MASTER

Design of the global supply chain network of polyamide 6 compound in a multi-commodity, two-level environment

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Design of the global supply chain network of Polyamide 6 Compound in a multi-commodity, two-level environment

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in partial fulfilment of the requirements for the degree of

Master of Science
in Operations Management and Logistics

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ABSTRACT

This Master's thesis describes the development of a two-level, multi-commodity supply chain network model. The analyses of the characteristics of the current supply chain network lead to clear model requirements. These model requirements, in combination with some scientific insights, are the basis of the development of the MILP model. The model aims to minimize total production, inventory and transportation costs in order to make optimal customer allocation and facility (i.e. production plants and warehouses) location decisions. The model is incorporated in a mathematical optimization tool (LogicNet) that enables the evaluation of different scenarios. Scenarios are focused on providing insight into the best supply chain network design for the both the current and future situation.
MANAGEMENT SUMMARY

Previous mentioned has led to the following research assignment:

“Develop a strategic global supply chain network model which is able to design the cost optimal supply chain network of PA6 C for both the current and future situation (i.e. in 2020). Apply the model such that the effect of market changes (e.g. cost changes) on the total performance (i.e. total costs, working capital, and customer service level) of the supply chain network can be measured”.

The Supply Chain Network model (SCN model) must be able to support strategic supply chain network design decisions. In order to design the SCN model such that it represents reality, a good understanding of the current situation is a prerequisite.

Next to this practical point of view, insights from a theoretical point of view are required as well. From a theoretical perspective it can be concluded that the SCN model must be a static/implicit dynamic, two-level, multi-commodity capacitated location-allocation model, which is solved in a discrete space. Moreover, the main objective of the SCN model is total cost minimization (i.e. shipment, inventory, and operating costs) by having a predefined customer service level as constraint. Decisions which are made by the model are location decisions of both warehouses and plants and allocation decisions of customers to facilities.

As the SCN model is a complex model, which cannot be solved exact, a mathematical optimization tool called LogicNet is used. This tool is fully specialized in solving supply chain network design problems and supports above mentioned theoretical foundations. As LogicNet is broadly used in practice, the use of this optimization tool has many advantages in terms of time, capability, flexibility, reliability and validity. Different strategic scenarios are evaluated by the SCN model in LogicNet regarding both the current and future situation in 2020. Scenarios differ from each other in terms of the year under consideration, capacity and transport time restrictions, the possibility of new production lines and intermediate warehouses, and the sourcing strategy of PA6 P MV. The main results of the scenario analyses are:

- An optimal ..
- By considering the capacity and transport time restrictions
- In general, it is optimal in the current situation to deliver
- In 2020,
- Towards 2020,
- The SCN model in LogicNet is a broadly applicable, appropriate tool for supporting strategic supply chain network design decisions. It can be used for other product lines or BUs as well. Moreover, as this project ignores local grades, which are about 13% of total demand and thus a significant amount, the SCN model can be also applied to these local grades.

Based on the results of this research project, the following is recommended:
This Master's thesis is the result of a six-month graduation project executed within the Business Unit Engineering Plastics of DSM. This challenging project marks the end of the Master Operations Management & Logistics at the Eindhoven University of Technology. During the past months I have had the opportunity to experience the ins and outs of working at DSM, within both the department Corporate Operations & Responsible Care and DSM Engineering Plastics. I have really enjoyed this time, which I would characterize as pleasurable, challenging, and a very learning experience. I would like to take this opportunity to express my gratitude towards the people who have supported me, both throughout this project and during my entire study.

I thank my company supervisors, Ralph van Wissen and Laurens Zaman, for providing me the chance to execute this challenging project within this interesting organization. The critical look of both of you, enthusiastic support, in combination with our interesting discussions, have led to this progressive project. I truly appreciate the time and effort, you both put into my project.

I would like to thank Tom van Woensel, my university supervisor, for his flexibility and time he made available for coaching me. The frequent, short meetings we had during the past 1.5 year of my Master’s have helped me to stay focused and to follow the right direction. I would like to thank Wim Nuijten for his feedback on my report.

I thank Rainer Meburger, Jacques Verdier, Peter Corbijn and Rogier den Dekker from DSM, for their time and useful feedback. Besides, everybody who helped me, by providing me the assistance and information on repeated occasions, thank you very much.

To conclude this preface I would like to thank my family and friends for showing their interests, and support. Special thanks to my parents for their compassion and being there for me all day. Last but certainly not least special thanks to Marc, who has been a great support at all times.

Denise Diederen
August 2012
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1. INTRODUCTION

The introduction starts with a brief description of DSM Royal N.V. It also includes a more detailed description of the Business Group (BG) and product line of interest. In section 2 and 3 respectively, the methodology and the report structure are presented.

1.1. Company description

In the following subsections, a short description is given about DSM in general and the specific BG and product line under investigation.

1.1.1. Royal DSM N.V.

Royal DSM N.V. is as a global science-based company, active in health, nutrition and materials. DSM began as a modest coal mining company in 1902 and transformed over the years to an international company that connects its unique competences in Life Sciences and Material Sciences. Today DSM employs 22,000 employees and delivers annual net sales of about € 9 billion. The company is listed on NYSE Euronext.

DSM has grouped its activities into eight BGs, which can be clustered into four different parts: Nutrition, Pharma, Performance Materials and Polymer Intermediates. In figure 1.1, the net sales of each cluster as a percentage of the total annual net sales of DSM can be found. Furthermore, in figure 1.2, the same is shown for all BGs separately.

![Figure 1.1: 2011 net sales per cluster (% of total)](image1)

![Figure 1.2: 2011 net sales per BG (% of total)](image2)

Nutrition, the largest cluster, consists of the BGs DSM Food Specialities (DFS) and DSM Nutritional Products (DNP). DSM is the world's largest vitamin producer and holds leading positions in the ingredient markets for human and animal nutrition and health, as well as personal care.

The Pharma cluster comprises the BGs DSM Pharmaceutical Products (DPP) and DSM SinoChem Pharmaceuticals (DSP). They concentrate on the generic antibacterial market and the Pharmaceutical outsourcing markets respectively, which makes them one of the world's leading independent suppliers to the pharmaceutical industry.

The cluster Performance Materials contains the BGs DSM Dyneema (DD), DSM Engineering Plastics (DEP) and DSM Resins & Functional Materials (DRF). These BGs are specialized in manufacturing technologically sophisticated, high-quality products that are tailored to meet customers' performance criteria. DSM's performance materials are used in a wide variety of end markets.

Polymer Intermediates consists of only one BG, DSM Fibre Intermediates (DFI). This cluster produces caprolactam (CAP) and acrylonitrile, which are raw materials for synthetic fibers and plastics. More specifically, CAP is a key feedstock for DEP's polyamide production. DSM is the largest merchant supplier of
CAP and the third largest merchant supplier of acrylonitrile. Moreover, this BG also produces ammonium sulphate, sodium cyanide, cyclohexanone and diaminobutane.

In addition, also the clusters DSM Advanced Surfaces (DAS), DSM Bio-based Products & Services (DBPS) and DSM Biomedical (DB) consist in the fields of innovation and sustainability, as two of the main growth drivers of DSM.

As mentioned before, the project is executed within the BG DEP of the Performance Materials cluster. The next subsection explains more about DEP.

1.1.2. DSM Engineering Plastics

DEP is established over the whole world with production locations in North America (Augusta and Evansville), Europe (Emmen, Genk and Russia), Asia Pacific (Jiangyin and Pune), and Russia (Togliatti). However, DEP has a very decentralized organization existing of three regions: DEP US, DEP EU, and DEP AP (Asia Pacific).

In figure 1.3, the position of DEP in the total value chain is shown. Value is added to their products by polymerization and compounding. Their products are sold as a ‘final product’ both after polymerization and after compounding. In the next section, this polymerization and compounding process is clarified in more detail.

Figure 1.3: Position of DEP in value chain

Key products of DEP are Akulon and Novamid polyamide 6, 66, 6/66, Stanyl polyamide 46, Stanyl ForTii, EcoPaXX, Arnite polyester (PBT, PET), and Arnitel copolyester elastomer/Thermoplastic Copolyester (TPC). This key product of DEP is focused on in this study and is introduced in more detail in the next section.

