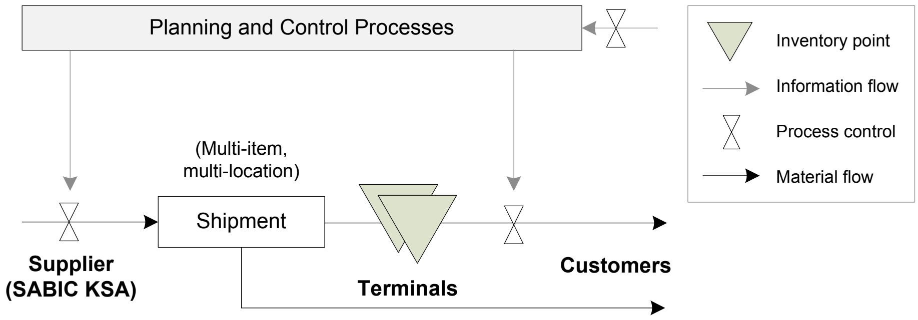

Figure 2.1 *Supply chain structure*

In the subsequent analyses only the import of MEG and DEG are considered. MEG and DEG are stored at four terminals, which will be denoted as terminals A to D. Since these products have a high (potential) sales volume, are distributed to most of the terminal locations and have a geographically diversified customer's base, the analysis of these two products will provide the most insight into the supply chain of imported products.

2.1.1 Supply

Several time points can be distinguished in the replenishment process (see Figure 2.2). Replenishment orders are released around the 20th day of a month, which is denoted as month *t*. Subsequently, a shipping schedule is made for the released orders. Shipment of the orders commences sometime in month *t*+2, when the products are lifted on the vessel ('the lifting month'). The shipment time of a replenishment order depends on the vessel route and external factors, such as vessel availability, material availability, weather conditions and port congestion. The total replenishment lead time is the time from releasing the replenishment order to the actual receipt of the replenishment order at the terminal or customer.

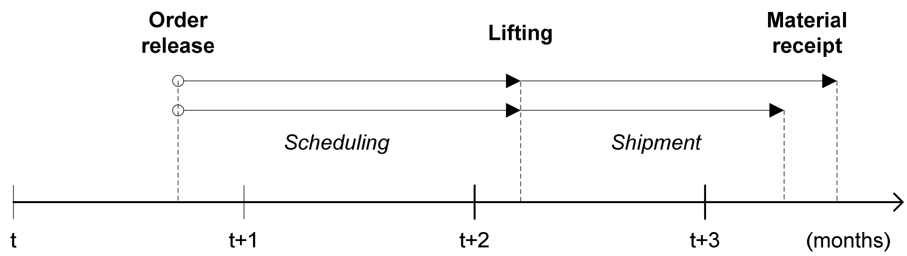

Figure 2.2 *Replenishment process*

We distinguish between two parts in the total replenishment lead time: the minimum lead time and the additional lead time. The minimum lead time is the time from releasing the order to the start of the lifting month. The additional lead time is the time from the start of the lifting month to the actual receipt of the order. The minimum lead time is deterministic (40 days) and the additional lead time is stochastic.

To obtain insights into the uncertainty of the additional lead time, data on the replenishments has been gathered and analysed (see Appendix A). Information on the timing and quantity of replenishment orders has been analysed for the period from October 2006 to August 2008. The analysis shows that the additional lead time can be modelled by a Gamma distribution. Table 2.2 gives the average and coefficient of variation of the additional lead times. It can be concluded that the total replenishment lead time is long and rather uncertain.

	Terminal A	Terminal B	Terminal C	Terminal D
average (days)	45.8	53.3	54.7	40.4
c.v.	0.12	0.14	0.11	0.25

Table 2.2 *Statistics additional lead time*

2.1.2 Demand

Sales contracts

SABIC Europe has a few dozen customers for MEG and DEG. Most of the sales volume is sold to several customers with whom long-term relationships have been established. A small part of the total sales volume is sold on the spot market. All long-term sales contracts are closed for one or more calendar years. In these contracts the total volume that the customer is committed to order in a year is specified. The contracts contain incentives for the customer to order the agreed sales volume as well as to order equally spread throughout the year. Usually, long-term sales contracts are closed at the end of the calendar year. Since the replenishment lead time is more than three months, it could happen that replenishment decisions at the year-end are being made under uncertainty in the closure of a long-term sales contract. Since the negotiation of a sales contract has merely two outcomes, conclusion or no conclusion, this uncertainty leads to large binomial demand uncertainty.

Customer demand

An analysis of the customer demand in the period from January 2006 to September 2008 (see Appendix B.1) shows that products sales are highly dependent on a few major customers. The largest customer of MEG at terminal A accounts for 90% of the total terminal sales; the largest customer of MEG at terminal C accounts for 87% of the total terminal sales. Furthermore, the two largest customers of MEG at terminal D account for 95% of the total sales volume. For DEG sales, the large customers account for 20 to 30% of the total product sales at a terminal.

The customers are delivered by different transportation modes. As a consequence, the sales characteristics differ significantly between terminals. Terminals A to C face a period (daily) demand pattern, because its customers are delivered by truck on a nearly daily basis. Since the major customers at terminal D are delivered once or twice a month by large vessels, terminal D faces large intermittent demand, i.e. demand that does not occur on a daily basis. In addition, terminal D faces period (daily) demand from small customers.

Product demand

The product demand per terminal has been analysed (see Appendix B.2). The product demand per terminal during the period from January 2006 to September 2008 is shown in Figure 2.3 and Figure 2.4. It shows that the average monthly sales had been quite stationary from January 2006 to mid 2007, except that the demand for MEG at terminal D shows evident trend effects. From mid 2007 to the beginning of 2008 production capacity for MEG and DEG had been limited at SABIC KSA. SABIC Europe could therefore only fulfil part of the demand. This is apparent from the data, since the sales for MEG at all terminals had been decreasing from mid 2007. The analysis of the product demand is therefore limited to the demand from January 2006 to July 2007, as the demand for MEG from July 2007 to the beginning of 2008 does not reflect regular demand behaviour. Since the beginning of 2008 the market conditions have been deteriorating. As a result, sales have been decreasing and have become more variable.

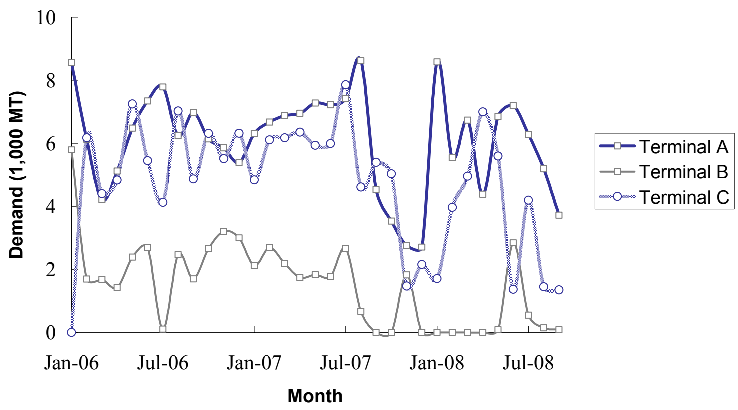

***Figure 2.3** Demand for MEG at terminals A-C*

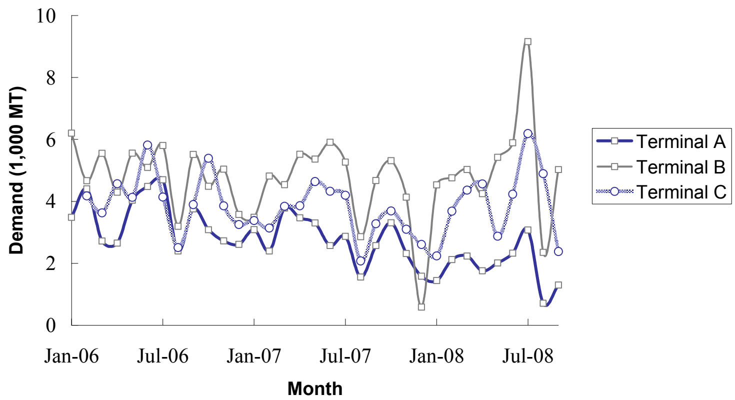

***Figure 2.4** Demand for DEG at terminals A-C*

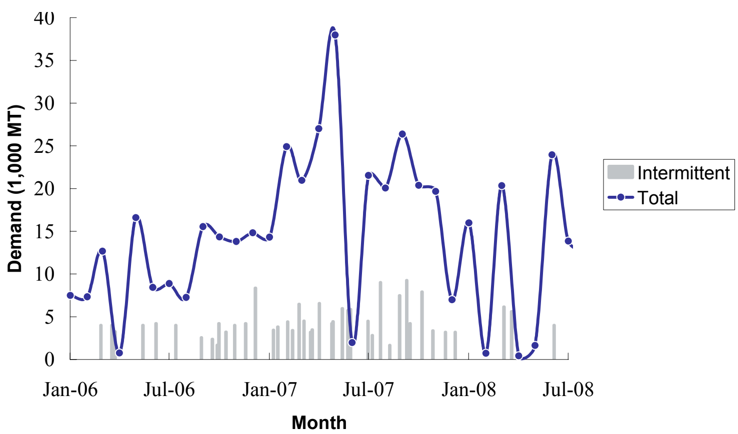

***Figure 2.5** Demand for MEG at terminal D*

Time series analysis shows that trend effects are present in some product demands. Especially, the demand for MEG at terminal D shows trend effects. The time series analysis confirms however that many product demands behave rather stationary. The demands without trend effects have been used to determine the distribution of the demand. The statistics for the demand without trend effects are given in Table 2.3. The demands have been fitted to different statistical distributions. Distribution fitting shows that the distributions of the daily demand and the intermittent demand are accurately modelled by a normal distribution. The distribution of the inter-arrival of intermittent demand can be modelled as an Erlang distribution.

		MEG		DEG	
		average (MT)	c.v.	average (MT)	c.v.
Daily demand					
Terminal A		265	0.46	170	0.61
Terminal B		100	0.80	240	0.59
Terminal C		230	0.58	160	0.79
Terminal D		20	1.31	135	0.90
Intermittent demand					
Terminal D	Size (MT)	3280	0.38		
	Interval (days)	17.7	0.75		

Table 2.3 *Demand statistics*

In conclusion, the supply chain faces period (daily) demand and intermittent demand. Most product demands behave rather stationary. The stationary demand process can be modelled by a normal distribution. The addition or loss of sales contracts and general market conditions could however cause non-stationary demand behaviour. The demand is highly dependent on a few major customers with whom long-term sales contracts are concluded. Consequently, large binomial demand uncertainty could occur when uncertainty exists in the closure of a long-term sales contract.

2.2 Planning and control

The planning and control structure describes which procedures are involved and how these procedures relate to each other, to decide on the timing and quantity of material releases, on both a tactical and operational level. The performance of the supply chain is determined by these planning and control processes. A model of the current planning and control structure is provided in Figure 2.6.

Budgeting

The import budget is established annually. The import budget specifies the total volume for each product that is planned to be sourced from SABIC KSA. It is specified on a monthly level for the next year and on an annual level for the subsequent three years. The import budget is the result of discussions between sales managers, supply chain management and SABIC KSA. It takes into consideration the market strategy, the (expected) sales contracts and the expected availability of production capacity at SABIC KSA.

Demand forecasting

Since the replenishment is largely driven by forecasts, the demand forecasting function is an important input of the sales and replenishment planning. The demand forecast accuracy determines to a large extent the quality of the decisions made in the current planning and control structure. At present, the demand forecasts are specified as part of updating the detailed sales planning for the next few months. The demand forecasts are based on human judgement. Uncertainty in closing long-term sales contracts at the year-end complicates the demand forecasting considerably. In spite of this, no procedures are available in the demand forecasting function, or the sales and replenishment planning process, to manage this uncertainty.

Sales and replenishment planning

Every month, the customers that are directly delivered from Saudi Arabia are asked to communicate their orders for delivery three months later, that is for delivery in month t+3, where t denotes the current month. These direct sales orders, the forecasts of sales delivered via terminals, and current inventory positions, are used to construct a sales and replenishment plan for month t+3. The exact determination of the order release quantities is based on human judgement. Although some safety buffers are taken into account in the replenishment decisions, it is neither based on a required customer service level, nor specified exactly. No procedures are in place to determine replenishment quantities when uncertainty exists in the conclusion of sales contracts.

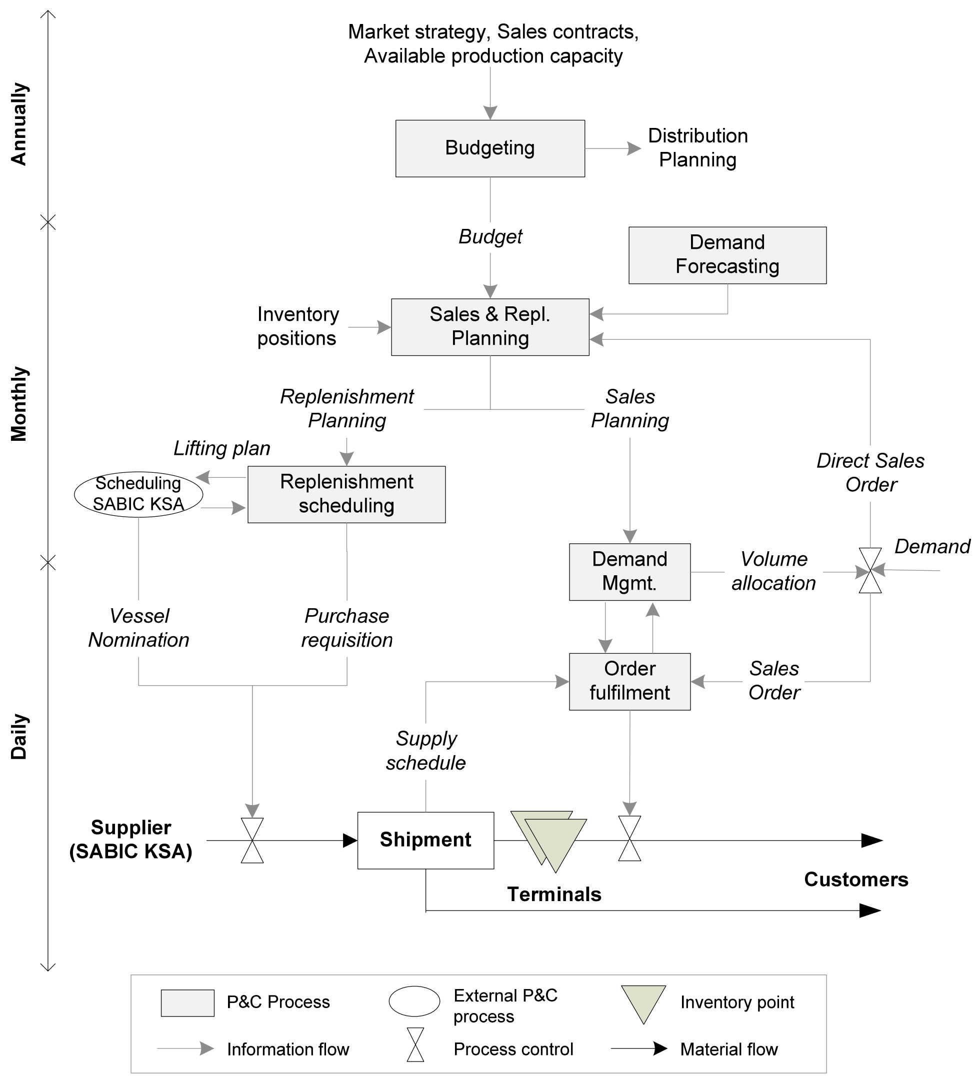

Figure 2.6 *Planning and control structure*

Replenishment scheduling

The result of replenishment scheduling is a lifting plan that specifies the requested products, quantities and discharging ports. The lifting plan is negotiated with SABIC KSA. Usually, replenishment orders are accepted by SABIC KSA without major changes in the shipment quantities. After agreement on the (revised) lifting plan, SABIC KSA schedules the shipments and provides the vessel nominations. A vessel nomination specifies which orders are delivered by a specific vessel and the planned delivery schedule in terms of 'laycans' for loading and discharging at the ports. A laycan is the period in which loading or discharging can commence and is often a period of 9 or 10 days.