1.1.3. Akulon Polyamide 6

Akulon is a high performance, all-purpose engineering material, for a wide range of applications. Akulon PA6 is sold by DSM as a final product both after polymerization, named PA6 Poly (PA6 P), and after compounding, named PA6 Compound (PA6 C). The latter product requires an extra production step. This extra production step (compounding), makes the product applicable for other purposes with other requirements than the product PA6 P. Compounding means that other raw materials are added to PA6 P, which makes it a higher quality material, called PA6 C. Two third of all raw materials (RMs) needed for compounding is PA6 P itself, which is the base polymer of PA6 C. However, not all types of PA6 P can be used for compounding. PA6 P differs with regard to its viscosity; Mid Viscose (MV) and High Viscose (HV).
As explained in the previous subsection, this project focuses on Akulon PA6, specifically, on PA6 C. To summarize this section, figure 1.4 visualizes the part of the value chain which is of interest regarding PA6 C.

![Figure 1.4: Visualization of value chain PA6](image)

### 1.2. Methodology

The project is executed according to the solution oriented approach of Kempen and Keizer (2000), which concerns a ten steps methodology that is specifically developed for supporting business problem-solving projects (Van Aken et al., 2007). The solution oriented approach follows the five phases (problem definition, analysis, design, implementation and evaluation) of the regulative cycle (Van Strien, 1997). Interrelated with the regulative cycle, in figure 1.5, the research model according to the design oriented approach of Verschuren and Doorewaard (1995) is depicted. The research model depicts the confrontation of theoretical knowledge on the one hand, and practice on the other. Moreover, this research model provides the structure of the report.
The main objective of the first phase of the regulative cycle, the orientation phase, is to identify and specify the key targets of the project by formulating a clear research assignment and defining the exact scope of the project. To achieve this, it is important to become familiar with the organization, the current situation of interest and corresponding problem area. In addition to the orientation phase, literature is used to obtain more insight into the research area from a theoretical point of view. As Verschuren and Doorewaard (1995) suggested, these two perspectives (theory and practice) must be compared to each other to come to a further diagnosis of the business problem and exploration of redesign directions.

After defining a clear problem definition and research assignment, a detailed analysis is done to get the required insight of the current situation. Subsequently, based on this detailed analysis, the model requirements are further analyzed, which lead to decisions regarding the scope of the next phase, the design phase. In the design phase the mathematical model is developed.

The implementation phase intertwines with the design phase. The mathematical model is implemented with an optimization tool called LogicNet. Different redesign directions, evaluated in LogicNet, are analyzed and discussed comprehensively. Subsequently, an implementation plan is developed which focuses on the follow-up of this project. To conclude, in the final evaluation phase the relevant conclusions are drawn and recommendations for DSM and further research are provided.

1.3. Report structure

The research model figured and discussed in the previous section visualizes the report structure already. A description of the report structure is as follows: After the current introductory chapter, in the next chapter the research approach is explained, including the research assignment. Chapter 3 presents the analysis phase of the current supply chain network of PA6 C. Based on this, in chapter 4, the model requirements are analyzed, which is an important starting point of the design phase. Chapter 5 reviews the existing literature on the research area and defines the theoretical framework of the model which is developed in this chapter as well. In chapter 6, the scenario analyses and corresponding results are discussed and an implementation plan is given. Chapter 7 concludes this project by providing the main conclusions and recommendations. Finally,
the reading guides (i.e. list of figures, tables, and abbreviations) and appendices are added at the end of the report.
2. RESEARCH APPROACH

This chapter outlines the research approach. The first section starts with describing the current situation and its corresponding problem area regarding Akulon PA6 C. In other words, it discusses the motives that led to the need of further investigation of improvement possibilities. This problem description is clustered into a cause-and-effect diagram, which represents the focus areas of this project. Based on this, in the second section the research assignment is clearly described, which is followed by the delineation of the exact scope of the project.

2.1. Current situation

......................... The overall problem is linked to questions regarding capacity expansion and the corresponding high level strategy to meet future demand. The main problem and causes behind it are summed up in below figured cause-and-effect diagram (Ishikawa, 1990). This figure shows exactly what the motives of the project are.

Figure 2.1: Cause-and-effect diagram (Ishikawa, 1990)

.........................

.........................

I Planning environment

.........................

II Supply chain network design

.........................

2.2. Research assignment

Based on the description of the current situation and its corresponding problem definition in the previous subsection, the aim of this project becomes clear. To solve the main problem as is described in the previous
subsection, a global supply chain network model (SCN model) is required, which is able to create insights and supports strategic supply chain network design decisions. Thereupon, a model which is able to evaluate different strategic scenarios makes it possible for DEP to evaluate the effect of changes in the supply chain network and/or market. Such a model creates understanding about the related (cost) factors which are most important in designing a cost efficient supply chain network. Finally, a model that is generally applicable would be helpful in the design of the global supply chain network of other product lines within DEP. These product lines are all interrelated with each other, since they can make use of the same production lines as PA6 C.

Based on above mentioned, the overall research assignment is formulated as follows:

<table>
<thead>
<tr>
<th>Develop a strategic global supply chain network model which is able to design the cost optimal supply chain network of PA6 C for both the current and future situation (i.e. in 2020). Apply the model such that the effect of market changes (e.g. cost changes) on the total performance (i.e. total costs, working capital, and customer service level) of the supply chain network can be measured.</th>
</tr>
</thead>
</table>
2.3. **Project scope**

After stating the overall research assignment, this section clarifies the exact scope of the project. The project scope is the basis of the analysis and design phase which is focused on in the next chapters.

2.3.1. **Supply chain trade off**

The logistic system of PA6 C is characterized by a level of investment (e.g. operating working capital), costs and a level of service. As Shen and Daskin (2005) mentioned, firms are often faced with competing demand of improved customer service and reduced costs (including working capital related costs). Finding the right balance between these components is very important. According to Ghiani et al. (2004) a general aim in business logistics is the minimization of the annual total logistics costs, subject to side constraints related to facility capacity and required customer service level. The SCN model focuses on total cost minimization, including holding costs (i.e. working capital of products in stock and in transit), such that the required service level is met.

2.3.2. **Research area**

The main focus of this project is the design of the supply chain network of PA6 C such that the network is cost optimal for a specific situation. According to Ballou and Masters (1993), four strategic planning areas are important when designing a supply chain network system: customer service levels, location decisions of facilities, customer allocation decisions, and vehicle routing decisions. This project is focused on only three of these strategic planning areas; customer service levels, location and capacity decisions of facilities (i.e. production plants and warehouses), and on customer allocation decisions. Vehicle routing decisions are out of scope since transport is outsourced within DEP.

2.3.3. **Planning level**

Decisions regarding the supply chain network design are strategic and are important for almost every company (Javid and Azad, 2010). The main reason why supply chain network design decisions are strategic is because of the high investment costs involved (Klose and Drexel, 2003; Ghiani et al., 2004).

Questions which are focused on in this project are; where to expand capacity (i.e. production possibilities) in the future, how many internal and intermediate warehouses must be used, and which type of products (i.e. grades) must be made in which production location for which customers in which quantity? Decisions on these types of questions are strategic since they determine the location, capacity and capability of facilities for the coming years, and involve high fixed (investment) costs. Therefore, the model must consider a high level of aggregation which is representative to support strategic decisions.

However, purely quantitative SCN models are not able to make strategic decisions in isolation. They can only support strategic decisions by contributing from a quantitative supply chain management perspective. This means that the model results in a solution which minimizes operational variable costs. More input (e.g. qualitative input) is needed before strategic location, capacity and allocation decisions can be made.

2.3.4. **Decision support method**

As the research assignment indicates, the decision support method is a SCN model which is able to optimize. A mathematical optimization problem is set up to support in answering the overall research assignment. Since the project is focused on strategic questions, a broader view is necessary than pure benchmarking or simulation of alternatives of the current system. Mathematical optimization is able to create a broader perspective of possible results. Moreover, a mathematical optimization problem is also able to answer what-if questions regarding alternatives to the current system (Ghiani et al., 2004).
2.4. Summary of research approach

This section contains the main conclusions regarding the research approach of this project. The goal of this chapter was to define the overall research assignment and scope of the project.

To support DEP in this, this project delivers a strategic global SCN model. The model must be able to make network design decisions by optimizing in terms of operational variable costs (including working capital) such that a required service level is met. The decision support method which is set up is therefore a mathematical optimization problem. However, in order to be able to make a final strategic decision, additional qualitative inputs and evaluations are required in parallel to these quantitative optimization results.
3. SUPPLY CHAIN NETWORK ANALYSIS

The overall objective of this chapter is to give an explanation of the current supply chain network of Akulon PA6 C. Decisions with regard to the supply chain network involving facility location and customer allocation decisions, are made on a strategic basis (Gebennin et al., 2009; Ghiani et al., 2004). Therefore, the aim of this analysis phase is gaining insight on the required aggregation level of the characteristics of the current supply chain network of PA6 C. A good understanding of the current situation is a prerequisite in order to design the SCN model which is able to answer the overall research assignment.

A supply chain is defined as an integrated process wherein a number of various business entities (suppliers, manufacturers, distributors, and retailers), work together in an effort to acquire raw materials, convert these raw materials into specified final products, and deliver these final products to customers. At its highest level, a supply chain is comprised of two basic integrated processes: (1) the Production Planning and Inventory Control Process, and (2) the Distribution and Logistics Process (Beamon, 1998). Figure 3.1 shows the overall supply chain of PA6 C, which shows the two integrated processes as well. Moreover, the focus of this analysis phase regarding the total supply chain is visualized by the blue dotted rectangle, which belongs to the second integrated process; the supply chain network.

Figure 3.1: Supply chain of PA6 C

Figure 3.1 also visualizes the structure of this chapter. The first section (section 3.1) explains the current supply chain network with regard to its demand, service level, supply, sourcing, and inventory characteristics of PA6 C. Section 3.2 focuses on the planning and control structure of corresponding supply chain network decisions.

3.1. Current supply chain network of PA6 C

This section explains the characteristics of the global supply chain network of PA6 C. Overall, the PA6 C supply chain network is complex, ........A good understanding of this complex supply chain network and its restrictions is a prerequisite for the development of a realistic model in the design phase. In appendix B.1 a high level (i.e. only flows which are > 0.002 kT) overview of the current global supply chain network of PA6 C is presented.
3.1.1. Demand
The design of the supply chain network is highly dependent on the industry and corresponding demand characteristics (Ghiani et al., 2004). An important starting point is explaining the demand characteristics of PA6 C in more detail.

Stock Keeping Units
PA6 C is a final product of DEP, which is sold directly to external customers. On the lowest level, PA6 C can be differentiated on Stock Keeping Unit (SKU) level. A SKU is equivalent to an end product. It is an item of stock that is completely specified to the characteristics it has (Silver et al., 1998). For PA6 C, the SKU level is determined by three specific factors, which are illustrated in figure 3.2.

![Figure 3.2: SKU characteristics](image)

Current and future demand
The demand side of the supply chain network, which consists of the goods flows between the production locations, warehouses and its customers, is the main focus of this project. In figure 3.3, the yearly sales\(^1\) in 2011 and corresponding customer locations are presented.

![Figure 3.3: Customer locations with corresponding demand (in pallets) in 2011](image)

\(^1\) As it is not known which part of the total demand of PA6 C was not met by DEP in 2011, from this point on sales is assumed to be equal to customer demand.
Figure 3.4: Demand per country and region as a percentage of total demand in 2011

In addition to the current yearly demand of PA6 C, ......

.........

Figure 3.5: Expected growth in demand per region towards 2020
3.1.2. Supply
Next to the demand side as explained in the previous subsection, an important part of interest of the supply chain network is the supply side. The supply side, outlined in this subsection, means the asset footprint with its corresponding production characteristics and strategy.

Asset footprint

Figure 3.6: Total and PA6 C capacity of current production lines

Production strategy
As explained before, the total PA6 C (global grades) production in 2011 was ................. The total production volumes per plant, used for sales, are shown in table 3.1.

Table 3.1: Total PA6 C (global grades) production volumes for sales in 2011

................. According to Cooper et al. (1991), this quality of service or the extent to which customer satisfaction is reached by for example having short lead times, is called the effectiveness of the distribution system. Next to the effectiveness, in the logistics management literature, emphasis is also placed on the possibility to achieve efficiency, simultaneously with effectiveness, which refers to minimizing logistic costs (Cooper et al., 1991). Both effectiveness and efficiency are important in making decisions about the distribution system, and are incorporated in this project. In the current situation effectiveness is thus created by producing near to the customers, called a decentralized production system. Another way to achieve effectiveness is by having a more decentralized warehousing system instead of a decentralized production strategy. Also decentralized warehouses lead to reduced lead times for at least MTF products (Ghiani et al., 2004).

From previous mentioned table 3.1 and figure 3.6, it is concluded that the total production capacity of PA6 C in the current ...........

........
Figure 3.7: Capacity expansion strategy of DE

Currently,......Overall, these characteristics of DEP's manufacturing and corresponding capacity expansion strategy are important to consider in the design of the supply chain network of PA6 C.

3.1.3. Sourcing

Many RMs are needed for PA6 C production. ..................For a total overview of the sourcing strategy of the main RM PA6 P MV is referred to appendix B.2.

Next to PA6 P MV, many other RMs exist.........................

3.1.4. Inventory

................

<table>
<thead>
<tr>
<th>Facility</th>
<th>Internal/external</th>
<th>Outsourced?</th>
<th>Average warehouse inventory (kT)</th>
<th>Inventory turnover ratio</th>
<th>% MTF vs. MTO</th>
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Table 3.2: Characteristics of warehouses used in 2011 for PA6 C

......

Moreover, table 3.2 shows the average inventory level and inventory turnover ratio of each warehouse. According to Simchi-Levi et al. (2003), the inventory turnover ratio is the total annual sales divided to the average inventory level. This ratio shows the number of times inventory is sold or used in a year. ............

....
3.1.5. Service level
According to Ballou and Masters (1993), four strategic planning areas are important when designing a distribution network system: customer service levels, placement of facilities and demand assignments, inventory decisions, and finally vehicle routing decisions. All these areas are inter-related and the customer service level is determined by the other three areas (Ballou and Masters, 1993). This means that the customer service level is determined by supply chain network decisions. Therefore, it is important to know the requirements of PA6 C regarding its customer service level before the supply chain network of PA6 C is redesigned.

This response time or lead time towards the customer is dependent on the design of the supply chain network. DEP strives to have a total lead time. The total transport time should be preferably. In case of is required, which mainly consists of transport time, since MTF products are delivered from stock. This means that in case of MTF, also a maximum transport time of about.

Most supply chain network studies, the focus is on the cost-service relationship (Ghiani et al., 2004). In figure 3.8, the cost versus level of service curve is outlined. As can be seen, the efficient or Pareto optimal solutions are on the black line of the figure. This means that these solutions are not dominated by other solutions.

Moreover, according to Ghiani et al. (2004), the level of logistics service greatly influences sales volume. Therefore, also the sales versus level of service kind of figures (see figure 3.9) can be used to determine the level of service that maximises the profit contribution to the firm.

However, in practice a slightly different approach is often used. First a customer service level is set (e.g. total). Subsequently, the supply chain network is designed in order to meet that service level at minimum cost.

Therefore, the supply chain network must be designed such that the required service level is met at minimum costs.

3.2. Current planning and control
In this section the planning and control structure of the supply chain network of PA6 C is explained. A conceptual overview of the total planning and control structure of DEP is presented in appendix C.1. The part of interest of this planning and control system is shown in figure 3.10.
Above figured structure shows that specific part of the total planning and control structure which the research topic of this project belongs to. Supply chain network design decisions belong to the highest planning and control level (i.e. strategic level). This means that these decisions are made for a long time period, normally 2-10 years and are made and agreed by top management. On this level, the strategic plan is made, which includes decisions like; long term capacity decisions (i.e. capacity (des)investment decisions, and production strategy decisions (i.e. centralized, or decentralized production strategy).