Demand management

The sales and replenishment planning, the expected arrival of replenishments, and the committed orders are used as an input to manage demand. Weekly, potential problems with material availability or terminal capacity are discussed in a meeting. Settling with customer to change the timing and quantity of sales orders, selling more or less products on the spot market, or negotiating a swap transaction with a competitor, may solve potential problems. Before the beginning of a month, demand management allocates the planned available material for the next month among the customers. This volume allocation is used to control the intake of orders.

2.3 Information

SABIC Europe uses the Enterprise Resource Planning (ERP) system 'SAP' (ECC) to support their processes. The SAP Supply Chain Management (APO) module is used for planning activities. It supports the budgeting, the monthly sales and replenishment planning, the replenishment scheduling and the (outbound) delivery and supply scheduling. For the processing of purchase requisitions, an interface is available with the ERP system of SABIC KSA.

Microsoft Excel is used to support activities such as specifying import budgets, lifting plans and nominations. Management information on the performance of processes is stored in the SAP Business Warehouse (BW) module, an online reporting system, and Excel spreadsheets.

2.4 Organisation

The business unit 'Chemicals & Intermediates' of SABIC Europe is responsible for distributing and selling the imported chemicals. The 'Supply Chain Management' department organises the distribution. Three groups within the Supply Chain Management department are involved: (1) 'Supply Chain Planning' plans and monitors the replenishments, and schedules goods delivery from Saudi Arabia directly to customers; (2) 'Order To Cash' (OTC) accepts and processes customer orders, schedules goods delivery from terminals to customers, and monitors inventory levels at the terminals; and (3) 'Sourcing & Contracting' organises the availability of logistical services, such as storage at terminals and transportation from terminals. The sales functions of the sub business units 'Olefins & Intermediates' and 'Aromatics & Oxygenates' are responsible for marketing and selling the imported products. Sales management concludes new contracts, forecasts demand and allocates sales volumes to customers so that OTC can accept and fulfil orders.

2.5 Performance

Supply chain performance comprises customer service, supply chain costs and meeting safety requirements.

Customer service

At present, the organisation has not specified targets for customer service levels. Most of the demand originates from long term sales contracts, which do not contain service level agreements. The organisation is required to fulfil the demand originating from long-term sales contract, unless a force majeure is declared. This implies that demands originating from long-term sales contracts are completely backordered when out-of-stock. Most likely, spot market demand which cannot be fulfilled from inventory on-hand, results in lost sales.

The on-time delivery to the requested and the first promised date, and possibly the delay length, are good indicators of customer service, given that most demand is backordered when out-of-stock. At the moment, the organisation keeps track of the last promised date and, for truck shipments only, the actual delivery date. The requested date and first promised date are not registered in the ERP system. For that reason, it is not possible to determine the customer service performance.

The data on the physical inventory shows that the physical inventory had been depleted during just few days in the period from January 2006 to August 2008. Therefore, it was estimated that customer service levels had been satisfactory or close to satisfactory in the past years, assuming that the outbound transportation activities had been working properly.

Supply chain costs

Costs are measured for storage capacity and outbound transportation processes. The costs of storage capacity and handling at the terminals are mostly fixed costs. The agreements with terminals are based on an expected material throughput, which means that the difference between the sales budget and the actual sales mainly determines the cost performance. Costs of outbound logistics relate to the customer order quantities, the distances to customers and the transportation modes used.

The exact costs of inbound transportation are unknown, because these costs are incurred by SABIC KSA. The decisions made in the replenishment planning do however (partly) determine the inbound transportation costs, since these costs are determined by the shipping loads, the number of discharging ports and the distances between the discharging ports. For that reason, it would be useful to monitor inbound transportation costs.

At present, some vessel nominations provide an indication of the inbound transportation costs. Comparing the freight rates given by these vessel nominations with an analysis of the costs of storage and outbound transportation, gives some insight in the cost structure of the distribution. The ratio of the costs of inbound transportation, storage, and outbound transportation is roughly 4:1:2.

The costs of capital tied up in inventory are not measured. Since these costs are directly related to the amount of inventory on-hand, the average inventory days provide an indication of these costs (see Appendix C). Since a target customer service level has not been defined, conclusions cannot be drawn on the cost level (too high or too low). Even though, it is estimated that the inventory levels are rather high at some terminals.

Process characteristics

A number of process characteristics can support the planning and control. At present, the physical inventory over time is measured and the realization of supply volume compared to the budget volume is monitored. The data to specify the demand forecast errors over the lead time are not registered, because the sales forecasts used for constructing the replenishment plans are not stored in the information systems. The lead times from releasing orders to actual receipt of the orders are not measured, although the data is available. Instead the number of replenishment shipments arriving inside the laycan is measured (on-time replenishment). Since the degree of on-time replenishments depends on external conditions, such as supply availability, vessel availability, port traffic and weather conditions, which cannot be influenced by the organisation, this measure is not useful in supporting the planning and control.

In conclusion, the performance metrics that the organisation currently has put into place do not reflect performance accurately and cannot support the planning and control sufficiently.

2.6 Evaluation

The supply chain can be evaluated by three dimensions as suggested by Bertrand, et al. (1998): complexity, uncertainty and flexibility. These dimensions are used to summarize the findings of the analysis.

Supply is sourced from SABIC KSA and distributed directly to the customer or via one of several terminals. Six different types of chemicals are regularly imported from Saudi Arabia. A large part of the imported chemicals are distributed frequently to several major customers. Since the number of suppliers, products and customers is low, the complexity of the supply chain is evaluated as low.

Supply uncertainty is very high as shown in Section 2.1. Demand uncertainty is relatively low during the year and when market conditions are stable. Even so, it is unknown how accurate the demand over the lead time is forecasted. When uncertainty exists on the conclusion of the sales contract at the year-end, the demand uncertainty is considerably higher. Storage capacity constrains the possibilities to buffer against uncertainties.

The flexibility of the supply chain is evaluated as low. Reacting to changing demand in the supply process takes a long time, because the replenishment lead times are long. Few methods are available to provide flexibility. The most important one is the swap transaction. Swap transactions with other companies can give some time flexibility in the amount of products available. In a swap transaction it is agreed to exchange material. Material can be exchanged in time or geographically. For example, an amount of product is taken from another company and the same amount of product is returned two weeks later (time swap). Swap transactions are common practice in the petrochemical commodities industry. Lateral transhipments between terminals are theoretically possible, but too expensive for products with low-value density. Rescheduling agreed replenishment quantities to other terminals might provide some flexibility in material availability between terminals. At present, this method is not often deployed, since transport documents are difficult to change and some contracts with vessel owners do not allow for rescheduling.

3 Research plan

In this chapter the research plan is described. In Section 3.1 the main problems in the supply chain under investigation are defined. Section 3.2 relates these problems to the existing theories and models in the scientific domain. In Section 3.3 the research questions are formulated. The research design is described in Section 3.4.

3.1 Problem definition

Based on the supply chain analysis, two main problems are identified in the supply chain under investigation:

1. The current supply chain planning and control processes do not properly anticipate uncertainties in supply and demand.

The planning and control structure itself contains all required functions to properly manage the supply chain. The processes performed for each of the functions are however poorly aligned with the supply chain structure. The decisions in the planning and control structure are not explicitly grounded on the uncertainties in supply and demand, and the desired customer service and costs performance. For instance, the replenishment planning is currently based on the sales planning and human judgement of how much safety inventory should be ordered. Further, the planning and control processes do not distinguish between different kinds of demand uncertainty. When facing uncertainty in the conclusion of sales contracts, the same sales and replenishment planning activities are deployed as when facing relatively low demand uncertainty. Since it is not possible to buffer against such large demand uncertainty for consecutive order releases given the regular storage capacity, it follows that adapted planning activities should be deployed when facing uncertainty in the conclusion of a sales contract. We conclude that the current planning and control processes do not properly anticipate the uncertainties in supply and demand. Since the current performance measurement system does not reflect performance accurately, the impact of this problem on the supply chain performance cannot be quantified.

2. The current performance measurement system does not reflect performance accurately and cannot support the planning and control processes sufficiently.

As concluded in Section 2.5 the performance metrics that the organisation currently has put in place do not reflect performance accurately and cannot support the planning and control sufficiently. Target customer service levels are not defined and the actual service levels, relevant costs and process characteristics are not measured completely.

3.2 Research domain

A literature study has been performed on the characteristics of the process industry, trends in the chemical industry, and on modelling and managing stochastic supply. In addition, the literature has been searched for theories and models that are related to the problems identified in Section 3.1. This section provides the main findings of the literature review.

Longer supply chains

Market reports of the chemical industry (Martin, 2004; McKinnon, 2004; Braithwaite, 2005) show that many chemical companies in Europe are trying to remain competitive in a globalizing market by extending their supply chains to lower-cost regions, that is, to other continents. In these extended supply chains lead times often increase. As a consequence, demand has to be forecasted over a longer time period and will therefore be less accurate. Further, high volumes can only be transported between continents by deep sea shipping. Lead times of deep sea shipping are highly uncertain, mainly due to unpredictable weather conditions and service times in ports. These longer and more uncertain lead times result in supply chains that are more difficult to control.

Stochastic supply

Only little research is available on stochastic exogenous lead times. This is also concluded by Mula *et al.* (2006). They reviewed the literature for models on production planning under uncertainty. Having reviewed 86 citations, they concluded that further research is needed on “the development of new models that contain additional sources and types of uncertainty, such as supply lead times [and] transport times, [..] since models with uncertain demand have received more attention in comparison to other types of uncertainty.”

Research on planning models mainly aims to find the optimal safety lead times in MRP controlled multi-echelon systems. Research has been found for supply chains facing stochastic lead times, but under the assumption of deterministic demand (e.g., Ould-Louly and Dolgui, 2004; Tang and Grubbström, 2003). De Kok and Fransoo (2003) state that the lead time is modelled as a deterministic parameter on purpose in planning models. Planned lead times are used as a control mechanism in hierarchical models. When workload control rules are used, so that lower level supply chain units should be able to deliver within the planned lead time, the use of deterministic lead times seems to be a good control mechanism. However, when resource utilization has less impact on the high lead time uncertainty, using a deterministic lead time might be the wrong approach, resulting in unavailability of materials or high safety inventory.

Few stochastic inventory models are described for single-echelon supply chains facing stochastic exogenous lead times and stochastic demand. Recent papers that study stochastic lead times for single-echelon systems, assume that demand is deterministic (e.g., Silver and Zufferey, 2005. Kim *et al.*, 2004). Inventory models that can be found in standard text books on inventory management mainly assume deterministic lead times. Nevertheless, in Silver *et al.* (1998) two methods are described to model lead time uncertainty. The first one is to measure the total demand during the lead time and subsequently base the reorder points on the upper values of the total lead time demand. In practice, this information is mostly not measured. The second one describes the situation that the period demand and the lead time are measured separately. By combining the distributions of the lead time and the demand, the distribution of the total demand over the lead time can be obtained. When a combined distribution is obtained, reorder settings for a desired service level can be obtained in the same way as for deterministic lead times. De Kok (2003) gives expressions for two situations: (1) the period demand and the lead time are normally distributed; (2) the inter-arrival time between customer orders is exponentially distributed, and the demand per customer and the lead time are normally distributed. Johansen and Thorstenson (2008) studied the periodic review, base-stock inventory system when the demand is Poisson distributed and the lead time is Gamma distributed. For this system the demand over the lead time is a Negative Binomial distribution. The combinations of distributions described by De Kok and Johansen and Thorstenson, give quite tractable computations. For the supply chain under investigation a more complex combined distribution is required to describe the demand over the lead time.

To our best knowledge, no research is currently available on applying stochastic inventory models in such a situation.

Large binomial demand uncertainty

Uncertainty could exist as to whether long-term sales contracts will be closed at the moment a replenishment decision needs to be taken for delivery after the sales contract's starting date. When uncertainty exists for a sales contract that will account for most of the demand at a terminal, the realization of the sales contract has a major impact on material availability at the terminal. Ordering for the entire customer's potential demand, might result in excess inventory and storage capacity shortages when the sales contract is not closed. Ordering less than the customer's potential demand, might result in many backorders when the sales contract is realized. At present, no research is available on such large binomial demand uncertainty.

3.3 Research questions

The literature review shows that little research is available to support the planning and control of supply chains under long and uncertain lead times. Further research is necessary on supply uncertainty in stochastic inventory control models and planning models. The supply chain under investigation provides a case on how importing supply over large distances complicates the planning and control. At present, the planning and control processes do not properly anticipate the uncertainties in supply and demand. Further, the planning and control processes do not provide for planning supply under large binomial demand uncertainty. Therefore, the following main research question is defined:

How to plan and control a single-echelon supply chain under stochastic supply and capacitated storage, so that customer service levels are met at minimal supply chain costs?

Related to the main research question, the following detailed research questions are defined:

(1) Which planning and control processes should be performed in the supply chain under investigation to anticipate for the present supply uncertainty and regular demand uncertainty?

(2) How to meet customer service levels at minimal supply chain costs given storage capacity constraints for these planning and control processes?

(3) Which planning and control processes should be performed in the supply chain under investigation when uncertainty exists as to whether a large sales contract will be realized?

(4) Which metrics should be measured to reflect supply chain performance accurately and to support the planning and control processes?

(5) How can the performance be (further) improved in the supply chain under investigation?

3.4 Research design

To solve research questions (1) and (3) the planning and control processes will be re-designed; in particular, the budgeting and capacity planning activities and the sales and replenishment planning activities. The current network structure is assumed in the re-design. In the re-design of the sales and replenishment planning processes, a distinction will be made between the processes to be deployed under regular demand uncertainty and when facing uncertainty in the conclusion of large sales contracts. Based on the re-design of the planning processes, the performance measurement system will be re-designed to address research question (4).

A stochastic inventory control model will support the operational planning processes under regular demand uncertainty. It will be specified how demand forecasting determines the deployment of this model. A model will be developed that specifies the quantitative relations between the reorder levels and several service levels for the given demand and lead time behaviour. To easily calculate the re-order levels, the model will be implemented as a tool in MS Excel. The model and its implementation are verified by a simulation study. The model development will address research question (2).

The re-designed supply and replenishment planning processes under regular demand uncertainty will be validated through a simulation with historical data. The inventory model will be used to perform a scenario analysis to provide insights in improvement opportunities in the supply chain (research question 5). This project ends with drawing conclusions and recommendations.

The research design to address the research questions is depicted in Figure 3.1

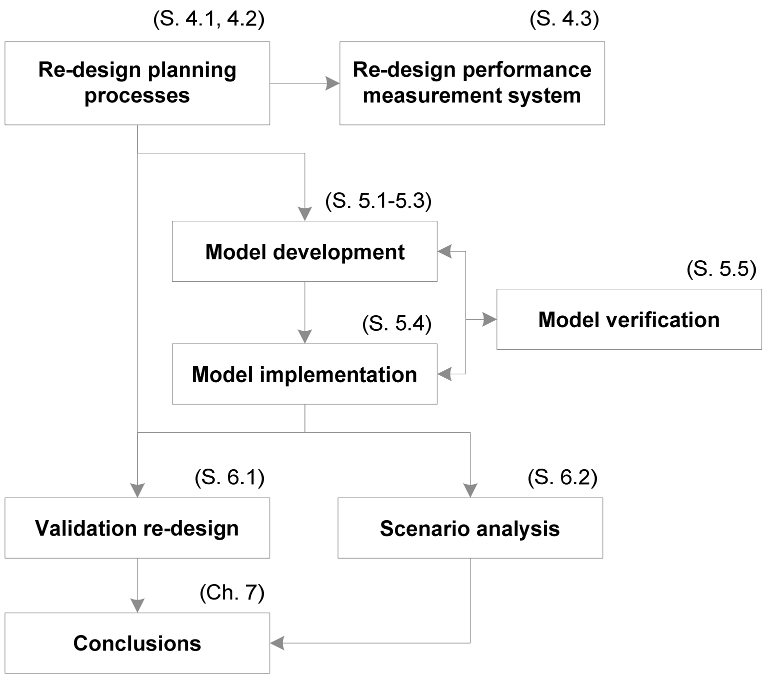

Figure 3.1 *Research design*

4 Re-design planning and control processes

The present planning and control processes of the company's supply chain do not anticipate the uncertainties in demand and supply properly. In this chapter, the planning and control processes are re-designed such that these uncertainties are better anticipated. The long-term planning, among which the network planning, will not be considered. The current network structure is thus assumed in the re-design of the planning processes. Section 4.1 describes the re-design of the budgeting and distribution planning. Section 4.2 gives the re-design of the sales and replenishment planning. In Section 4.3, the performance measurement is re-designed. Conclusions are drawn in Section 4.4.

4.1 Budgeting and distribution planning

The annual budgeting function specifies the sales and replenishment budget. The budget can be regarded as the tactical planning of sales and replenishments. Budgeting synchronizes the sales planning with the replenishment planning. The sales planning is based on the market strategy, sales contracts and the mid-term sales forecast; the replenishment planning is constrained by the available production capacity at SABIC KSA. The sales planning needs to specify forecasted monthly sales volumes as well as the corresponding safety inventories to achieve service level targets. Since safety inventories are constrained by the storage capacity, it is necessary to align the budget with the tactical distribution planning. The tactical distribution planning specifies the planned storage capacity and the planned transportation capacity. By synchronizing the budgeting and distribution planning one can decide on the trade-off between sales volumes (demand), storage costs and service levels. For instance, it might be decided that when the planned sales are higher in the second half of the budget year, the target fill rate for the second half year is decreased, so that storage capacity does not have to be extended. The tactical planning functions and the relations between them are given in Figure 4.1.

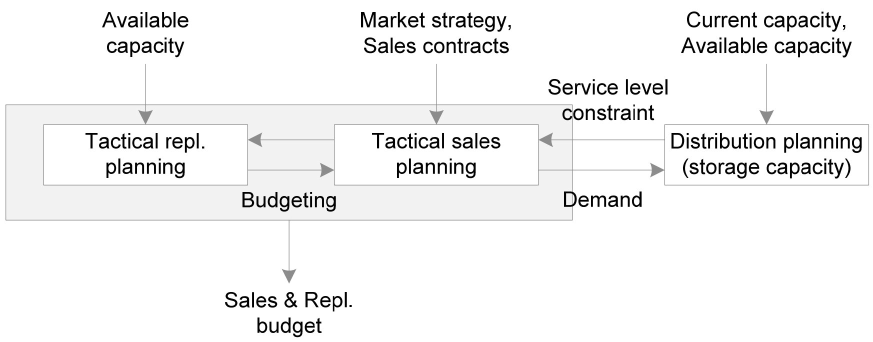

Figure 4.1 *Budgeting and distribution planning*

4.2 Sales and replenishment planning

The sales and replenishment planning (S&RP) function aligns the operational demand planning with the operational replenishment planning. The sales and replenishment budget and the (operational) demand forecast are input of the S&RP. We distinguish explicitly between the demand forecasting function and the S&RP function, because the demand forecasting function should not take potential limits on material supply or distribution capacity into consideration. The objective of the forecasting function is to “decide about input data of planning processes and not about the results of planning” (Fleishmann and Meyr, 2003). In the S&RP the sales planning is synchronized with the replenishment planning which specifies the order releases. In the re-design of the sales and replenishment planning, it is assumed that the sales planning is mostly equal to the demand forecasts.

It is beneficial to execute the S&RP on a monthly basis. Replenishment orders are released once a month, so that a combination of replenishment orders can be transported by the same vessel. A minimum order quantity per terminal exists. Since the minimum replenishment order quantity is small compared to the monthly sales volumes at a terminal, the minimum replenishment order quantity has not limited the release of orders in practice. Since SABIC KSA executes the transportation scheduling (vessel nomination) after having received the replenishment order, the transportation capacity is flexible. Consequently, the replenishment order release quantity is not restricted by the transportation capacity.

Most of the demand originates from long-term sales contracts. In sales contracts the expected sales volume for one year is specified and incentives are described so that the customer purchases the sales volume equally spread throughout the year. It is therefore likely that monthly demand volumes tend to behave quite stationary, i.e. the demand pattern is not changing with time. For a stationary demand situation, the replenishment planning can be based on the state of the inventory system, which means that replenishment decisions are based on the inventory position. The inventory position reflects the amount of physical inventory and the amount on-order that is available to satisfy future demand (inventory on hand, plus outstanding orders, minus back-orders). Controlling inventory by demand forecasts is only beneficial when it mitigates the natural variation of the demand process. Otherwise, using demand forecasts might only add to instability in the inventory system by increasing the variability of the replenishment order. At present, it is unknown how accurate the demand forecasts are. General market developments (trend effects) and the addition or loss of large sales contracts can however cause structural demand changes. Consequently, the replenishment planning should not only take the state of the inventory system into account, but also the state of the demand process.

In the next section, it is specified how a stochastic inventory control policy can be used in the replenishment planning when facing this demand uncertainty. After that, the additional planning and control activities which should be undertaken when facing uncertainty in sales contracts are described.

4.2.1 Regular replenishment planning

The inventory control policy that is commonly used to control a replenishment system that requires resource sharing is a periodic review, base-stock (order-up-to) policy (Silver *et al*, 1998, Section 7.4). Sharing of transportation resources is required to minimize the transportation costs. The periodic review, base-stock policy is proven to be optimal under a standard cost structure (Zipkin, 2000, Section 9.6). In a base-stock policy, the order release quantity is determined by the difference between the base-stock and the inventory position at the review instance. When maintaining the base-stock level, this difference is the total demand in the last review period. The base-stock has to cover the demand during the lead time and review period such that the required customer service levels are met against minimum costs.

To prevent build up of excessive inventory or an increase in back-orders, the base-stock has to be adjusted if non-stationary demand behaviour is expected to occur. The base-stock is then dependent on the state of the demand process. Increasing the base-stock is only possible when sufficient storage capacity is available. Before adjusting the base-stock level, the reliability of the demand forecast is assessed. When the development of the demand is highly uncertain, it could be better to intervene in the control policy. A comparison of base-stock and demand scenarios can then support the order release decision. When uncertainty exists on the addition or loss of sales contracts for the planning period considered, options to source additional storage capacity or outsource production need to be considered. This make and source decision is described in more detail in the next subsection. Figure 4.2 shows the flow diagram of the proposed S&RP function.

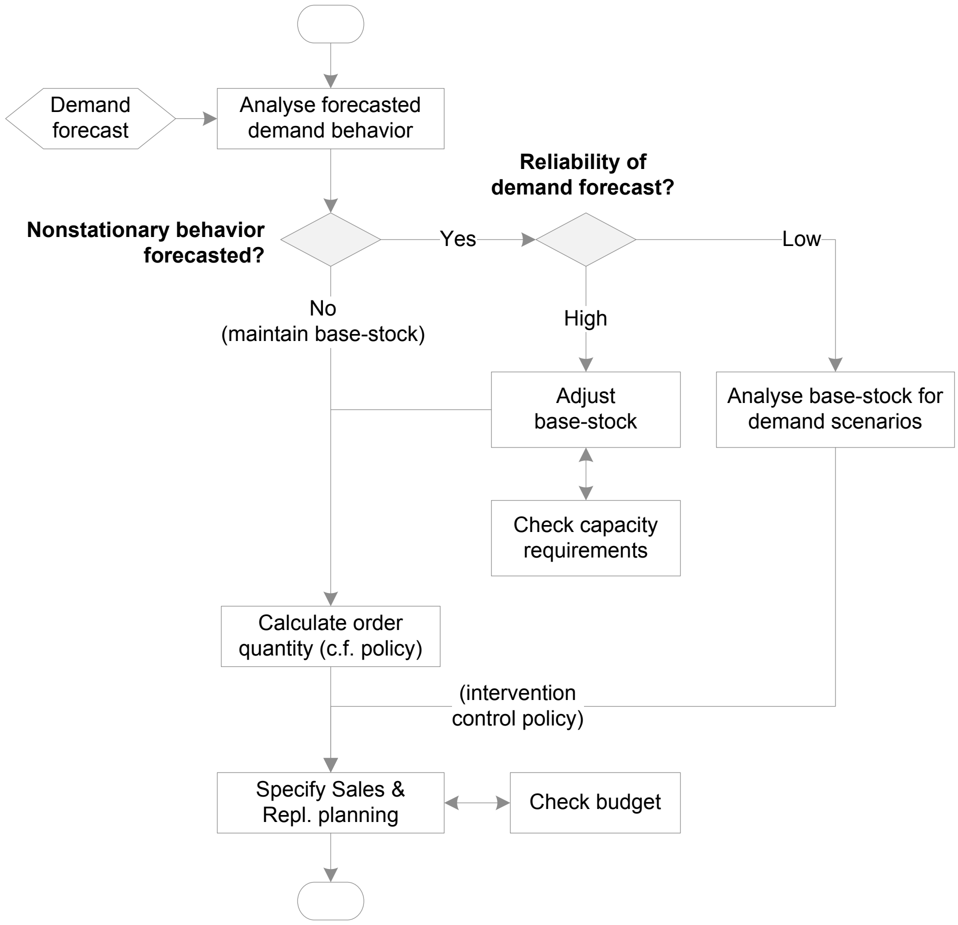

Figure 4.2 *Flow diagram of sales and replenishment planning*

Non-stationary demand behaviour

The analysis shows that, though the demand is rather stationary, the demand might behave non-stationary. To prevent build up of excessive inventory or an increase in back-orders, the base-stock has to be adjusted as the forecasted demand changes. Note that the latest demand observation(s) could also be used as a demand forecast.

Base-stock calculation

When demand forecasts are used to adjust the base-stock level, the forecast errors are typically used as an estimate for the demand variance. The demand process is then considered as stationary to calculate the required inventory. Graves (1999) considered the adaptive base-stock policy for non-stationary demand and deterministic lead times, in which the forecast is provided by exponential smoothing. He observed that when demand is truly non-stationary, the safety stock required for non-stationary demand is much greater than for stationary demand. Since the demand process at the company is not considered as truly non-stationary, a stationary demand process is assumed in determining the base-stock.

Frequency of base-stock adjustments

Exponential smoothing is an often used single-item forecasting technique. It bases the new demand forecast on the latest demand realization and the previous demand forecast. A smoothing factor determines how much weight is put on the latest demand observation and, consequently, the previous demand forecast. Using exponential smoothing in the supply chain under investigation requires a high smoothing factor, because changes in demand have to be recognized quickly as the delay time, i.e. the replenishment lead time, is long. A high smoothing factor might induce more variability in the supply chain. This is confirmed by research on the bull-whip effect. Chen *et al.* (2000) show that when a high smoothing factor is chosen, the forecast would recognize changes in demand quickly, but at the expense of more variability in the supply chain. Thus frequent adjustments of the base-stock might induce more variability when the demand process tends to behave stationary. To prevent unnecessary adjustments of the base-stock, the base-stock should only be adjusted when the underlying demand process changes significantly.

Statistical process control

Statistical process control (SPC) methods can signify whether the demand process changes significantly. SPC is “a powerful collection of problem-solving tools useful in achieving process stability and improving capability through the reduction of variability” (Montgomery, 2001). SPC is widely used for quality control and improvement in manufacturing. A process control chart plots observations from a process versus the time (see Figure 4.3). The chart has a center line and control limits. When unusual sources of variability are present, the observation will plot outside the control limits. This signifies that the process should be investigated and possibly that corrective actions need to be undertaken. We believe that control charts can also be used to monitor demand processes and to prevent unnecessary adjustments in the supply process. According to Montgomery (2001), preventing unnecessary process adjustments is one of the major reasons for the popularity of control charts.

One relevant paper has been found in literature on the use of SPC in relation to inventory control. Watts *et al.* (1994) developed a conceptual model for detecting and diagnosing problems in reorder point systems by using process control charts. In their paper, control charts are used reactively in diagnosing the causes of inventory system deviations. We propose to proactively adjust reorder levels in a periodic review system in response to changes in demand levels signified by control charts. This corresponds to their suggestions for future research.

Using control charts in adjusting the base-stock has two potential advantages. First, it might reduce the variability of replenishment orders. Second, it can lead to a better understanding of the demand behaviour among the organisational members. By visualising the demand behaviour organisational members become more aware of natural demand variation, structural demand changes, how the demand forecasts relate to demand realizations, and how demand realizations and forecasts relate to the demand distribution used in determining the base-stock. Since no research is available on the effect of SPC control rules on the optimality of replenishment orders under stationary and non-stationary demand, the use of SPC control rules is of an exploratory nature.

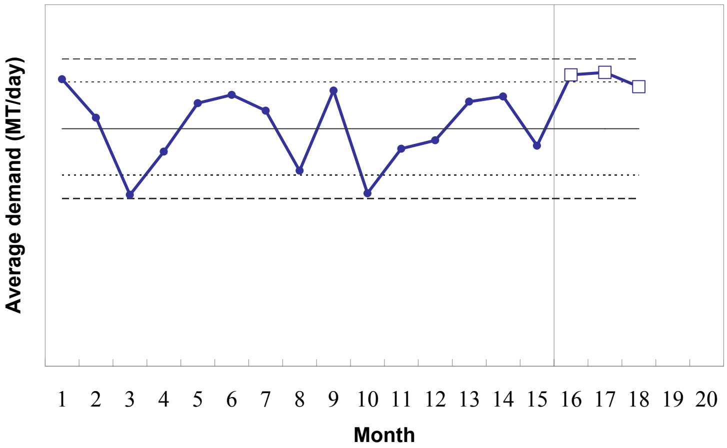

Figure 4.3 *Control chart*

Control rules

A control chart displays how demand observations relate to the demand distribution on which the present base-stock is based. A control chart displays the expected demand as the center line, and thresholds to identify special causes of variation as control limits and warning limits. The control and warning limits relate to the standard deviation. From the analysis, it has been concluded that daily demand, or the intermittent demand size, can be modelled by a normal distribution. For a normal distribution it holds that about 67% of the demand realizations will be within one standard deviation of the mean, and 95% of the demand realizations will be within two standard deviations of the mean. This information can be used to determine appropriate control rules; let us assume that it needs to be investigated whether the demand process has changed when (1) consecutive demand observations cross the warning limit set at one standard deviation from the mean, or (2) one demand observation crosses the control limit set at two standard deviations from the mean. Figure 4.3 provides an example of a control chart. In this figure, the demand observations in month 16 and 17 cross the warning limits. This means that it needs to be investigated whether the demand process has changed. When it is concluded the demand process has changed, the base-stock has to be adjusted.

In conclusion, we propose to control the inventory system according to a state-dependent base-stock policy. The base-stock policy is adjusted when the control chart signifies that the demand is significantly different from the demand distribution on which the present base-stock is based. The base-stock calculation is based on stationary demand. In Chapter 5 we develop a model to calculate optimal base-stock levels.

4.2.2 Uncertainty in conclusion of a sales contract

Uncertainty could exist as to whether a critical sales contract will be concluded. A critical sales contract is a contract that accounts for a major part of demand at a terminal. Additional planning activities need to be deployed when this uncertainty exists. Sales contracts are concluded per calendar year, thus uncertainty on the conclusion of sales contracts could arise in the S&RP meetings of September, October and November (see Figure 4.4). The orders released in these S&RP meetings are planned to cover the demand of the beginning of the new calendar year, that is, the demand of January, February and March.