3.3. Summary of current supply chain network analysis

The total sales of PA6 C (i.e. global grades) in 2011 was equal and the production capacity is equal to . In 2011, the largest markets in .... Towards 2020, a questions like where to expand capacity to meet the future demand of these countries in a cost efficient way are of major interest in this project.
Finally, regarding the planning and control structure of DEP, supply chain network decisions are made by higher management for a time period of 2-10 years. This strategic plan directly influences the aggregate production plan of the production plants which is reviewed in the local S&OP meetings monthly. ....... This means that the tactical planning and control structure is regionally organized.
4. MODEL REQUIREMENTS

Based on the project scope description and the analysis of the current supply chain network in the previous chapters, in this chapter the requirements of the SCN model are stated. More specifically, this chapter explains what is taken into account in the development of the SCN model and in which way. The first section is focused on model requirements regarding the supply chain network characteristics of PA6 C. In the second section the requirements with regard to the cost drivers of the SCN model are outlined. How these model requirements are translated into the model formulation is clarified in chapter 5.

4.1. Supply chain network characteristics

In the previous chapter, the supply chain network characteristics of PA6 C are outlined. This section focuses on these characteristics as well, by explaining shortly what is taken into account by the SCN model.

4.1.1. Data aggregation

Since the design of a supply chain network is a strategic decision, this project does not require the same level of detail as operational research questions. In sum, a time period of one year is chosen in which input and output data is expressed, demand input and allocation output of the model are on grade level, customers are aggregated on city level, and finally transportation costs are aggregated on country level. For a more detailed explanation of these decisions is referred to appendix D.1.

4.1.2. Time horizon

Since high investment costs are involved, the solution in terms of the supply chain network design should be sustainable for the coming years. Therefore, the output of the model should deliver insights which support strategic network design decisions towards 2020. In order to create a solution for the coming years, the model should be able to create insights in the effect of market changes on the outcome.

4.1.3. Yearly demand and customer locations

Demand of PA6 C (global grades) is expressed on grade level (in pallets) for all customer cities worldwide. The model considers a static, deterministic yearly demand per customer city on grade level as main input of the model. For the current situation, demand in 2011 is taken as starting point (presented in figure 3.4). Regarding 2020, an expected future demand is considered, based on the demand growth analysis, presented in figure 3.5.

4.1.4. Asset footprint

...the SCN model incorporates these production lines separately. With regard to the future network (towards 2020) the model considers multiple new optional production lines and/or warehouses. The model should be able to vary the maximum number of open production lines and/or warehouses to create insight in both centralized and decentralized production strategies.
4.1.5. **Average inventory**
Based on the inventory analysis in chapter 3, it is concluded that the average inventory turn differ from Europe, USA and AP. The model takes a fixed average inventory turnover ratio for each warehouse into account. Small differences in the average inventory turn between fast and slow mover grades are ignored, because of the strategic nature of the model. Furthermore, as inventory decisions are tactical decisions which are out of scope, it is assumed that the current inventory policy and thus average inventory levels remain in the future. For future warehouses on new locations, an average inventory of ....days is assumed (i.e. inventory turn of 12), since this is the weighted average inventory turn of all existing warehouses and grades in 2011. See appendix D.2 for a more detailed clarification of this calculation.

4.1.6. **Production line capability**
Since ........ As decisions regarding the allocation of grades to production lines are made on a lower level (i.e. tactical level), these are out of scope. Therefore, only the allocation of grades and customers to production plants in general is optimized by the SCN model.

4.1.7. **Production line capacity**
An important restriction of the model is the capacity restriction of the production lines. The capacity of the production lines are assumed to be fixed, based on 2011 figures, as this is based on tactical decisions (i.e. number of SKUs per line) which are out of scope. The SCN model only takes these production lines into consideration which structurally produce PA6 C (see figure 3.6). In case of a new production line, ............

4.1.8. **Transport times**
The design of the supply chain network influences the transport time to customers. Transport times are taken into account because of two reasons: (1) the customer service level is influenced by the transport time as part of the total lead time (2) the transport time influences the total holding costs of a product in transit. In appendix D.3 an overview of the transport times (days) of all possible shipment lanes from door to door in the current and future situation are shown. These transport times are the realized transport times in 2011 and are based on real data from Cash Board (data base linked to SAP). The SCN model should have a transport time restriction which makes sure that the total transport time is limited to a maximum number of days for at least a significant proportion of the customers.

4.1.9. **Market dynamics**
Since the SCN model is applied to answer supply chain network design questions towards 2020, it is important to recognize that parameters can change over time. Therefore, yearly inflation rates are considered to deal with expected market dynamics of the static input data of the model (World Fact Book, 2012). Thereupon, sensitivity analyses are very important to evaluate the outcome of the SCN model for its optimality in 2020.

4.1.10. **Exchange rates**
All cost data is expressed in Euros by assuming fixed exchange rates\(^2\). The model does not incorporate the effect of exchange rate changes on the outcome of the model. The reasons for this is that a lot of data is based on world indexes and therefore independent on exchange rates. Through sensitivity analyses, the effect on the outcome of this assumption is evaluated.

\(^2\) The following exchange rates are used: 1 Dollar = 0.7538 Euro, 1 CNY = 0.1211 Euro, 1 INR = 0.0147 Euro, 1 RUB = 0.0258 Euro.
4.2. Cost drivers of the supply chain network

Many different models on the research topic of this project are described in the literature. However, these models cover formulations which range in complexity (i.e. level of input parameters and type of model). It is concluded that transportation costs, inventory costs and operating costs are the most important cost drivers in all SCN models. No investment costs are included, since these are fixed costs on a specific moment in time and are not influenced by the level of production (Shen and Qi (2007), Javid and Azad (2010)). Based on a study of KPMG (2012) it is concluded that transportation costs, inventory costs (warehousing lease costs and holding costs), and production costs (especially labor and energy) are major location sensitive cost factors, which account for 80% of total location costs. This section clarifies in the following subsections how the SCN model takes these transportation, inventory and production costs of PA6 C into account.

4.2.1. Transportation

4.2.2. Inventory

Next to transportation costs, also inventory costs are location sensitive, which means that they differ from different internal and external warehouses worldwide. Inventory costs consist of warehousing costs and holding costs of products in stock and in transit. The model requirements regarding these costs are explained:

- **Warehousing costs**: In appendix D.6 and D.7, the warehousing costs are presented for existing and future warehouses in the current situation (2011) respectively.

- **Holding costs**: Next to the warehousing costs, also holding costs are incorporated as input of the SCN model. Supply chain network design decisions influence the transport times and total inventory level, and therefore the holding costs of products in transit and in stock. These holding costs impact the OWC, which is an important performance indicator. The holding costs of products in transit and in stock are based on a.............The stock values of each global grade and corresponding holding costs in transit and in stock are presented in appendix D.8.

4.2.3. Production costs

PA6 C has .... This means that these costs are highly location sensitive and therefore important to incorporate. With regard to production, the model requirements regarding extrusion costs and raw material costs are explained below:

- **Extrusion costs**: In the SCN model, only direct extrusion costs are considered, since only these costs are influenced by the amount of PA6 C produced on a specific line. The direct extrusion costs per line consist of direct labor, energy, maintenance, scrap and packaging costs. .... As the direct costs per line in Euro/kg are dependent on the capacity of the production line, which is assumed to be a fixed given, also fixed direct extrusion costs in Euro/kg are assumed. The total direct extrusion costs in 2011 are presented in appendix D.10, in addition to an overview of the characteristics of the production lines in appendix D.9. Appendix D.11 shows the assumptions which are made regarding the extrusion costs of new production lines in different regions of the world.

- **Raw material costs**: As explained in section 3.1.3, ......... The RM costs, as used by the model for the current and future production plants, are shown in appendix D.13.
4.3. **Summary of model requirements**

A conceptual model is based on a problem entity, i.e. the system to be modelled. A model is only valid when it represents reality. Therefore, a clear understanding of the problem entity is a must in the development of a conceptual model (Sargent, 2003). Based on the characteristics of the supply chain network of PA6 C, described in chapter 3, this chapter describes how these supply chain network characteristics are taken into account in the development of the SCN model. In addition, also an explanation is given of the cost drivers which are incorporated by the SCN model, including an explanation of the assumptions and decisions regarding these inputs.
5. SUPPLY CHAIN NETWORK MODEL: MATHEMATICAL MODEL

In the previous chapter, the model requirements are described. In this chapter the model requirements are translated into a mathematical representation of the SCN model. In order to provide the required insights from a theoretical point of view, in the first section an overview of relevant literature is given, followed by the theoretical framework of the SCN model in section 2. In figure 5.1, part of the research model is presented, which shows the link between the theoretical and the practical side of the project, and also the focus of this chapter.