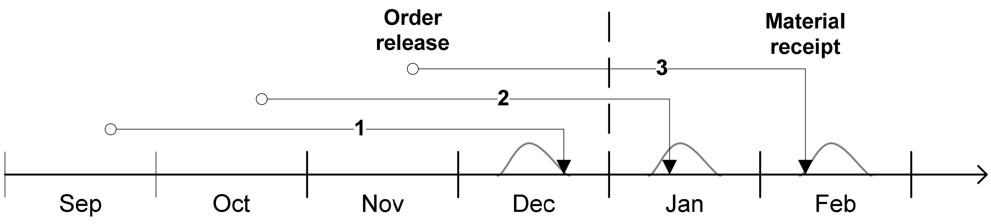

Figure 4.4 *Timeline of replenishment orders at year-end*

Large capacity shortages will occur when all the potential demand of the sales contract under negotiation has been ordered for consecutive months and the sales contract is not closed in the end. The terminal capacity is based on the demand of one month and some safety buffer, so it does not has sufficient capacity to store the demand of consecutive months. However, due to the long lead time, multiple orders have to be released to fulfill potential demand. Therefore, options need to be evaluated to acquire temporary storage capacity or to partly source production externally. The activities to be employed for the S&RP under uncertainty in the conclusion of a sales contract are shown in Figure 4.5.

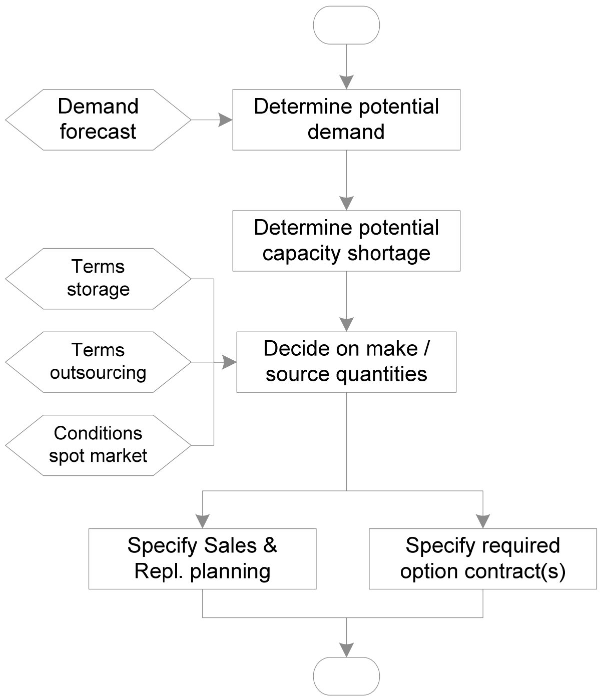

Figure 4.5 *Flow diagram of planning under uncertainty in sales contract conclusion*

Firstly, the potential demand is specified assuming the conclusion of the sales contract. Secondly, the potential capacity of the focal terminal, the terminal from which the customer is delivered, and the network is determined. To utilize all storage capacity in the European network, it is beneficial to enable a change of destination of the replenishment orders after release. Thus making arrangements with the vessel owner which allow changing the delivery route. In fact, the material on-order can then be considered as a floating stock.

Given the potential demand and shortage of storage capacity, a decision is made on the fraction that is sourced from SABIC KSA (make), and which fraction is sourced externally (source). When planning to source from SABIC KSA, storage capacity needs to be available at the focal terminal or other terminals, or temporarily acquired. When planning to outsource part of the production, one can decide to arrange contracts for production. Further, it can be decided to buy material from the spot market later on, or to arrange swap transactions. The preferred way to acquire temporary production or storage capacity is via option contracts. An option contract gives the right, but not the obligation, to buy capacity. When the sales contract is not realized, an option contract saves capital investments in inventory. The benefit of outsourcing production is that the order release decision can be postponed until it is known whether the sales contract is closed. This only holds when the order lead-time of outsourced production is small compared to the replenishment lead time from SABIC KSA. Further, the potential benefit of outsourcing production also depends on whether customers can be delivered directly from the supplier.

The relevant costs of several decision options, given whether a sales contract is closed, are specified in Table 4.1. When the sales contract is not closed, the costs of the decision option to source from SABIC KSA are that the destination of replenishment orders might need to be rescheduled and that capital will be tied up in inventory. Outsourcing production might lead to higher material costs. Temporarily acquiring additional storage capacity results in higher storage costs. Closing option contracts for storage capacity or outsourced production capacity results in option costs. Additional transportation costs might be incurred, depending on the location of the capacity supplier.

	Make (source from SABIC KSA)		**Source** (externally)	
	Current storage	**Option add. storage**	**Option outsourcing**	**Spot contracts, swap deals**
Sales contract closed		• Option	• Option • Material • Transport	• Material • Transport
Sales contract not closed	• Capital • Floating stock	• Option • Storage • Transport • Capital • Floating stock	• Option	

Table 4.1 *Relevant costs of make and source options*

The replenishment planning has to decide on which part of the potential demand to make internally (source from SABIC KSA) and which fraction to source externally, and under which conditions. This decision can be supported by evaluating the relevant costs of the make and source options under the expected probability of whether a sales contract is closed. This is an optimization problem wherein available storage capacity constrains the feasible solutions. The aim is to find the best solution of all feasible solutions. After having decided on the make and source quantities, the replenishment planning and the required option contracts can be specified.

4.3 Performance measurement system

We have had several discussions on performance metrics with organisational members. We identified which performance metrics are necessary to measure the supply chain performance and to support the planning and control processes. The performance of the budgeting and capacity planning activity can be measured by the difference between actual sales and the budget, and the costs of storage capacity. The performance of the sales and replenishment planning is measured by customer service metrics and the costs of inbound transportation and working capital tied up in inventory. Further, the performance of the planning and control activities can be measured by the costs of outbound transportation and the organisational costs (people, information systems, etc.). To support the planning activities, the actual sales, the demand forecast accuracy, the replenishment lead times and the physical inventory needs to be measured and evaluated. The customer service is measured by both on-time delivery as well as delay characteristics. Delays can be caused by material unavailability or delays in the outbound transportation. The determination of the base-stock used in the replenishment planning is based on minimizing certain delays caused by material unavailability. Table 4.2 summarizes the most relevant performance metrics from a planning and control perspective. Most of the identified performance metrics correspond to the performance metrics that are currently implemented by SABIC KSA and will be implemented in the European organisation in the near future.

We have also indentified which data is required to measure these metrics. At present, the data to measure on-time delivery and demand forecast accuracy is not collected. Modifications have to be made to the ERP system to collect this data. The organisation aims to make these modifications as soon as possible.

Customer service	Supply chain costs	Process characteristics
• On-time delivery-to-request • On-time delivery-to-first promised • Delays	• Inbound transportation • Storage capacity • Outbound transportation • Working capital • Organisation	• Actual sales • Actual sales vs. budget • Demand forecast accuracy • Replenishment lead time • Physical inventory

Table 4.2 *Performance metrics*

4.4 Conclusions

The planning and control activities have been re-designed. The budgeting activity should be aligned with the distribution planning, as the distribution planning restricts the demand that can be fulfilled for a given customer service level. In the sales and replenishment planning, two demand situations are distinguished. For the regular demand situation, it is proposed to control the replenishments according to a state-dependent base-stock policy. The base-stock policy is adjusted when the control chart of the demand signifies that the demand is significantly different from the demand distribution which was used to calculate the present base-stock. The base-stock setting is calculated assuming a stationary demand situation. For the situation that uncertainty exists as to whether a sales contract will be closed, the replenishment planning activity should decide on which fraction to source from SABIC KSA, which consequently requires storage capacity, and which fraction to source externally. This make and source decision depends on whether it can be arranged that the delivery location of replenishment orders can be changed after specifying the vessel nominations. Based on the re-design of the planning and control activities, the performance measurement system has been re-designed.

5 Inventory control

The sales and replenishment planning can be supported by deploying an inventory control policy to determine how large replenishment orders should be, to anticipate to the uncertainties in demand and supply. In this chapter, the periodic review, base stock model is developed. Section 5.1 introduces the inventory control policy. The demand and the lead time processes are modelled in Section 5.2. In Section 5.3 the performance measures are derived. Section 5.4 describes the implementation of the model as a MS Excel tool. The model and its implementation are verified in Section 5.5. This chapter ends with drawing conclusions in Section 5.6.

5.1 Periodic review, base-stock policy

We define:

S	Base-stock level.
R	Review period (periods).
$p(t)$	Quantity that becomes available at the start of period *t*.
$r(t)$	Order release quantity at the start of period *t*, immediately after receipt of *p(t).*
$D(t)$	Demand in period *t.*
$X(t)$	Physical inventory at start of period *t*, immediately before receipt of *p(t).*
$B(t)$	Backlog at start of period *t*, immediately before receipt of *p(t).*
$O(t)$	Outstanding orders at start of period *t*, immediately before receipt of *p(t).*
$Y(t)$	Inventory position at start of period *t*, immediately before receipt of *p(t)*, which is defined as $Y(t) = X(t) - B(t) + O(t)$.
$L(t)$	Lead time (periods) of an order released in period *t*, i.e. throughput time between time of release of an order and time at which the ordered items are available.
$\underline{L}$	Minimum lead time (periods).
$L^{+}(t)$	Additional lead time (periods) of an order released in period *t*, which is defined as $L^{+}(t) = L(t) - \underline{L}$.

The order release quantity *r*(*t*) in each review period *R* is the difference between the base-stock level *S* and the inventory position *Y*(*t*). The order release quantity should be nonnegative and is as follows:

$$r(t) = S - Y(t), \quad t = 0, R, 2R, .. \; . \tag{5.1}$$

The lead time from ordering products to the time that the parts become available is long and uncertain. As discussed in Section 2.1.1, after deciding on order release quantities, the earliest time the shipment commences is at the start of the lifting month. We therefore decide to treat the lead time $L(t)$ as consisting of a deterministic part, the minimum lead time $\underline{L}$, and a stochastic part, the additional lead time $L^{+}(t)$. The additional lead times are assumed to be generated by an exogenous, sequential supply system (Zipkin, 2000). This means that the additional lead time does not depend on the amount of orders that are released and different replenishment orders do not cross in time. We assume that lead times are an integer number of periods so that material becomes available at the start of a period.

Demand occurs periodically. Demand which cannot be fulfilled from inventory is backordered and fulfilled as soon as possible. In the next section we specify the demand distribution during the review period and the lead time. This demand distribution is used to determine optimal base-stock levels for given performance measures.

5.2 Demand and supply

We model the demand distribution during the review period and the lead time as a convolution between (1) the demand during the review period and the minimum lead time $D(t,t+R+\underline{L}]$, and (2) the demand during the additional lead time $D(t,t+L^{+}(t)]$ (Figure 5.1). The demand during the additional lead time follows a conditional probability distribution, since the demand distribution is dependent on the lead time distribution.

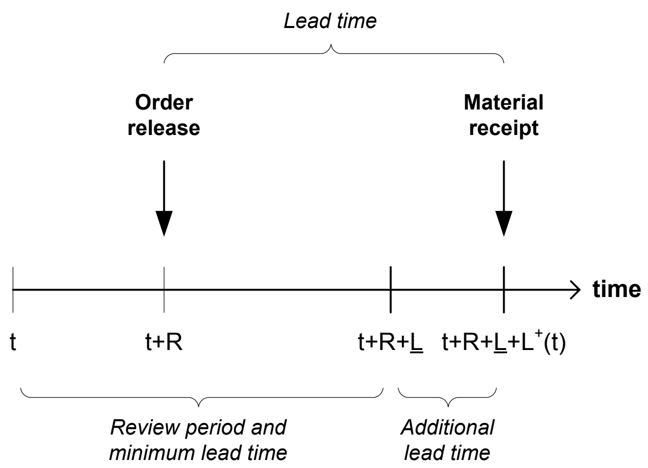

Figure 5.1 *Timeline of releasing orders and receiving material*

For the inventory system under investigation the conditional probability distributions that represent the demand during the lead time at the different terminals are a mixture of different continuous distributions. For instance, daily demand and (additional) lead times at terminals A to C are normal and Gamma distributed, respectively. The mixture of a normal and Gamma distribution is quite complex and, consequently, hard to compute. To simplify computations discretized continuous distributions are used for the demand and additional lead time. Since orders are placed in the inventory system in discrete quantities and the lead time is assumed to be an integer number of periods, it seems appropriate to use discretized continuous distributions. Our work differs from the existing literature, e.g. Johansen & Thorstenson (2008), in that we distinguish between different parts of the replenishment lead time and that we use discretized continuous distributions to deal with a more complex mixture of distributions.

Two demand situations are considered. First, we treat the system which faces normal distributed period demand. This system corresponds to terminals A to C. Then, we study the system which faces both intermittent demands as well as normal distributed continuous demands. This system corresponds to terminal D. For both situations the (additional) lead time is Gamma distributed.

5.2.1 Period demand

The inventory system faces normal distributed period demand and Gamma distributed additional lead times. Let $f(i)$ denote the probability density function (pdf) and let $F(i)$ denote the cumulative distribution function (cdf) of a random distributed variable i.

The demand $D(t)$ follows a normal distribution with average μ and variance σ^2. The discretized pdf of the demand during l periods is as follows:

$$f_D(x;l) = \Phi\left(\frac{x - 0.5 - l\mu}{\sigma\sqrt{l}}\right),\ x = 0,$$
$$f_D(x;l) = \Phi\left(\frac{x + 0.5 - l\mu}{\sigma\sqrt{l}}\right) - \Phi\left(\frac{x - 0.5 - l\mu}{\sigma\sqrt{l}}\right),\ x = 1,2,..,$$

where $\Phi(.)$ denotes the Gaussian function. (5.2)

Then the pdf of the demand during the review period and minimum lead time, $D(t,t+R+\underline{L}]$, is:

$$f_1(x) = f_D(x; R + \underline{L}),\ x = 0,1,... \qquad (5.3)$$

The additional lead time $L^+(t)$ follows a Gamma distribution with shape k and scale θ. The continuous cdf of the additional lead time is:

$$F_L(x;k,\theta) = \int_0^x x^{k-1} \frac{e^{-x/\theta}}{\theta^k \Gamma(k)},\ x \in \mathbb{R}\ .$$

where $\Gamma(.)$ denotes the gamma function. (5.4)

The discretized pdf of the additional lead time $L^+(t)$ is defined as:

$$f_L(x) = F_L(x),\ x = 0,$$
$$f_L(x) = F_L(x) - F_L(x-1),\ x = 1,2,... \qquad (5.5)$$

The pdf of the demand during the additional lead time, $D(t,t+L^+(t)]$, is the summation, for all possible additional lead time values, of the probability that the demand equals the random value y in l periods, given that the additional lead time equals l periods:

$$f_2(y) = \sum_{l=1}^{\infty} \left[f_D(y;l) \cdot f_L(l) \right],\ y = 0,1,... \qquad (5.6)$$

The convolution of $f_1(x)$ and $f_2(x)$ results in the pdf of the demand during the review period and total lead time, $D(t,t+R+L(t)]$:

$$f_{12}(z) = \sum_{i=0}^{z} f_1(i) f_2(z-i)\,,\ z = 0,1,..\ . \tag{5.7}$$

5.2.2 Intermittent demand

We now consider the inventory system which faces intermittent demands in addition to period demands. Since the intermittent demand is significantly larger than the period demand, the intermittent demand needs to be modelled apart from the period demand. The intermittent demand occurs on average every p periods. We assume that the interval for intermittent demand is deterministic, while in practice the demand-interval is uncertain. However, to model the demand interval uncertainty, a relationship is required between the probability of the interval length and the probability of demand occurrences in a time period. Exponentially distributed inter-demand has this property (in this case the number of order occurrences is Poisson distributed). The analysis in Section 2.1 shows that the order inter-arrival is Erlang distributed and cannot be modelled as Poisson distributed. Since the uncertainties in demand size and supply have probably a much greater impact on the inventory than the uncertainty in the demand-interval, we expect that under this assumption the demand distribution over the review period and lead time still gives a practical approximation of the real demand and supply processes.

The total demand thus consists of period demand and large intermittent demand that occurs every p periods. The intermittent demand size is normal distributed. The total demand distribution is the convolution of the period demand distribution and the intermittent demand distribution.

Then the pdf of the total demand during the review period and minimum lead time, $D^*(t,t+R+\underline{L}]$, is:

$$f_1^*(x) = \sum_{i=0}^{x} f_1(i) \cdot f_{D,A}\left(x-i;\frac{R+\underline{L}}{p}\right),\ x = 0,1,\ldots \tag{5.8}$$

The pdf of the total demand during the additional lead time, $D^*(t,t+L^+(t)]$, is:

$$f_2^*(y) = \sum_{i=0}^{y}\left(f_2(i)\sum_{l=1}^{\infty}\left(f_{D,A}\left(y-i;\frac{l}{A}\right)\cdot f_L(l)\right)\right),\ y = 0,1,\ldots \tag{5.9}$$

The convolution of $f_1^*(x)$ and $f_2^*(x)$ gives the pdf of the total demand during the review period and lead time, $D^*(t,t+R+l_1+L_2(t)]$:

$$f_{12}^*(z) = \sum_{i=0}^{z} f_1^*(i) f_2^*(z-i)\,,\ z = 0,1,\ldots \tag{5.10}$$

In the next section we specify the performance measures for period demand. The performance measures for the combination of period demand and intermittent demand can be obtained by replacing the distribution for period demand by the distribution for total demand.

5.3 Performance measures

The demand distributions can now be used to obtain performance measures. First, the cycle service level, the fill rate and the average physical inventory are determined. Then, the distributions for the maximum physical inventory and the customer order waiting time are derived. The customer order waiting time distribution is used to calculate the optimal base-stock for service objectives specified as time windows. Within these time windows a given percentage of all customer orders should be delivered.

Cycle service level

The probability of not being out-of-stock in a replenishment cycle P_1 is the probability that the demand during the review period and the lead time is smaller than or equal to the base-stock level:

$$P_1(S) = \Pr\{D(t, t + R + L(t)] \leq S\} = F_{12}(S) . \tag{5.11}$$

Fill rate

The fill rate P_2 is the fraction of total demand that is fulfilled from inventory without delay. Hence, the fill rate is the complement of the fraction of total demand that is fulfilled from inventory with delays. This fraction is the expected shortage per replenishment cycle *ESPRC* divided by the total demand during a replenishment cycle $E[D(t,t+R]]$:

$$P_2(S) = 1 - \frac{ESPRC}{E[D(t, t + R]]} . \tag{5.12}$$

The expected shortage per replenishment cycle *ESPRC* is:

$$ESPRC(S) = \sum_{x=S+1}^{\infty} (x - S)\Pr\{D(t, t + R + L(t)] = x\} = \sum_{x=S+1}^{\infty} (x - S) f_{12}(x) . \tag{5.13}$$

Average physical inventory

The average physical inventory is calculated based on the average demand during a replenishment cycle and the expected physical inventory immediately before replenishment:

$$E[X(t)] = S - D(t, t + R + L(t)] + \frac{E[D(t, t + R]]}{2} . \tag{5.14}$$

Maximum physical inventory

Storage capacity is limited. The probability that the physical inventory exceeds the available storage capacity should therefore be taken explicitly into account when choosing a base-stock level. The maximum physical inventory during a replenishment cycle is the physical inventory immediately after replenishment. The physical inventory immediately after replenishment, which we denote as $X_{\max}(t)$, equals the physical inventory immediately before replenishment plus the replenishment quantity that becomes available, which is released $L(t)$ periods ago:

$$\begin{aligned} X_{\max}(t + L(t)) &= X(t + L(t)) + r(t) = S - D(t - R, t + L(t)] + S - Y(t) \\ &= S - D(t - R, t + L(t)] + D(t - R, t] = S - D(t, t + L(t)],\ t = 0, R, 2R, \ldots \end{aligned} \tag{5.15}$$

Then the distribution of the maximum physical inventory is given by:

$$f_{X,\max}(x;S) = \sum_{y=0}^{S-x} f_D(y;l_1) \cdot f_2(S-x-y)\,,\ x = 0,1,... \tag{5.16}$$

Customer order waiting time

In the remainder of this section we derive a procedure to calculate the (customer order) waiting time distribution. To our best knowledge, no research is currently available to calculate the waiting time distribution in a periodic review, base-stock inventory system with stochastic lead times. Tempelmeier (2000) studied the order waiting time distribution for a periodic review, base-stock system with a deterministic replenishment lead time. He determined an exact procedure to calculate the order waiting time distribution under the condition that the lead time is deterministic and smaller than the review period, $L<R$. We extend his procedure to the case of stochastic lead times that are larger than the review period.

As in Tempelmeier (2000) we assume that:

(i) each period demand is counted in total as a single demand event,

(ii) the demand in the period that the physical inventory falls to zero is completely counted as backordered, and

(iii) the base-stock level is sufficiently large to ensure that the physical inventory immediately before a review instance is positive.

Starting point of his analysis is the probability distribution of the coverage, which is the number of period demands that can be completely served from a given physical inventory. The coverage measure uses the review event as a reference point. The complementary measure of the coverage is the stock-out duration. Since the stock-out duration uses the replenishment event as a reference point, it has a direct relationship with the lead time. We therefore use this measure as a starting point of our analysis.

The stock-out duration is the time period during which the physical inventory has fallen to zero and newly arriving demand is added to the backorder queue. The probability that the stock-out duration J equals j is as follows:

$$\begin{aligned} f_J(j;S) &= \Pr\{D(t,t+R+L(t)-j] \le S\} - \Pr\{D(t,t+R+L(t)-(j-1)] \le S\} \\ &= F_{12}^J(S;j) - F_{12}^J(S;j-1) \end{aligned} \tag{5.17}$$

The probability that the demand during the review period and the lead time minus a given stock-out duration, R+$L(t)$-j periods, equals S is:

$$f_{12}^J(S;j) = \sum_{l=0}^{j}\left(f_D(S;R+\underline{L}+l-j)\cdot f_L(l)\right) + \sum_{l=j+1}^{\infty}\left(f_L(l)\cdot\sum_{i=0}^{S}\left(f_1(i)\cdot f_D(S-i;l-j)\right)\right) \tag{5.18}$$

In the first summation of equation (5.18) the probability that the stock-out duration j is larger than the additional lead time l is evaluated, i.e. the probability of demand during the additional lead time equals zero. In the second summation of the equation the probability that the stock-out duration j is smaller than the additional lead time l is evaluated.

The stock-out duration can now be used to calculate the expected number of orders observing a given waiting time, based on assumption (iii) which state that the stock-out duration is less than the review period ($j<R$). The expected number of orders without any delay is:

(1) The number of orders directly delivered when the physical inventory is not depleted during the entire replenishment cycle, i.e. the review period multiplied by the cycle service level;

(2) The number of orders arriving in periods before depletion, i.e. the summation of the number of periods without depletion n multiplied by the probability of a stock-out duration of R-n periods; and

(3) The partially delivered order arriving in the period when the physical inventory falls to zero, which is the probability that the stock out-duration is equal or greater than one period, i.e. the probability of being out-of-stock in a replenishment cycle.

The expected number of orders without any delay is then given by:

$$H(W(S)=0)=R\cdot F_{12}(S)+\sum_{n=1}^{R-1}\left(n\cdot f_J(R-n;S)\right)+\left(1-F_{12}(S)\right) \tag{5.19}$$

The expected number of orders with delay w is the probability that the stock-out duration is equal to or larger than w:

$$H(W(S)=w)=1-F_J(w-1;S)\,,\quad w=1,2,..,R\ . \tag{5.20}$$

Then the pdf of the waiting times is as follows:

$$f_W(w;S)=\frac{H\left(W(S)=w\right)}{\sum_{t=0}^{R}H\left(W(S)=t\right)}\,,\quad w=0,1,..,R\ . \tag{5.21}$$

The calculation of the order waiting time distribution is exact under the given assumptions. In particular, this means that the calculation is only exact when the base-stock level is sufficiently large to ensure that the probability of a stock-out duration larger than the review period approximates zero ($f_{12}^J\left(S;j\right)\approx 0.000$, $j>R$).

5.4 Inventory control tool

The model is implemented as a tool in MS Excel. The model equations are programmed as a macro in ‘Visual Basics for Applications’ (VBA). The input parameters of the macro are depicted in Figure 5.2. For the situation that demand only occurs on working days (which applies to period demand), the review period, the minimum lead time and the shape parameter of the gamma distribution for the additional lead time are multiplied with a factor ‘5/7’. The parameters are used to calculate the following distributions: the demand during the review period and lead time (equation 5.7 or 5.10), the maximum physical inventory (equation 5.16), the stock-out duration (equation 5.18) and the waiting time (equation 5.21). The distribution of the demand during the review period and lead time is used to find the lowest base-stock level that results in a service level P_1 and P_2 equal to or greater than {0.90, 0.95, 0.97, 0.99, 0.999}.

It is not useful to calculate the probability distributions for each integer value, since it is sufficient to calculate the required base-stocks with an accuracy of 100 MT for the supply chain under investigation. Therefore, a step size is used in evaluating the probability distributions. To speed up calculations, the distributions are only evaluated within a search range. The boundaries of the search range are determined by a half-interval (binary) search method. For the probabilities of the demand conditional to the lead time, the lead time probabilities are evaluated from zero to a maximum lead time value $l_{\max}$. The maximum lead time value $l_{\max}$ is the smallest value l for which holds that the probability is smaller than 0,01%, $f_L(l) < 0.0001$.

The tool does not calculate the waiting time distribution for intermittent demand, since it takes too much time to calculate the nested summations of the waiting time distribution under intermittent demand.

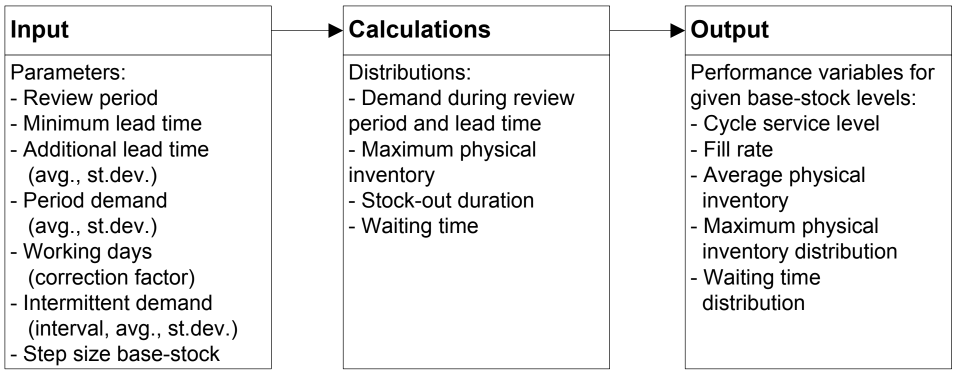

Figure 5.2 *Inventory control tool*

5.5 Verification

In this section we study whether the model and its implementation in MS Excel is correct. By performing a number of verification tests we assess whether the model equations have been derived correctly and whether the model has been implemented properly.

For this purpose we set up a simulation model in 'Anylogic Advanced 6.2', a Java-based simulation software program. The simulation model represents exactly the same system as the (quantitative) model. In the simulation model an event is scheduled for each period to execute actions of releasing orders, generating demand, and fulfilling backorders and demand. Orders are released according to the periodic review, base-stock policy. When an order is released, a dynamic event is scheduled for the receipt of $p(t)$. A dynamic event can delete itself after execution of the action. Multiple instances of a dynamic event can be scheduled concurrently. For every shipment an instance of the dynamic event is created where the scheduled execution time is the stochastic additional lead time. The period demand and the additional lead time follow a normal and Gamma distribution, respectively.

To verify the quantitative model we compared the results of the quantitative model with the simulation model for different demand and (additional) lead time scenarios. These scenarios are given in Table 5.1. The review period was set at $R = 30$ and the minimum lead time at $l_l = 40$. With the quantitative model we calculated the base-stock levels to achieve fill rates of 0.90, 0.95 and 0.99 for each scenario (with step size $\Delta S = 100$). These base-stock levels were used as an input parameter of the simulation experiments. In the simulation experiments we performed 30 simulation runs for each scenario with a run-length of 10,000 periods (warm-up period of 200 periods).

Scenario	Add lead time		Period demand	
	Mean	*St.dev.*	*Mean.*	*St.dev.*
1	40	10	100	50
2	40	10	50	50
3	40	10	100	25
4	20	10	100	50
5	20	10	50	50
6	20	10	100	25
7	40	5	100	50
8	40	5	50	50
9	40	5	100	25

Table 5.1 *Verification tests*

The results of the quantitative model and the simulation model on the performance measures were compared with each other. The results show that the quantitative results are consistent with the simulation results. For instance, the results of the probability of no delay, when using a base-stock level targeting at a fill rate of 0.90, are shown in Table 5.2. For this performance measure, almost all quantitative results fall within the 99% confidence interval of the simulation results. Only one result falls just outside the confidence interval, but we consider this difference as negligible. This verification test also shows the implication of the assumption in calculating the waiting time distribution that the demand in the period that the physical inventory falls to zero is completely counted as backordered. It causes the calculated probability of no delays to be slightly smaller than the fill rate.

Scenario	Base-stock	Fill rate	Waiting time probability Pr{$W(t)$=0}	
		Simulation 99% C.I.	*Quantitative result*	*Simulation 99% C.I.*
1	11,300	(0.891, 0.903)	0.890	(0.886, 0.898)
2	5,800	(0.885, 0.901)	0.895	(0.884, 0.900)
3	11,300	(0.906, 0.916)	0.900	(0.901, 0.911)
4	9,300	(0.893, 0.903)	0.894	(0.889, 0.899)
5	4,800	(0.894, 0.908)	0.900	(0.893, 0.907)
6	9,300	(0.903, 0.913)	0.902	(0.898, 0.908)
7	11,000	(0.897, 0.907)	0.899	(0.891, 0.901)
8	5,700	(0.901, 0.913)	0.909	(0.901, 0.911)
9	10,900	(0.903, 0.911)	0.900	(0.893, 0.903)

Table 5.2 *Results of verification test (probability of no delay)*

In conclusion, the verification tests show that the quantitative results are consistent with the simulation results on all of the performance measures. Thus the quantitative model passed our verification tests.

5.6 Conclusions

An inventory model for the periodic-review, base-stock policy with stochastic period demand and stochastic continuous replenishment lead times has been developed. The method that has been applied to determine the demand distribution over the lead time and review period is to split the lead time in a deterministic part, the minimum lead time, and a stochastic part, the additional lead time; and to discretize the continuous distributions of the demand and additional lead time. Standard service levels have been derived for this policy. Further, we derived the distribution of the physical inventory immediately after replenishment for a given base-stock, so that storage capacity requirements can be determined. To determine the customer order waiting time distribution we have adapted the procedure of Tempelmeier (2000) for stochastic lead times. Subsequently, the inventory model and the performance measures have been implemented as a tool in MS Excel. The inventory model and its implementation have been verified by comparing the results of the inventory control tool with the results of simulation experiments for different demand and lead time scenarios.

6 Results

In this chapter, the results of validation tests and a scenario analysis are presented. In Section 6.1, the validation of part of the re-designed planning and control activities is discussed. Section 6.2 provides the results of the scenario analysis. Conclusions are formulated in Section 6.3.

6.1 Validation

In this section we assess whether the re-designed sales and replenishment planning procedure perform as intended. For historical data on demand and lead time we investigate how the net inventory would have changed over time when applying the procedures as described in Chapter 4. The evolution of the net inventory gives an adequate indication of the supply chain performance, in terms of customer service as well as costs. By carrying out three distinct validation tests the capabilities and limitations of these procedures are evaluated.

Validation tests are performed on three replenishment processes which differ in demand characteristics. The planning procedures are validated with historical data for three demand and supply processes: (1) MEG at terminal A, (2) DEG at terminal C, and (3) MEG at terminal D. Terminal A and C face period (daily) demand; terminal D faces both intermittent demand and period (daily) demand. These demand processes are regarded as representative for the demand processes of the other MEG and DEG products.