![Figure 5.1: Link between theoretical and practical side of business problem solving project](image)

In section 3 and 4, the mathematical model is formulated and the model inputs and outputs are explained respectively. Finally, the last section explains how the SCN model is solved.

5.1. Literature

The challenge of deciding the best locations to open production plants and warehouses, and allocating customers to these open facilities, are the main focus of facility location models (called SCN models in this project) for distribution planning. This topic has inspired a large body of literature that spans well over two decades. An extensive review of all corresponding facility location models can be found in the preliminary study of this project (Diederen, 2011). The relevant conclusions are quoted below:

- Most SCN models are generally constructed as Mixed-Integer Programs (MIP) (Ghiani et al., 2004; Nagy and Salhi, 2007; Klose and Drezel, 2003).
- The problem regarding the design of the supply chain network are difficult to solve exact. Therefore, a lot of different heuristics are studied which are able to generate good results; Greedy heuristic/Add heuristic, the Drop heuristic, the Improvement/Search heuristics (e.g. exchange heuristic), the Lagrangian (relaxation) heuristic, and the Benders decomposition procedure (Torres-Soto and Ster, 2010; Ghiani et al., 2004; Current, Daskin and Schilling, 2001; Pirkul and Jayaraman, 1998; Brandeau and Chiu, 1989).
- By designing a good distribution network, one is able to achieve a variety of supply chain objectives, ranging from low costs to high responsiveness (Ballou and Masters, 1993; Javid and Azad, 2010). Also multi-objective models exist, which focus on both customer satisfaction and logistic cost minimization, by considering two objective functions (ReVelle and Laporte, 1996).
- An optimal distribution network is a key driver of the overall productivity and profitability of a supply chain (Javid and Azad, 2010). Good location decisions of facilities can result in significant productivity improvements, an improved distribution network, and new business and markets, resulting from the location decision. However, suboptimal location decisions can be the cause of productivity problems, resulting from transportation system inefficiencies, inadequate qualified labor, increased capital expenditures, inadequate availability of RM sources, and/or large distances
to end-product markets. The factors that influence the location decision usually vary among organizations and industries (Randhawa and West, 1995).

- Full understanding of the simultaneous relationship between location, inventory and transportation related issues is critical for the success of any firm. Moreover, the customer service level of a supply chain network is determined by decisions regarding these three planning areas: location, inventory and transportation (Ballou and Master, 1993). The interdependence of these components are proved by Jayaraman (1989), Ballou and Master (1993), Shen et al. (2003), Shen and Qi (2007), and Javid and Azad (2010). However, not all available models take all these three planning areas into account. Models range in complexity regarding the level of integration of these three planning areas. Shen and Qi (2007) classify the facility location models based on the level of integration into sequential models, partially integrated models and fully integrated models (Shen and Qi, 2007).

- High costs savings can be achieved when integrating inventory and/or routing decisions with location decisions simultaneously. Moreover, these savings increase when the level of integration increases, since fewer warehouses would be opened (Jayaraman, 1989; Current et al., 2001; Ozsen, 2004; Shen and Qi, 2007; Javid and Azad, 2010). In addition to this, it is concluded that if the inventory and transportation costs account for a large portion of the total costs, it is more beneficial to take these decisions into consideration when making strategic location decisions (Shen et al., 2003; Shen and Qi, 2007; Javid and Azad, 2010). The range of improvement is 9.78-27.90% depending on the problem size (Javid and Azad, 2010). The transportation aspect should be explicitly taken into account when each vehicle makes deliveries to several points (i.e. routing aspect). Based on previous research it is well established that modeling distribution costs as the cost of a simple round trip from a facility to a customer may significantly misrepresent the actual costs and thus may result in the selection of sub-optimal facility sites when multi-stop tours are used (Current et al., 2001).

- On a lower level, facility location models can differ from each other on different aspects regarding their objective function, echelon level, location decision level, single vs. multi-commodity, static vs. dynamic, deterministic vs. stochastic, and solution space (Klose and Drexl, 2003; Nagy and Salhi, 2007). In addition to the integration level of the model, also these characteristics determine the complexity of facility location models.

### 5.2. Theoretical framework

The intended model requirements in the previous chapter ask for a static/implicit dynamic, two-level, multi-commodity capacitated location-allocation model, solved in a discrete space. Moreover, based on the overall research assignment and project scope, it can be concluded that total costs minimization is the main objective, such that a predefined service level is met.

First of all, as stated in the model requirements, the model considers an aggregation level of one production year, and makes a decision at one point in time for the coming at least 2 years. Moreover, since factors which influence strategic facility location decisions vary over time and the costs involved in these kinds of decisions are high, it is very important to take the dynamic nature of these factors into account. This is done by sensitivity analyses of the input factors. According to Current et al. (2001) this is called an implicit dynamic model. It means that the model is static in the sense that all facilities are to be opened at one time and remain open over the planning horizon, since high investment costs are involved. The model is dynamic because they recognize that parameters may vary over time (Current et al., 2001). As is addressed in the previous chapter, an evaluation regarding the dynamic nature of the input factors of the model is done by sensitivity analyses. As Klose and Drexl (2003) mentioned, the practical relevance of explicit dynamic models, where facilities have a close or open option available in every period, is limited. They mentioned that a ‘right’ planning
horizon does not exist, the amount of data required is enormous, 'disaggregated' models are more sensitive to parameter/data adjustments and the complexity of dynamic models increases, compared to static or implicit dynamic models (Klose and Drexl, 2003).

A second important characteristic of the model, which enhances the complexity, is the two-level (multi-echelon) characteristic. In multi-echelon models, multiple layers of the distribution system are taken into account. In the basic form of multi-echelon models, called single-level models, only facilities on a single level have to be located (Klose and Drexl, 2003). However, this project focuses on a multi-level location model, where next to warehouses also production plants must be located. This multi-level aspect must be modeled to be able to create insights in the difference between a single-echelon and a two-echelon (i.e. with intermediate warehouses) network design. In the current situation, only a single-echelon strategy is followed in the design of the supply chain network of PA6 C. However, for the future, a multi-echelon approach could be interesting for DEP. Figure 5.2 shows the difference between a single-echelon and two-echelon (single or multi-level) approach.

![Figure 5.2: Single versus multi echelon (single and multi level) approach](image)

Next to this, the model requirements indicate the multi-commodity aspect of the model, since the demand aggregation level is on grade level. Most models described in the literature are all based on aggregate demand, costs, and capacity for all products. However, such an aggregation is not valid anymore if some cost drivers, capacity or capability restrictions are dependent on the type of product (Klose and Drexl, 2003).

As is said in the previous section, models can have different objective functions. According to Current et al. (1990), four broad categories can be distinguished. The largest category is cost minimization (i.e. total distance models), which include distance minimization. The second most common category is a demand oriented objective, which include demand coverage and demand assignment. The remaining two categories are profit maximization and objectives addressing environmental concerns (Current et al., 1990). For DEP, both cost minimization and customer service level (i.e. response time towards customers) are important. The model is therefore a total distance model, which must meet a pre-defined customer service level. In practice, this approach is often used: first, a customer service level is set; then the logistics system is designed in order to meet that service level at minimum cost. In addition to this, the model is developed in such a way that it is able to determine the level of service that maximizes the profit contribution to the firm. The optimal service level usually lies between the low and high extremes (Ghiani et al., 2004).

Regarding the level of integration, the model is an integrated model which takes location, allocation and inventory decisions (i.e. number of warehouses and thus number of products in stock) into account. In literature, also routing decisions are integrated in some models. However, the routing decision part is not interesting for DEP.
since all transport is outsourced. They only pay a fixed rate per shipment lane, independent on the shipment route. Overall, it can be concluded that the model requirements best fit with the location-inventory (routing) models studied by Jayaraman (1998), Shen and Qi (2007) and Javid and Azad (2010). These studies all take transportation, operation and inventory costs into account, by making location, allocation, inventory (and routing) decisions. Moreover, the corresponding complex models developed in these studies are the most relevant models for practice and are therefore a good starting point.