6.1.1 Validation procedure

The available historical data on the demand and the additional lead time is used for the validation tests. Data on the demand is available from January 2006. It is subtracted from data on the physical inventory in a similar way as for the demand analysis (Appendix A). Data on the additional lead time is available for replenishment orders released from July 2006. At a few review instances during this period, orders were not released and a replenishment lead time has thus not been realized (it concerns two review instances for DEG at terminal C and three review instances for MEG at terminal D). We assume that the additional lead time at these review instances equals the average additional lead time.

The order release quantity in each month is the difference between the base-stock and the inventory position at the review instance. Orders are released at the 20th day of each month. It is assumed that the total sales volume of the current month is known at the time of reviewing. The base-stock is maintained for consecutive order releases until the control chart indicates that the forecasted demand differs significantly from the specified average demand level. The control chart displays the total daily demand in a month or the total intermittent demand in a month. The warning limits are set at one standard deviation from the control level and the control limits at two standard deviations from the control level. The forecasted demand is considered as significantly different from the control level when a demand point is outside the control limit or when two consecutive demand points are outside the warning limit.

To calculate base-stock levels we use the time periods and the lead time statistics as given in Table 6.1. The values of the additional lead time are based on the values found in the supply analysis (see Section 2.1.1). The average and standard deviation of the monthly demand from January 2006 to June 2006 is used to calculate the initial base-stock for the order release at the end of July 2006. For the periods considered in the validation tests, adjustments of the base-stock are based on the latest expected demand level and the initial standard deviation. To react quickly to changes in demand, the latest demand observation provides the best forecast for the future demand. However, to prevent overestimation in the adjustment of the base-stock to the latest demand observation, the latest demand observation is slightly smoothed to calculate the new base-stock level. An exponential moving average of the demand with a smoothing factor of 0.75 is used to determine the new expected demand level.

		MEG, Terminal A	DEG, Terminal C	MEG, Terminal D
Review period		30	30	30
Minimum lead time		40	40	40
Additional lead time	average	45	55	40
	c.v.	0.10	0.10	0.25

Table 6.1 *Parameter values validation tests*

6.1.2 Validation results

MEG, terminal A

The control chart for MEG at terminal A is shown in Figure 6.1. The demand of the last period is used as the demand forecast for the next periods. Based on the demand behaviour from January 2006 to June 2006, the average demand level and the standard deviation are set. The aim is to obtain a fill rate of 99.0%. The corresponding base-stock is 21,900 MT. In May 2007 the observed demand is considered significantly different from the control level. Consequently, the base-stock is adjusted. From September to December 2007 the company had been forced to restrict sales because of production difficulties. Since this has been regarded as a highly exceptional event, this period is omitted in the validation. In January 2008 the base-stock is adjusted once more. Table 6.2 shows the base-stock required for the distinct demand levels. In addition, the theoretical average physical inventory and the maximum physical inventory with 99% confidence are given.

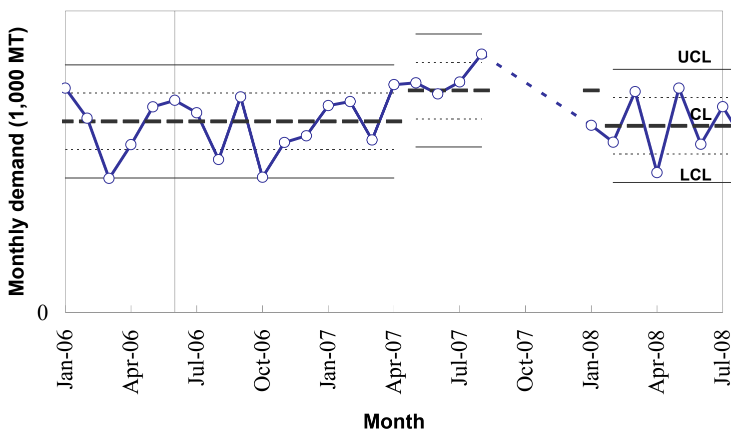

Figure 6.1 *Control chart daily demand MEG, terminal A*

Period	Base-stock	Avg. inv.	Max. inv. (99%)
Jul 07 – Apr 07	21,900	4,600	10,800
May 07 – Jan 08	25,300	5,300	12,000
Feb 08 – Jul 08	21,400	4,540	10,600

Table 6.2 *Base-stock levels MEG, terminal A*

Controlling the inventory with these base-stock levels gives a net inventory over time as depicted in Figure 6.2. The net inventory seems to behave as intended: it happens only few times that the demand is backordered (fill rate 99.3%) or that the inventory is exceeding the available storage capacity.

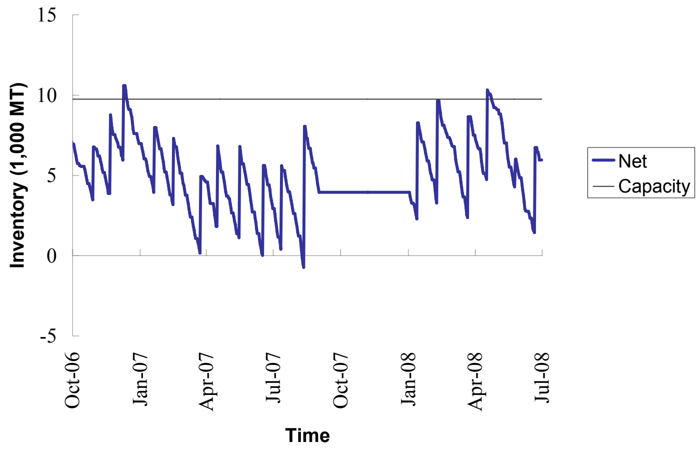

Figure 6.2 *Inventory MEG, terminal A*

DEG, terminal C

Figure 6.3 shows the demand behaviour of DEG at terminal C. The initial base-stock for the order release in July 2006 is based on the average and standard deviation of the demand from January to June 2006, and a target fill rate of 99.0%. The base-stock is adjusted frequently from August 2006 on (see Table 6.3). Figure 6.4 shows the resulting net inventory. The inventory control does not perform sufficiently: the number of backorders is too high (fill rate 96.7%). This is caused by the delay time, i.e. the replenishment lead time, between adjusting the base-stock and the receipt of corresponding replenishment orders. It takes about 3 months before the physical inventory is adapted to the new demand level. In between, the inventory on-hand is expected to be rather small when the base-stock has been increased and rather large when the base-stock has been decreased. This system behaviour underlines the importance of demand forecasting.

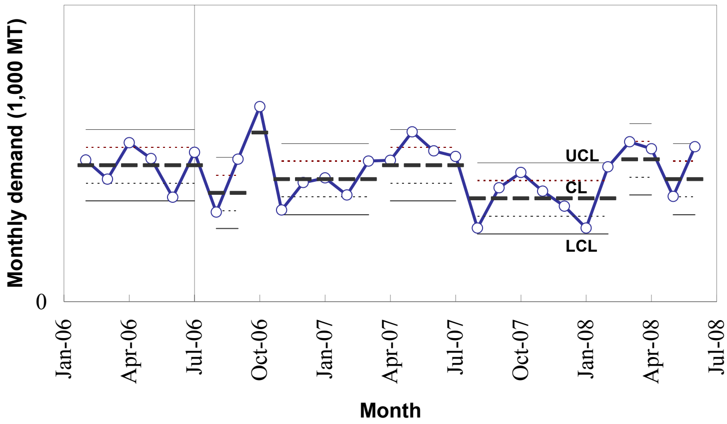

Figure 6.3 *Control chart daily demand DEG, terminal C*

Period	Base-stock	Avg. inv.	Max. inv. (99%)
Jul 06, Apr 07 – Jul 07	6,600	1,410	3,100
Aug 06 – Sep 06	5,300	1,210	2,600
Oct 06	8,000	1,640	3,600
Nov 06 – Mar 07, May 08 – Jun 08	6,000	1,360	2,900
Aug 07 – Feb 08	5,100	1,170	2,600
Mar 08 – Apr 08	6,900	1,480	3,200

Table 6.3 *Base-stock levels DEG, terminal C*

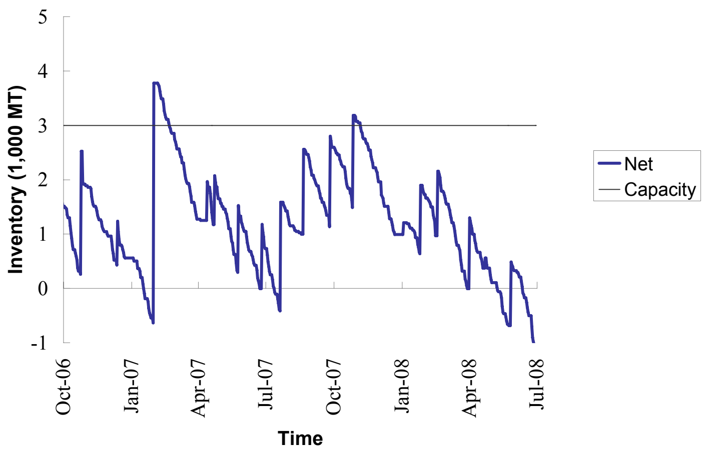

Figure 6.4 *Inventory DEG, terminal C*

MEG, terminal D

Terminal D faces intermittent demand and period demand. The period demand has been quite stationary for the periods considered and it is just a small fraction of the total demand. We therefore focus on the intermittent demand. The control chart of intermittent demand is depicted in Figure 6.5. The intermittent demand has been fluctuating heavily during the last two years.

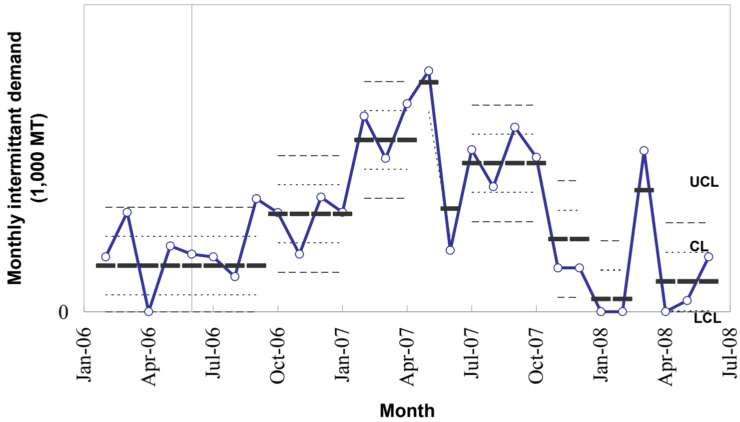

Figure 6.5 *Control chart intermittent demand MEG, terminal D*

The base-stock levels for the identified demand levels have been calculated. Table 6.4 displays the base-stock levels to achieve a fill rate of 90.0% for the period from June 2006 to May 2007. At first sight, the base-stock levels seem to be quite high in relation to the present storage capacity. However, the high base-stock levels are justified by the high uncertainty in both demand size and replenishment lead time. Since the calculated maximum physical inventory levels are considerably higher than the present storage capacity of 10,000 MT, the corresponding base-stock levels cannot be put into place. We have calculated base-stock levels for lower target fill rates, but these are still too high to put into place.

Period	Demand interval (days)	Base-stock	Avg. inv.	Max. inv. (99%)
Jul 06 – Sep 06	15	14,300	7,340	11,300
Oct 06 – Jan 07	15	24,200	10,950	14,600
Feb 07 – Apr 07	10	39,300	17,060	21,700
May 07	10	51,600	22,347	32,000

Table 6.4 *Base-stock levels MEG, terminal D*

The inventory can only be controlled properly with a lower base-stock, when the uncertainties in demand and replenishment lead times are reduced considerably. It is likely that this has been done in practice by making the timing and quantity of demand fulfilment dependent on the timing and quantity of the receipt of replenishment orders. Consequently, it does not make sense to evaluate the inventory over time. The demand correlates with the replenishments in the historical data, while the policy assumes independent demand and replenishment lead times. Making the demand fulfilment dependent on the replenishment process obviously results in low customer service levels. However, it depends on the agreements and communications with the customers whether it has had an impact on the perceived customer service. It is probably inevitable to reschedule demand fulfilment at this terminal, when it is too expensive to hold the amount of safety inventory given the present uncertainties in demand and supply.

In the next section, it is investigated how a reduction of the minimum lead time and the variance of the additional lead time can contribute to a reduction in base-stock levels.

6.2 Scenario analysis

A scenario analysis is performed to investigate the relations between the base-stock, fill rates and lead times. In particular, it is studied how the length of the minimum lead time, and how the variance of the additional lead time, influences the base-stock for different fill rates. The parameter values used in this scenario analysis are based on the demand and supply processes of MEG at one of the terminals, see Table 6.5.

		Base scenario
Review period (days)		30 days
Minimum lead time (days)		40 days
Additional lead time	average (MT)	40 days
	c.v.	0.25
Daily demand	average (MT)	200 MT
	c.v.	0.50
Step size (MT)		100 MT

Table 6.5 *Parameter values base-scenario*

6.2.1 Minimum lead time

First, three scenarios for the minimum lead time are studied. The minimum lead time is currently 40 days, but it might be possible to decrease the minimum lead time. The effect of reducing the minimum lead time from 40 days to 30 days, and to 20 days is studied. Figure 6.6 depicts, for each scenario, the base-stock and the maximum physical inventory with 99% confidence for different fill rates. The inventory levels increase substantially with increasing fill rates.

Two observations can be made on the difference in inventory levels between the scenarios. Firstly, the base-stock decreases with roughly the same size for each reduction in the minimum lead time. The reason is that a reduction in the minimum lead time results in a proportional reduction of the material on-order. Secondly, reducing the minimum lead time has little effect on the maximum physical inventory. This is caused by two mechanisms: (1) the reduction in the minimum lead time does not proportionally reduce the uncertainty in the minimum lead time demand (the uncertainty decreases with the square root of reduced days), and (2) the uncertainty in the minimum lead time demand is smaller than the uncertainty in the additional lead time demand in these scenarios. So we conclude that the effect of reducing the minimum lead time is small.

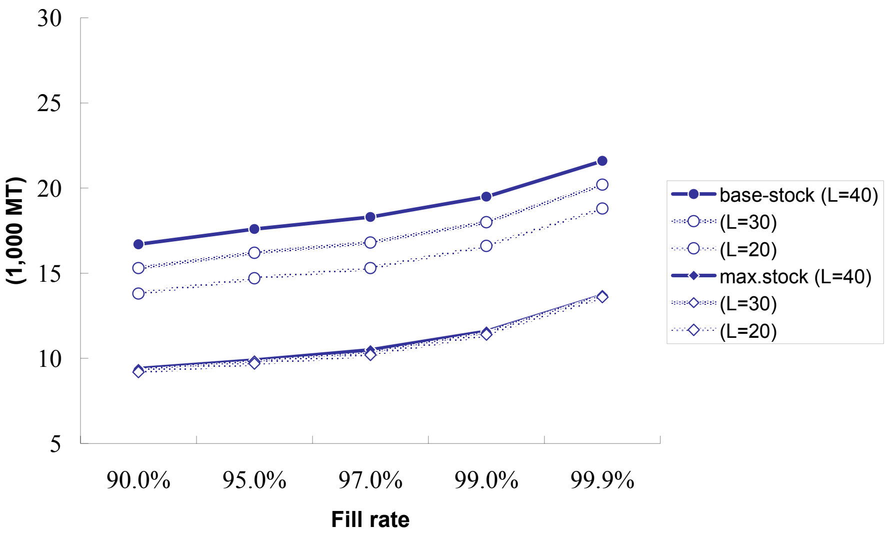

***Figure 6.6** Effect of minimum lead time on base-stock and maximum physical inventory*

6.2.2 Variance additional lead time

Now three scenarios for the additional lead time variance are studied. At present, the variance of the additional lead time for MEG at terminal A is 25% of the expected additional lead time. We study the effect of changing the coefficient of variation of the additional lead time to 50% and 12.5% on the inventory levels. For each scenario, the base-stock and the maximum physical inventory with 90% confidence are depicted in Figure 6.7.