First of all, the model of Jayaraman (1998) is a two-level model which focuses on total costs minimization consisting of transportation costs, costs to open and operate warehouses, delivery costs, holding costs of products in transit and in stock, and costs to open and operate plants. Also the SCN model incorporates these costs. Jayaraman (1998) focuses next to decisions with regard to inventory and location decisions, also on the determination of some parts of the transportation policy and takes the strong interdependency of these different issues into account. This partially integrated model simultaneously determines 1) which transportation alternative transports a certain quantity of a specific product from plant i to warehouse j and from warehouse j to customer k, 2) what is the optimal inventory level, and 3) what are the number and location of both plants and warehouses. All these decisions are made in such a way that it would lead to the lowest total inventory, transportation and location costs. For the SCN model, only the third decision is of interest, since only one transportation alternative and a fixed average inventory turn for each warehouse is assumed.

Secondly, also the even more complex models of Shen and Qi (2007) and Javid and Azad (2010) are a good starting point for the SCN model. In contrast to the model Jayaraman (1998), these models are single-level models and calculate the inventory costs based on a safety stock level and order quantity decision, which are both made by the model. The total costs which are taken into account are the same as the model of Jayaraman (1998). The unique part of the model of Shen and Qi (2007) and Javid and Azad (2010) is the routing aspect. As mentioned in the previous section, by making location, allocation, inventory and routing decisions simultaneously, a high level of integration is created and therefore high cost savings can be achieved. However, the total logistic costs of PA6 C are not influenced by the routing aspect, since transport is fully outsourced. Therefore, only location, allocation and inventory decisions are taken into account by the SCN model.

With regard to the solution space of the model, it can be concluded that a discrete model is developed. In discrete models, demand generally arises on the nodes and facilities are restricted to a finite set of candidate locations. Moreover, distances or costs between any pair of nodes in discrete models are arbitrary, although in general, they follow some rule (e.g. Euclidean, Manhattan etc.) (Daskin, 2008). As was indicated by the model requirements, regarding the SCN model, customer locations are located on nodes which represent cities, facilities are restricted to a predefined set of candidate locations and the Haversine formula is used to calculate distances and transport costs.

5.3. **Mathematical formulation**

The model requirements in chapter 4 presented what should be taken into account by the model and in which way, based on a practical view. Thereupon, in the previous section 5.2 also the theoretical framework of the model was outlined. In this section these practical model requirements and theoretical knowledge is translated into the mathematical formulation of the SCN model. Moreover, also an explanation of corresponding objective function and constraints are given.
Assumptions:

- Demand is divisible, which means that the demand of a specific customer can be delivered from more than one warehouse and production plant.
- Demand is deterministic, which means that the demand is inelastic with travel costs, travel time and/or distance.
- Demand of each customer must be satisfied.
- The model is static and recognizes the dynamic nature of the input parameters of the model, called implicit-dynamic model (Current et al., 2001)
- Material flows are not homogeneous (multi-commodity).
- Only one carrier is available.
- Two-echelon (two-level) situation, which means that both production plants and warehouses are taken into account. Thereupon on both levels location decisions can be made.
- Production lines have fixed capacity constraints, warehouses do not have capacity constraints.
- Fixed average inventory levels are assumed for each warehouse, by taken into account a fixed average inventory turn for each warehouse.
- Transportation costs include both transport or carrier costs and import duties and are the total costs to ship products from door to door (i.e. from production line to customer).
- Holding costs of products in stock and in transit are based on WACC/year = 7.5% (after tax).

Sets:

- $V_1$: Set of production lines
- $V_2$: Set of warehouses
- $V_3$: Set of customer demand points
- $G$: Set of grades

Parameters:

- $d_{kg}$: Demand of customer(s) in city k of grade g (pallets)
- $t_{ij}$: Transport time from production line i to warehouse j
- $t_{jk}$: Transport time from warehouse j to customer(s) in city k
- $t_{ijk}$: Total transport time from production line i to customer(s) in city k via warehouse j
- $k_{ijk}$: Total distance (km) from production line i to customer(s) in city k via warehouse j
- $v_j$: Average inventory turn at warehouse j
- $r_i$: Capacity of production line i (pallets/year)
- $q_{vehicle}$: Capacity of vehicle (pallets)
- $l_{max}$: Maximum allowed transport time from the warehouses to its corresponding assigned customers
- $p$: Maximum number of open production lines
- $g$: Maximum number of open warehouses
- $C_{inbound}$: Variable inbound costs at warehouse j (Euro/stored pallet/year)
- $C_{outbound}$: Variable outbound costs at warehouse j (Euro/stored pallet/year)
- $C_{storage}$: Variable storage costs at warehouse j (Euro/stored pallet/year)
- $C_{extrusion}$: Direct extrusion costs of production line i (Euro/pallet)
- $C_{raw}$: Total average raw material costs at production line i
- $C_{stock}$: Holding costs of grade g in stock (Euro/pallet/year)
- $C_{transport}$: Holding costs of grade g in transit (Euro/pallet/day)
Holding costs of grade g in transit (Euro/pallet/day)

Shipping costs of full vehicle (i.e. transport costs and import duties) from production line i to customer(s) in city k through warehouse j (Euro/km)

Decision variables:
- $x_{ijkg}$: Fraction of total demand $d_{kg}$ of customer(s) in city k for product g, which is routed through warehouse j and produced on production line i.
- $w_{ijkg}$: Variable which is equal to 1 if customer(s) in city k for product g are assigned to warehouse j, and 0 otherwise.
- $y_i$: Variable which is equal to 1 if production line i is opened, and 0 otherwise.
- $z_j$: Variable which is equal to 1 if warehouse j is opened, and 0 otherwise.

\[
\sum_{i \in \mathcal{I}, j \in \mathcal{J}, k \in \mathcal{K}, g \in \mathcal{G}} x_{ijkg} \cdot d_{kg} \cdot C_{ij}^{\text{shipping}} \cdot k_{jk} + \sum_{i \in \mathcal{I}, j \in \mathcal{J}, k \in \mathcal{K}, g \in \mathcal{G}} \left( \sum_{t \in \mathcal{T}_i} \sum_{j \in \mathcal{J}} \sum_{g \in \mathcal{G}} x_{ijkg} \cdot d_{kg} \cdot C_{inbound}^{\text{storage}} + C_j^{\text{outbound}} \right) + \sum_{i \in \mathcal{I}, j \in \mathcal{J}, k \in \mathcal{K}, g \in \mathcal{G}} x_{ijkg} \cdot d_{kg} \cdot (C_i^{\text{extrusion}} + C_i^{\text{raw material}}) + \sum_{i \in \mathcal{I}, j \in \mathcal{J}, k \in \mathcal{K}, g \in \mathcal{G}} x_{ijkg} \cdot d_{kg} \cdot t_{ijk} \cdot C_{ij}^{\text{in transit}}
\]

Subject to
- $\sum_{j \in \mathcal{J}, k \in \mathcal{K}, g \in \mathcal{G}} x_{ijkg} \cdot d_{kg} \leq r_i \quad \forall i, l \in \mathcal{V}_i \quad (1)$
- $\sum_{i \in \mathcal{I}, j \in \mathcal{J}, k \in \mathcal{K}, g \in \mathcal{G}} x_{ijkg} = 1 \quad \forall k, l \in \mathcal{V}_i \quad (2)$
- $x_{ijkg} \leq y_i \quad \forall i, j \in \mathcal{V}_i; \forall j, k \in \mathcal{V}_i; \forall k, g \in \mathcal{G} \quad (3)$
- $x_{ijkg} \leq z_j \quad \forall i, j \in \mathcal{V}_i; \forall j, k \in \mathcal{V}_i; \forall k, l \in \mathcal{V}_j; \forall g, g \in \mathcal{G} \quad (4)$
- $x_{ijkg} \leq w_{ijk} \quad \forall i, j \in \mathcal{V}_i; \forall j, k \in \mathcal{V}_i; \forall k, g \in \mathcal{G} \quad (5)$
- $w_{ijk} \cdot t_{jk} \leq l_{max} \quad \forall j, k \in \mathcal{V}_i; \forall k, g \in \mathcal{G} \quad (6)$
- $\sum_{j \in \mathcal{J}, k \in \mathcal{K}, g \in \mathcal{G}} z_j \leq g \quad \forall i, j \in \mathcal{V}_i; \forall j, k \in \mathcal{V}_i; \forall k, g \in \mathcal{G} \quad (7)$
- $x_{ijkg} \cdot w_{ijk} \geq 0 \quad \forall i, j \in \mathcal{V}_i; \forall j, k \in \mathcal{V}_i; \forall k, g \in \mathcal{G} \quad (8)$
- $y_i, z_j \in \{0,1\} \quad \forall i, l \in \mathcal{V}_i; \forall j \in \mathcal{V}_j \quad (9)$

Where $t_{ijk} = t_{ij} + t_{jk}$

Above mentioned objective function minimizes the total supply chain network costs consisting of transportation costs (including transport costs and import duties), warehousing costs, holding costs, and production costs (including extrusion costs and raw material costs). As can be concluded from the literature (see section 5.2), these cost drivers are the most important cost drivers in supply chain network design studies.