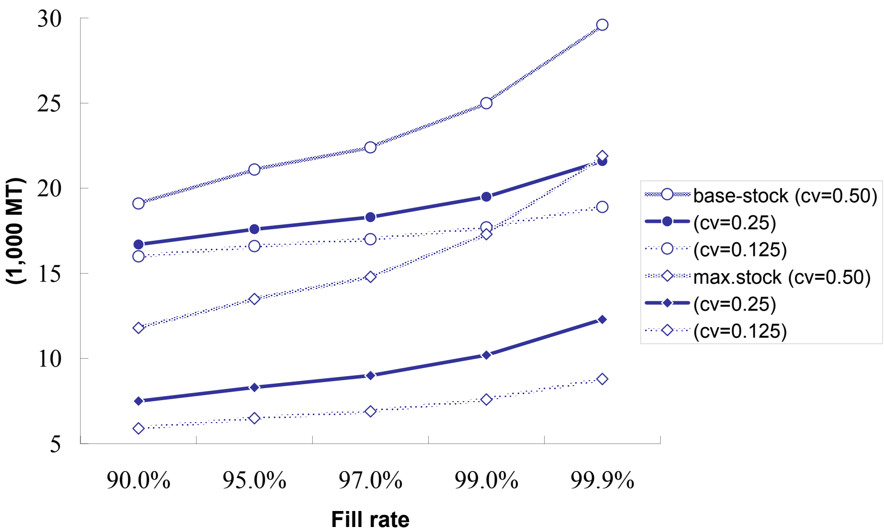

***Figure 6.7** Effect of variance additional lead time of base-stock and maximum physical inventory*

The figure shows that the base-stock and the maximum physical inventory are increasing more than proportionally with increasing variance in the additional lead time. Let us consider the inventory levels to obtain a fill rate of 99%. Suppose that the coefficient of variation increases from 25% to 50%; then the base-stock increases with 5,500 MT and the maximum physical inventory increases with 7,100 MT. When the coefficient of variation is decreased from 25% to 12.5%, then the base-stock is decreased with 1,700 MT and the maximum physical inventory with 2,400 MT. The results show that the variance of the additional lead time has a large effect on the base-stock and thus the maximum physical inventory. Thus when the maximum physical inventory is higher than the actual storage capacity, one can decide to acquire additional storage capacity, reduce the fill rate or reduce the variance in the additional lead time.

Through re-designing the replenishment scheduling, the uncertainty in the lead time might be reduced. For instance, lifting the same material on the same days in each month in combination with standardizing the sequence of delivery to terminals might reduce the variability of planned lead times, and consequently the lead time uncertainty. A constraining factor is the delivery of supply to direct customers. It needs to be investigated whether customers can be delivered according to a fixed planned delivery period instead of a variable planned delivery period as requested by the customer.

6.3 Conclusions

We expect that the re-designed planning and control process will perform satisfactory for the replenishment of MEG and DEG to the terminals that face daily demand. The validation tests show that the re-designed sales and replenishment planning might work in practice for MEG at terminal A and DEG at terminal C. These demand processes are regarded as representative for the demand processes of the other MEG and DEG products at the terminals that face daily demand. The re-designed process could not be validated for terminal D which faces intermittent demand, since the demand fulfilment has been made dependent on the state of replenishments at this terminal. The validation tests show however that with the current uncertainties large base-stocks should be put into place. These base-stocks require large investments in additional storage capacity. This makes the use of a state-dependent base-stock policy infeasible for the present replenishment and demand processes at terminal D.

The performance of the re-designed processes depends to a large extent on the control levels and the demand statistics used in calculating the base-stock. These settings determine both the base-stock level as well as the base-stock is adjustments. In the validation tests, a smoothed value of the latest demand observation is used to determine the new demand levels and the initial standard deviation is maintained when adjusting the base-stock. The control levels are set to two standard deviations, and the warning limits are set to one standard deviation. Figure 6.8 shows the relation between these settings and the performance. The relation is largely affected by the demand forecast accuracy. Including more demand variation in the specification of the base-stock leads to fewer adjustments in the base-stock, but at the expense of more safety inventory. The (safety) inventory is restricted by the available storage capacity. Base-stock adjustments might lead to deteriorating performance during the reaction time, which is the replenishment lead time, if the demand change is not forecasted accurately in advance. More fundamental research is necessary to demonstrate the general validity of using a state-dependent base-stock policy in combination with control charts. It needs to be investigated how the base-stock and control settings are related to the performance, for different demand processes and demand forecasting accuracies.

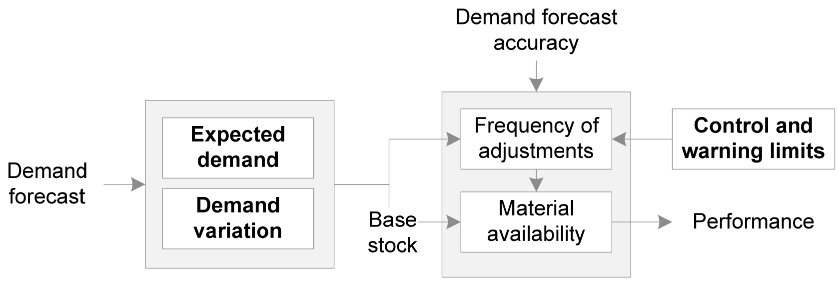

Figure 6.8 *Performance of replenishment planning*

The scenario analysis shows that the variability of the additional lead time has a large effect on the physical inventory that needs to be put into place. By reducing the uncertainty in the lead time, the required storage capacity and the working capital tied up in inventory can be reduced or the service levels can be improved. The company needs to investigate how the variability in the additional lead time can be decreased by a re-design of the scheduling function and how this impacts the customer service of direct customers and the costs of inbound transportation.

7 Conclusions and recommendations

In this chapter the project is evaluated. Section 7.1 presents the conclusions of the project. In Section 7.2 recommendations are formulated. Areas for further research are defined in Section 7.3.

7.1 Conclusions

Companies who extend their supply chains to low-cost regions often face longer and more uncertain lead times. In this project, the planning and control of a petrochemical commodities supply chain that faces long and uncertain lead times has been investigated. Storage capacity is often constrained in process industries, like the petrochemical industry. A supply chain analysis of imported products at SABIC Europe confirms that long and uncertain lead times complicate the planning and control processes considerably. The company's current planning and control processes do not anticipate the uncertainties in demand and supply properly. The analysis shows that demand for imported MEG and DEG at SABIC Europe is highly dependent on a few major customers with whom long-term sales contracts are concluded. Product demands tend to behave rather stationary at most of the terminals. The addition or loss of sales contracts and general market conditions could however cause non-stationary behaviour. As the long lead times require to release orders well in advance, large binomial demand uncertainty could occur when a long-term sales contract with a major customer is still under negotiation at the year-end. Based on the analysis of SABIC Europe's supply chain and a literature review, the following main research question was defined:

How to plan and control a single-echelon supply chain under stochastic supply and capacitated storage, so that customer service levels are met at minimal supply chain costs?

To address this research question, the company's planning and control processes have been re-designed. In the re-design of the sales and replenishment planning, a distinction was made between planning for regular demand and planning under uncertainty in the conclusion of sales contract. Further, the performance measurement system of the company has been re-designed, so that it reflects supply chain performance more accurately and provides better support to the planning and control processes. A periodic review, base-stock policy under stationary stochastic demand and supply has been developed to support the decisions in the sales and replenishment planning. This model has been implemented as an MS Excel tool. Validation tests were performed on the re-designed sales and replenishment planning process under regular demand uncertainty to assess whether it performs as intended. An analysis of lead time scenarios has provided insight into further improvement opportunities of the supply chain performance.

The main conclusions of this project are:

1. The sales and replenishment planning can be supported by deploying a **state-dependent base-stock** control policy. To anticipate on the uncertainties in demand and supply, a model has been developed to calculate the optimal base-stock levels for given customer service levels.

2. The method that has been applied to model the **demand distribution** over the lead time and review period is to split the lead time in a deterministic part, the minimum lead time, and a stochastic part, the additional lead time; and to discretize the continuous distributions of the demand and additional lead time.

3. The **storage capacity requirements** can be determined by evaluating the distribution of the physical inventory immediately after replenishment for a given base-stock.

4. The customer **order waiting time distribution** in a periodic review, base-stock policy can be calculated based on the distribution of the stock-out duration, when the base-stock level is sufficiently large to ensure that the probability of a stock-out duration larger than the review period is approximately zero.

5. To prevent unnecessary adjustments of the base-stock when demand behaves stationary, which may induce more variability in the inventory system, a statistical process **control chart** can be used to support decision making on whether to adjust the reorder level.

6. When facing **uncertainty in the conclusion of a sales contract** in the replenishment planning, different decision options for acquiring supply should be evaluated. The make or source decision is an optimization problem wherein available storage capacity constrains the feasible solutions.

7.2 Recommendations

The re-design of the planning and control processes and the results lead to the following recommendations to the company:

1. Improve the **performance measurement** system (key performance indicators) so that it supports the planning and control processes better. Make modifications to the ERP-system to register requested delivery dates, first promised dates and the demand forecasts used in the sales and replenishment planning.

2. **Align the budget with the capacity plan**, as the distribution planning restricts the demand that can be fulfilled for a given customer service level. Discuss and decide on the desired customer service performance in the tactical planning. The customer service performance at the terminal that faces intermittent demand is of special interest, since the project results indicate that the present order fulfilment has been made dependent on the timing of the replenishments.

3. Invest in improving **demand forecasting**. Register the demand forecasts used in the replenishment planning and discuss the demand forecast accuracy regularly.

4. For the sales and replenishment planning, **construct control charts** of the demand. These control charts might lead to a better understanding of the demand behaviour and could support decision making whether to adjust the reorder levels of the inventory control policy.

5. Support the sales and replenishment planning (for the terminals that face period demand) by **calculating optimal replenishment quantities** with the inventory control tool.

6. Study how facing **uncertainty in the conclusion of sales contracts** in the operational replenishment planning can best be avoided. When uncertainty in the conclusion of sales contracts does arise, discuss it explicitly in the sales and replenishment planning. Decide on which part of the potential demand to make internally (source from the mother company in Saudi Arabia) and which part to source externally.

7. Research how the **replenishment scheduling** can be organised in such a way that the total supply chain performance increases.

7.3 Further research

This project has investigated the planning and control of supply chains facing long and stochastic lead times given storage capacity constraints. Our research has given rise to two main areas for further academic research:

1. *The use of statistical process control charts in inventory control.*

   The validation tests have shown that the use of control charts in relation to adjusting the reorder levels of an inventory control policy might work in practice. We have argued that the use of control charts might lead to a better understanding of the demand processes among organisational members. It also might reduce the variability of replenishment orders when demand behaves rather stationary. Further research is necessary on the general validity of using control charts in inventory control. The following research question needs to be addressed; Can control charts indeed reduce the variability in a supply chain? If so, under which demand conditions does this apply? Moreover, how do the inventory control policy and the control chart settings affect the supply chain performance?

2. *Managing large binomial demand uncertainty.*

   We have identified which decision options should be considered to acquire the potential required supply, when facing large binomial demand uncertainty in the supply chain under investigation. We have not elaborated on the optimization problem itself, since the relevant costs of the decision options are unknown. However, it is especially interesting to know to which extent the trade-off between the decision options is determined by the relevant costs or by the storage capacity constraints.
   In general, we wonder whether more supply chains face large binomial demand uncertainty. For the general problem of large binomial demand uncertainty, research questions that might be addressed are the following; What are the causes in these supply chains of this large binomial demand uncertainty? What are mitigation and contingency strategies to manage large binomial demand uncertainty? Further, what is the performance of contingency strategies for different supply conditions, and, if applicable, capacity conditions?

References

Bemelmans TMA. *Bedrijfskundig ontwerpen van bestuurlijke informatiesystemen*. Eindhoven: Technische Universiteit Eindhoven, 1988.

Bertrand JWM, Wortmann JC and Wijngaard J. *Productiebeheersing en Material Management*. Houten: Educatieve Partners Nederland BV, 1998.

Braithwaite A. (ed.) *Maximizing Performance: The Power of Supply Chain Collaboration*. Report. Brussels: The European Petrochemical Association / Cefic, 2005.

Chatfield C. *The Analysis of Time Series: An Introduction.* Florida: CRC Press, 6th edition, 2004.

Chen YF, Ryan JK, Simchi-Levi D. "The Impact of Exponential Smoothing Forecasts on the Bullwhip Effect". *Naval Research Logistics* 2000; 47; pp. 269-286.

Dennis D, Meredith J. "An Emperical Analysis of Process Industry Transformation Systems". *Management Science* 2000; 46(8); pp. 1085-1099.

Kok AG de. *Analysis of one product / one location inventory control model.* Eindhoven University of Technology: reader course Logistics-1, 2003.

Fleishmann B, Meyr H. "Planning Hierarchy, Modeling and Advanced Planning Systems". In: Kok AG de, Graves SC (ed.), *Supply Chain Management: design, coordination and operation* (Handbooks in Operations Research and Management Science series). Amsterdam: Elsevier, 2003.

Graves SC. "A Single-Item Inventory Model for a Nonstationary Demand Process". *Manufacturing & Service Operations Management* 1999; 1(1); pp. 50-61.

Johansen SG, Thorstenson A. "Optimal base-stock policy for the inventory system with periodic review, backorders and sequential lead times". *International Journal of Inventory Research* 2008; 1(1); pp. 44-52.

Kok AG de, Fransoo JC. "Planning Supply Chain Operations: Definition and Comparison of Planning Concepts". In: Kok AG de, Graves SC (ed.), *Supply Chain Management: design, coordination and operation* (Handbooks in Operations Research and Management Science series). Amsterdam: Elsevier, 2003.

Martin J. "Success and the Supply Chain: How Chemical Companies Can Master Complexity". *Chemical Market Reporter* 2004; 266(2), pp. 17-19.

McKinnon A. (ed.) *Supply Chain Excellence in the European Chemical Industry.* Brussels: The European Petrochemical Association / Cefic; 2004.

Montgomery DC. *Introduction to statistical quality control*. New York: John Wiley & Sons, 4th edition, 2001.

Mula J, Roler P, Garcia-Sabater JP, Lario FC. "Models for production planning under uncertainty: A review". *International Journal of Production Economics* 2006; 103; pp. 271-285.

Ould-Louly M, Dolgui A. “The MPS parameterization under lead time uncertainty”. *International Journal of Production Economics* 2004; 90; pp. 369-376.

Silver EA, Pyke DF, and Peterson, R. *Inventory Management and Production Planning and Scheduling*. New York: John Wiley & Sons, 3rd edition, 1998.

Tang O, Grubbström RW. “The detailed coordination problem in a two-level assembly system with stochastic lead time”. *International Journal of Production Economics* 2003; 81-82; pp. 415-429.

Tempelmeier H. “Inventory service-levels in the customer supply chain”. *OR Spektrum* 2000; 22; pp. 361-380.

Watts AC, Hahn CK, Sohn BK. “Monitoring the Performance of a Reorder Point System: A Control Chart Approach”. *International Journal of Operations Management & Production Management* 1994; 14(2); pp. 51-61.

Zipkin PH. *Foundations of Inventory Management.* Boston: McGraw-Hill, 2000.

List of abbreviations

cdf	cumulative distribution function
c.v.	coefficient of variation
CODP	Customer order decoupling point
DEG	Diethylene glycol (product)
ERP	Enterprise Resource Planning
ESPRC	Expected shortage per replenishment cycle
MEG	Monoethylene glycol (product)
MEOH	Methanol (product)
MT	metric ton
MTBE	Methyl tert-butyl ether (product)
OTC	Order To Cash
pdf	probability density function
SABIC KSA	SABIC organisation in the Kingdom of Saudi Arabia
SM	Styrene Monomer (product)
SPC	Statistical Process Control
S&RP	Supply and Replenishment Planning

A. Supply analysis

For each terminal, the additional lead time of replenishment orders for MEG and DEG has been analysed. Information on the timing and quantity of replenishment orders has been analysed for the period from October 2006 to August 2008. Replenishment orders for MEG and DEG shipped on the same vessel to the same terminal have been treated as one observation of the lead time. In this way, 22 to 24 observations per terminal have been collected for the lead time of replenishment orders for MEG and DEG. The histograms of the additional lead time observations are displayed in Figure A.1 and Figure A.2.