Constraint (1) is the capacity constraint of the production lines. Constraint (2) ensures that the total demand of every customer for product g ($d_{kg}$) is satisfied. Constraint (3), (4) ensure that production line i and warehouse j must be also opened if a customer k is assigned to it and is delivered from production line i via warehouse j. Constraint (5) says that if a customer with demand $d_{kg}$ is delivered from production line i
Constraint (1) is the capacity constraint of the production lines. Constraint (2) ensures that the total demand of every customer for product g \((d_{kg})\) is satisfied. Constraint (3), (4) ensure that production line \(i\) and warehouse \(j\) must be also opened if a customer \(k\) is assigned to it and is delivered from production line \(i\) via warehouse \(j\). Constraint (5) says that if a customer with demand \(d_{kg}\) is delivered from production line \(i\) through warehouse \(j\), this customer must be always assigned to warehouse \(j\). Constraint (6) is the customer service constraint, which ensures that the maximum transport time from the warehouse to the corresponding assigned customer is at maximum \(l_{max}\) days. Constraint (7), (8) says that the number of open production lines and warehouses do not exceed \(p\) production lines and \(g\) warehouses. Finally, constraint (9) is the non-negativity restriction placed on two sets of decision variables \(x_{ijkg}, w_{ijkg}\) and constraint (10) ensures the binary nature on two other sets of decision variables \(y_{i}, z_{j}\).

### 5.4. Model inputs and outputs

In the previous section, the mathematical model is developed and explained. This section presents the corresponding required inputs and final outputs of the model in Table 5.1.

The below mentioned inputs mainly concern the data items that need to be collected for the system of interest. Quality is a main factor of determining the usefulness of information (Alter, 2002). Therefore, in order to accurately model the real-life PA6 C supply chain network, the most reliable and recent data is recommendable. For that reason, the data is collected from various sources, of which an overview is presented in Appendix D.14.

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly demand on grade-city level (pallets)</td>
<td>Total supply chain network costs</td>
</tr>
<tr>
<td>Customer locations on city level</td>
<td>Total working capital</td>
</tr>
<tr>
<td>Production line locations</td>
<td>Transport times (customer service level)</td>
</tr>
<tr>
<td>Warehouse locations</td>
<td></td>
</tr>
<tr>
<td>Transportation times from all production lines to all warehouses (days)</td>
<td></td>
</tr>
<tr>
<td>Transportation times from all warehouses to all customer cities (days)</td>
<td></td>
</tr>
</tbody>
</table>

#### Cost drivers:

- a) Total shipment costs (transport costs + import duties) from all production lines to all customer cities via all warehouses (Euro/km/full vehicle)
- b) Warehousing costs of all warehouses (Euro/stocked pallet/year)
- c) Holding costs of all grades in transit (Euro/pallet/day)
- d) Holding costs of all grades in stock (Euro/pallet/year)
- e) Direct production costs of all production lines (Euro/kg)

#### Design output:

- a) Location decision of production lines (i.e. number, location, and capacity of production lines, overall capability of production plants)
- b) Location decision of warehouses (i.e. number and location of warehouses)
- c) Allocation decision (i.e. allocation of customers to production plants)

#### Constraints:

- a) Capacity constraints of production lines
- b) Service level requirement regarding transport time (i.e. maximum transport time from warehouse to assigned customer city)
- c) Maximum number of to be opened production lines and warehouses

Table 5.1: model inputs and outputs

During the entire project, data is gathered by interviews with employees at different positions in the organization. Data validation is ensuring that the data necessary for model building, model evaluation and testing is adequate and correct (Sargent, 2003). All data is discussed many times with involved people from Supply Chain Management (SCM), Sourcing and Finance, to assure that the right data is used. In the end, a
summary of all input data with corresponding sources, is presented, discussed and agreed on, during a meeting with all people involved.
5.5. Solving the mathematical model

The SCN model described in section 5.3 can be classified as a Mixed Integer Linear Programming model (MILP). After formulating the mathematical problem, finding an optimal or near to optimal solution is the next step. Solving can be done by using heuristics, or can be done exact. A well known exact method is the branch and bound or cutting planes. However, they are only useful for small problems (Ghiani et al., 2004; Nagy and Salhi, 2007). Because of the fact that even the most basic location models are classified as NP-hard, using these methods quite often consume unacceptable computational resources (both computer memory and time), with no guarantee of success (Current et al, 2001). Therefore, a lot of different heuristics are studied in the literature.

As both the project scope and the model already indicate, the decision support method should be a tool which solves mathematical optimization problems. The mathematical model indicates that in order to find the best supply chain network design for a predefined scenario, the objective function should be minimized. Therefore, a mathematical optimization tool is required which is capable of solving MILP problems.

Because of the complexity of the mathematical SCN model which can be classified as NP-hard, it is impossible to solve the problem in an exact way. To deal with this complexity, the short time period of the project, and finally to strive for the best results, it is chosen to use a mathematical modeling tool of IBM, named ILOG LogicNet Plus XE. This dedicated software tool is a specialized solver of supply chain network problems. This tool uses mathematical programming techniques, by using a sophisticated blend of MIP heuristics and cutting-edge algorithmic developments.

Since LogicNet is fully specialized in solving supply chain network problems, this tool has many advantages compared to general-purpose mathematical programming software or general heuristics. The most relevant advantages are: 1) easy to use Windows interface; 2) high flexibility in terms of input data and constraints modeling, which makes it possible to use LogicNet for supply chain network problems in all types of companies and industries; 3) highly specified model’s solution in terms of costs, which can be viewed, compared, and easily exported to tables and graphs for presentations and further analysis; 4) valid and verified solver, which correspond to literature findings and which is applied a lot in practice; 4) Very short run time, even for very complex problems; 5) advanced algorithms in LogicNet offer the ability to create larger and more realistic models, and to solve them faster.

5.6. Summary of SCN model

In this chapter both the theoretical framework and mathematical formulation of the SCN model is outlined. From a theoretical perspective it can be concluded that the model is a static/implicit dynamic, two-level, multi-commodity capacitated location-allocation model, which is solved in a discrete space. Moreover, the main objective of the SCN model is total cost minimization (i.e. shipment, inventory, and operating costs) by having a predefined customer service level as constraint. Decisions which are made by the model are location decisions of both warehouses and plants and allocation decisions of customers to facilities. Overall, the SCN model mainly correspond to the models described by Jayaraman (1998), Shen and Qi (2007) and Javid and Azad (2010).

As the SCN model is complex and cannot be solved exact, a mathematical optimization tool called LogicNet is used. This tool is fully specialized in solving supply chain network design problems and is broadly used in practice. Therefore, using this optimization tool has many advantages in terms of time, capability, flexibility, reliability and validity.
6. REDESIGN

In the previous chapter the SCN model is defined. After outlining the base case in the first section, the model is applied to different scenarios which are described in the second section. The results of the scenario analyses are discussed in the second section as well. In section 3, an implementation plan is developed. Finally, this chapter is summarized in section 4.

6.1. Base case

In this first section, the performance of the base case is presented. Also the verification and validation process of the software tool is outlined.

6.1.1. Base case performance

The base case defines the supply chain network of PA6 C given the asset footprint and parameter settings as they exist at this moment (see also chapter 3). This base case scenario is compared to other scenarios described in the next section.

In appendix E.1, a visualization of the base case supply chain network on city-grade level is shown. Figure 6.1 shows the customer allocation outcome of the base case on country level, aggregated over all customers and grades. This figure is generated by LogicNet and shows the same outcome as the analysis phase presents (see appendix B.1). The exact parameter settings and assumptions of this base case are explained extensively in chapter 3 and 4 and are summarized in appendix E.2.