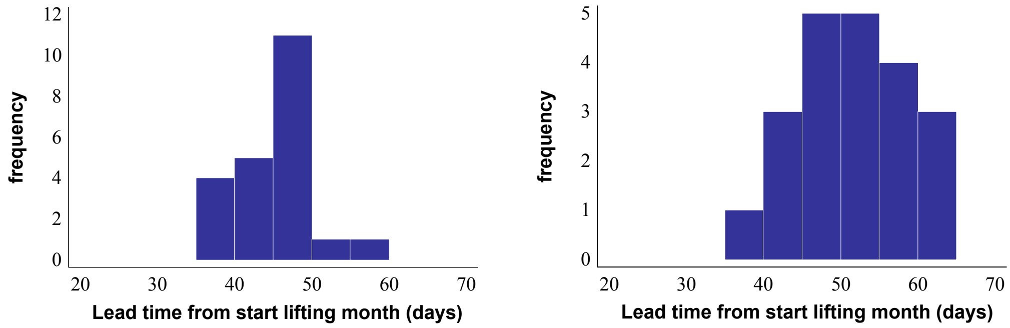

Figure A.1 *Histogram of additional lead times to Terminal A (left) and Terminal B (right)*

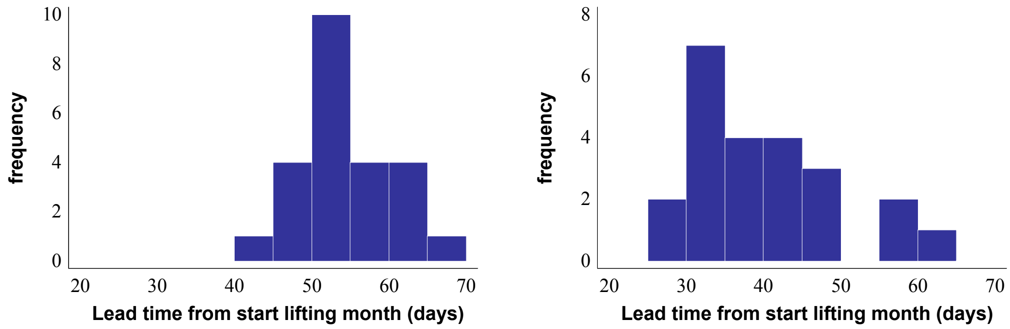

Figure A.2 *Histogram of additional lead times to Terminal C (left) and Terminal D (right)*

The lead time observations have been fitted to different statistical distributions (Normal, Gamma, Erlang, Exponential, and Poisson) in Statgraphics, a statistical software program. Distribution fitting shows that the differences between the observed distribution and expected distribution are smallest for the fitted Gamma distribution. The p-values of different significance tests show that the additional lead times can be adequately modelled by a Gamma distribution. Table A.1 shows the shape and scale parameters of the fitted Gamma distribution and the p-value of the chi-square significance test.

	shape	scale	p-value
Terminal A	77.74	1.698	0.192
Terminal B	52.45	0.984	0.693
Terminal C	84.29	1.541	0.391
Terminal D	18.92	0.468	0.419

Table A.1 *Fitted Gamma distribution of the additional lead time*

B. Demand analysis

B.1 Customer demand

The order deliveries from the terminals to customers are analysed to obtain insights in the customer demand characteristics and the transportation modes used. Table B.1 provides a summary of the deliveries to customers from January 2007 to September 2008. For the large customers, the delivery mode and the share of the customer demand in the total terminal demand are specified.

	MEG			**DEG**		
Terminal	**Customer**	**Transport mode**	**Demand share**	**Customer**	**Transport mode**	**Demand share**
A	A-1	Truck	89.6%	A-1	Truck	21.4%
	A-2	Truck	3.1%	A-2	Truck	14.7%
	A-3	Truck	1.3%	A-3	Truck	9.6%
	A-4	Truck	1.0%	A-4	Truck	7.0%
	A-5	Truck	0.9%	A-5	Truck	6.9%
	Other (19)		*4.0%*	*Other (18)*		*40.4%*
B	B-1	Truck	29.4%	B-1	Truck	33.8%
	B-2	Truck	17.2%	B-2	Truck	21.1%
	B-3	Truck	9.4%	B-3	Truck	13.0%
	B-4	Truck	8.9%	B-4	Truck	8.3%
	B-5	Truck	7.7%	B-5	Truck	4.3%
	Other (13)		*27.4%*	*Other (18)*		*19.6%*
C	C-1	Truck	87.3%	C-1	Truck	21.4%
	C-2	Truck	4.2%	C-2	Truck	14.8%
	C-3	Truck	1.5%	C-3	Truck	11.6%
	C-4	Vessel	1.4%	C-4	Truck	9.3%
	C-5	Truck	1.2%	C-5	Truck	8.9%
	Other (13)		*4.0%*	*Other (22)*		*34.0%*
D	D-1	Vessel	47.8%	D-1	Truck	32.6%
	D-2	Vessel	47.3%	D-2	Barge	26.2%
	D-3	Truck	1.4%	D-3	Truck	6.5%
	D-4	Rail	1.1%	D-4	Truck	6.0%
	D-5	Truck	1.1%	D-5	Truck	5.2%
	Other (5)		*1.8%*	*Other (23)*		*23.4%*

Table B.1 *Deliveries to customers (Jan 07 – Sep 08)*

B.2 Product demand

To analyse the demand behaviour, information on the daily demand is required. This information is not directly available for two reasons. First, only the actual sales are measured and not the lost sales. Second, the daily demand from January 2006 to September 2008 is registered in two different information systems, of which only one contains information on monthly sales. We therefore assume that lost sales do not occur. This certainly holds for fulfilment of the demand that originates from long-term sales contracts. Furthermore, we decided to derive the actual sales per day from the data on the physical inventory. The physical inventory per day is known for the whole period. A day-to-day decrease in the physical inventory results of the actual sales per day. A day-to-day increase represents the receipt of a replenishment order. Since replenishment orders only happen about once a month, the day-to-day decrease in the physical inventory gives a fairly good representation of the actual daily sales. So the actual daily demand is assumed to be equal to the actual daily sales as subtracted from the data on the physical inventory. Since period (daily) demand only happens on working days, non-working days are removed from the data. In the demand data of terminal D, a distinction is made between period demand and intermittent demand by assuming that large daily demand (> 400 MT) represents intermittent demand.

Trend and seasonal effects

We performed time series analysis on the daily demand data. The analysis is done with the software program Matlab. First, possible trend effects have been investigated. The analysis is limited to the demand from January 2006 to July 2007, for the reason that the demand for MEG from July 2007 to the beginning of 2008 does not reflect regular demand behaviour because of the limitation in production capacity. After removing trend effects, we determined the autocorrelation coefficients of the time series. None of the autocorrelation effects was found to be significant (based on visual inspection and setting a bound for significance at $1/\sqrt{(N)}$, where N is the number of observations). It is therefore concluded that the data does not contain seasonal effects (Chatfield, 2004). However, it has to be noted that it is difficult to prove seasonal effects when the data only covers 1.5 year of demand.

Daily demand distribution

The demand without trend effects has been fitted to several statistical distributions (Normal, Gamma, Erlang, and Exponential) with the software program Statgraphics. As the demand size is related to the capacity of the transportation mode used, many observed daily demand values approximate some multiple of the maximum truck capacity. The daily demand seems therefore in practice not continuous for every point. However, this discontinuous behaviour seems to be neglectable when considering demand for longer time periods, e.g. over the total replenishment lead time. Visual comparison of the observed values with the fitted distributions show that the distribution of daily demand is best modelled as Normal distributed. The figures B.1-B.4 provide the normal probability plots of the daily demand.

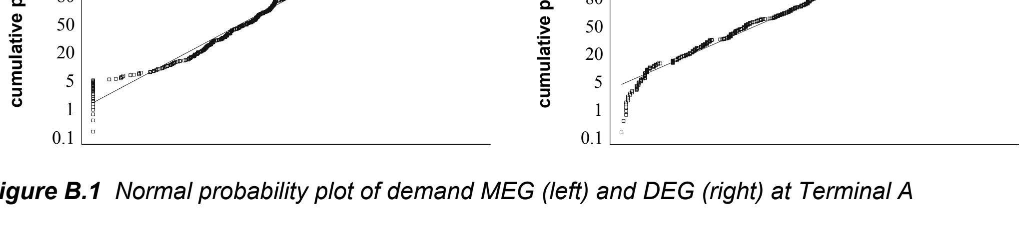

***Figure B.1** Normal probability plot of demand MEG (left) and DEG (right) at Terminal A*

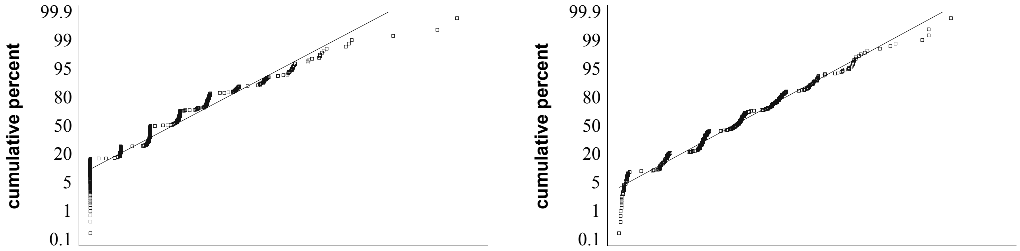

Figure B.2 *Normal probability plot of demand MEG (left) and DEG (right) at Terminal B*

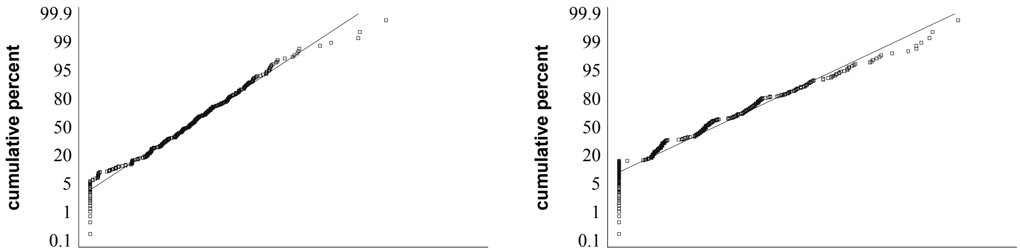

Figure B.3 *Normal probability plot of demand MEG (left) and DEG (right) at Terminal C*

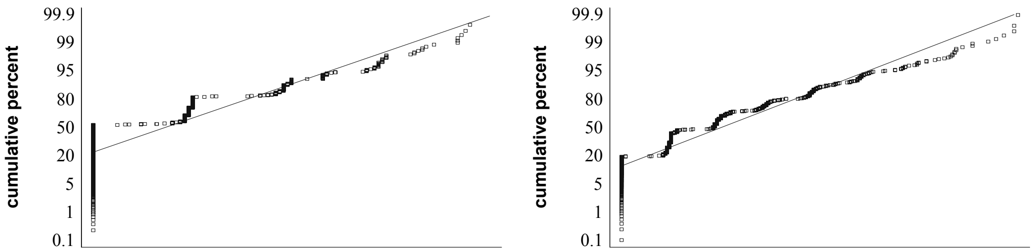

Figure B.4 *Normal probability plot of demand MEG (left) and DEG (right) at Terminal D*

Intermittent demand distribution

Distribution fitting shows that the distribution of intermittent demand for MEG at terminal D is accurately modelled by a Normal distribution. The inter-arrival time of the intermittent demand is Erlang distributed. Table B.2 shows the parameters of the fitted distributions and the p-value of the chi-square significance test. The Poisson distribution has also been fitted, but the hypothesis is rejected that the Poisson distribution can accurately model the distribution of the inter-arrival of the demand. The distribution of the period demand for DEG at terminal D could not be fitted to a statistical distribution. Since the demand process of DEG seems similar to the demand process of MEG at this terminal, it is assumed that the demand process can be modelled by the same demand distributions.

		Distribution	average	c.v.	p-value
MEG	size	Normal	2050	0.38	0.448
	interval	Erlang	17.7	0.75	0.314

Table B.2 *Fitted distribution of intermittent demand at Terminal D*

C. Inventory analysis

The average physical inventory in 2006, 2007 and the first half of 2008 are analysed, based on the average daily demand in the given year. Figures C.1 and C.2 depict the average inventory days at the terminals. The safety inventory is the average physical inventory just before replenishments. The figures show that large differences exist between the terminals in the amount of inventory on-hand to cover the daily demand. Further, the inventory days have been increasing during the last years at most of the terminals.

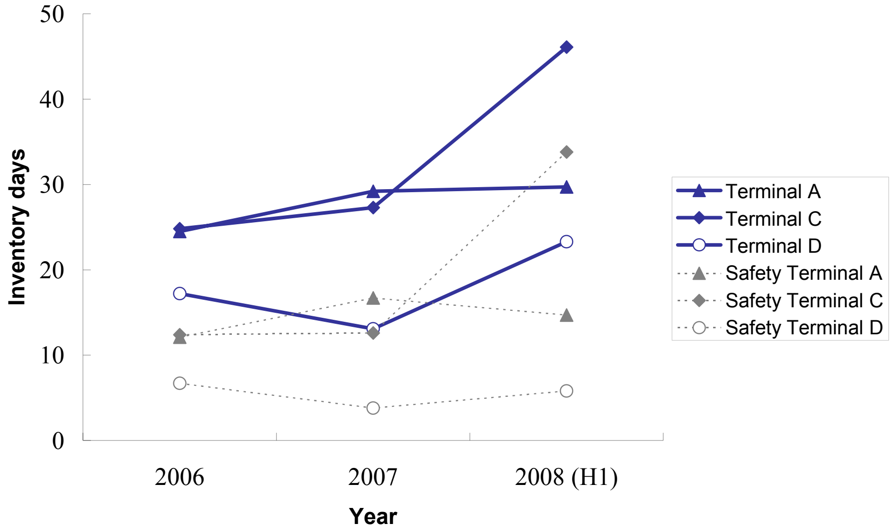

Fig C.1 *Inventory days of MEG*

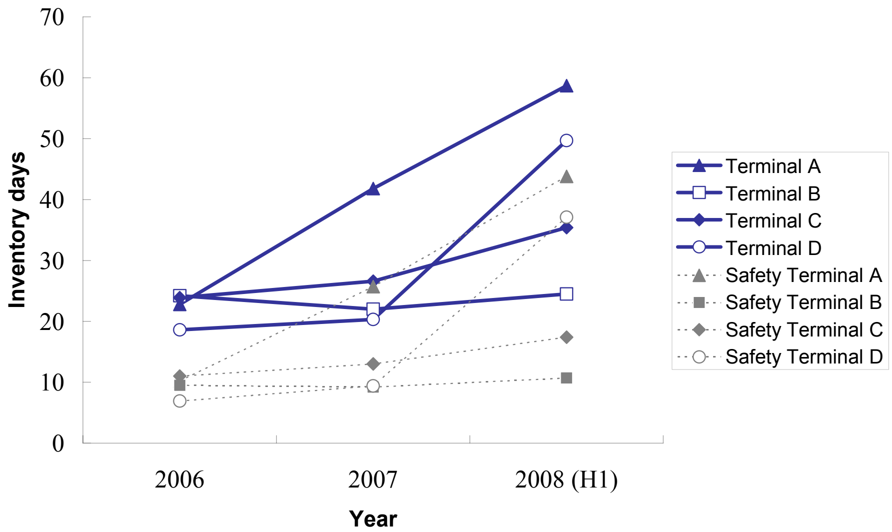

Fig C.2 *Inventory days of DEG*