Figure 6.1: Customer allocation outcome on country level of base case

As was already concluded in chapter 3, a decentralized production-allocation strategy is applied in the current situation. The most remarkable results of the base case scenario are summed up below:

……………………
Table 6.1 shows an overview of the most important performance indicators of the current supply chain network of PA6 C: Operating costs, OWC and customer service in terms of transport times. As direct comparison of these results presented by LogicNet with real performance data is not possible, these results are validated with people from different departments of DEP. These people have all agreed that the results are representative for the current situation. More about the validation process is said in the next subsection.

<table>
<thead>
<tr>
<th>Performance indicator</th>
<th>Result</th>
<th>% of total costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shipping costs plant - warehouse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shipping costs warehouse - customer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warehousing costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Working Capital</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holding costs in transit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holding costs in stock</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total logistic costs</td>
<td>€ 174,197,233</td>
<td>100%</td>
</tr>
<tr>
<td>Customer service</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weighted average transport time (days)</td>
<td>4.86</td>
<td></td>
</tr>
<tr>
<td>% customers with transport time &lt; 10 days</td>
<td>90% (i.e. 90% of volume)</td>
<td></td>
</tr>
<tr>
<td>% customers with transport time &gt; 20 days</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>% production for non regional customers</td>
<td>2.3%</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1: Performance of base case scenario

In the base case the total stock value amounts approximately ..............................................

Figure 6.2 shows the production quantity of each plant and the throughput per year of each internal warehouse in the base case.

6.1.2. Validation and verification

Verification and validation is important to ensure that the software tool gives reliable results and is representative to apply for the supply chain network challenge of DEP.

Verification

Verification of a (computerized) model is defined as assuring that the computer programming and implementation of the conceptual model is correct (Sargent, 2003). This means that the verification step checks if the (computerized) model performs as intended (Law and Kelton, 1982; Sargent, 2003). As LogicNet is a specialized, broadly-used software tool developed by IBM, verification is done already. It is assumed that algorithms were implemented correctly and all errors and bugs were excluded. A small additional verification step which is done is evaluating the output and costs calculations of LogicNet. These results are presented in appendix E.1 and E.3 respectively. It is concluded that the costs calculations made by LogicNet are the same as the mathematical model in section 5.3 indicates. Moreover, the output of LogicNet in terms of location-allocation decisions correspond to the analysis of the as-is situation in chapter 3 (see appendix B.1).
**Validation**

The quality of the proposed model is an important aspect of the design phase. Validation is determining whether a model is an accurate representation of the real-world system under study (Law and Kelton, 1982). According to Aken et al. (2007), model validity can be decomposed into construct, internal and external validity.

First of all, construct validity refers to the quality of the operationalization of the model. This process is described extensively in chapter 4 and 5. It can be concluded that the model is valid in terms of construct validity, as it is based on a clear and detailed description of the problem entity in chapter 3. Furthermore, the recognition of the results by professionals in the organization is an important validity criterion, even the most important criterion in this project. Overall, this criterion is a very important instrument in business problem-solving projects (Van Dijk et al. (1991). Therefore, during the data gathering process, as well as after generating the first results by LogicNet, all data and results are discussed with professionals within DEP in order to get a very accurate picture of reality. The data and model results are presented and discussed with people from SCM, Sourcing and Finance. These representatives have agreed that the model represents the actual situation accurately and have accepted the results.

Internal validity refers to the adequacy of the internal causal relationships as defined in the model. As the causal relationships assumed by the SCN model correspond exactly to findings in the literature (see theoretical framework in section 5.2), it can be concluded that the SCN model is internally valid.

External validity means the generality of research results to other situations. Since this research project is focused on a specific business problem, external validity of the research results is of less importance. However, as the mathematical SCN model is a general model which matches to multiple models described in the literature focused on different industries, the external validity of the SCN model is high. Only the parameter settings as they are described in chapter 4 are adapted to the supply chain network characteristics of PA6 C.

### 6.2. Scenario analyses

In this section different scenarios with regard to the supply chain network of PA6 C are evaluated. Figure 6.3 outlines the options which are available to construct the scenarios. The scenarios differ from each other with regard to the year under consideration, capacity and transport time restrictions, the possibility of new production lines and intermediate warehouses, and the sourcing strategy of PA6 P MV which is assumed.

![Figure 6.3: Structure to construct scenarios](image)

Combining the scenario options presented in figure 6.3, multiple scenarios can be created. However, not all scenarios are of interest for this project. An overview of the selected scenarios is presented in figure 6.4.
In the next two subsections, the outcome of the different scenarios with regard to the current (i.e. 2011) and future (i.e. 2020) situation, as outlined in figure 6.4, are discussed.

6.2.1. Current situation scenarios
In this subsection, insights regarding the current situation are discussed. This is done by focusing on the 2011 scenarios shown in figure 6.4 above. For a detailed overview of the parameter settings and assumptions for each current situation scenario is referred to appendix F.1.

Scenario 1: Optimal current situation
The first scenario analysis regards the optimal customer allocation decision of the current global asset-footprint. This scenario focuses on 2011 demand, current set up of production plants and internal warehouses, and the current sourcing strategy of RMs. Capacity restrictions of production lines are considered and a maximum transport time from the warehouses to the customers is set. In table 6.2, the performance of scenario 1 is compared to the performance of the base case.
Table 6.2: Difference in performance between base case and scenario 1

<table>
<thead>
<tr>
<th>Performance indicator</th>
<th>Base Case</th>
<th>Scenario 1</th>
<th>Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.5: Production plant throughput per year in base case and scenario 1

A more detailed overview of all customer allocation decisions and changes can be found in appendix F.2 and F.3 respectively.

Table 6.3: Main customer allocation changes of scenario 1 in contrast to base case

<table>
<thead>
<tr>
<th>Customer allocation change</th>
<th>% of total change volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sensitivity analysis

Scenario 2: No transport time restriction in current situation

Based on the second scenario, it is evaluated what DEP pays in the current situation to achieve short transport times of about....................... The only difference with the previous scenario is that no transport time restrictions are considered. In table 6.4, the performance of scenario 2 is compared to the performance of the base case.

................
Table 6.4: Difference in performance between base case and scenario 2

------------

Figure 6.6: Countries with average transport time of more than 10 days in both scenario 1 and 2

------------

A detailed overview of all customer allocation decisions and production quantities per plant in scenario 2 is shown in appendix F.4 and F.5 respectively.

Scenario 3: No capacity restriction in current situation

In contrast to scenario 1 and 2, this scenario ignores capacity restrictions to evaluate if centralized production could save money in the current situation compared to a decentralized production strategy. Compared to the previous scenarios, capacity of reference lines (i.e. production lines which are representative for new lines in terms of costs and capacity) is unlimited in this scenario. Other assumptions and parameter settings are the same as in scenario 1 and 2 (see table F.1). The performance of scenario 3 is shown in table 6.5.

Table 6.5: Difference in performance between base case and scenario 3

------------

Some other unlimited capacity scenarios are evaluated in order to create more insights in improvement opportunities for the current situation. Appendix F.6 shows these different scenarios, including its overall performance. Appendix F.7 shows corresponding new PA6 P MV prices for adapted sourcing strategies of these scenarios. Based on these scenarios presented in appendix F.6, the following insights are created:
To conclude, ....

**Sensitivity analysis**
Based on some sensitivity analyses on scenario 3 it is ............

**Scenario 4: No restrictions in current situation**
As the previous scenarios all have transport time restrictions and/or capacity restrictions, this scenario creates insight in the optimal production-allocation decisions if no restrictions are considered. Despite the fact that this scenario is not realistic to apply in practice, it generates useful insights in the maximum saving and thus the most cost efficient decisions. Table 6.6 shows the performance of scenario 4, compared to the base case.

<table>
<thead>
<tr>
<th>Performance indicator</th>
<th>Base Case</th>
<th>Scenario 4</th>
<th>Saving</th>
</tr>
</thead>
</table>

*Table 6.6: Difference in performance between base case and scenario 4*

.................

**Conclusion of current situation**

..........................
6.2.2. Future scenarios

In this second subsection, insights regarding the future supply chain network design of PA6 C are discussed. This is done by focusing on scenarios regarding 2020, shown in figure 6.5. For a detailed overview of the parameter settings and assumptions of each future situation scenario is referred to appendix G.1. As inflation rates must be taken into account towards 2020, appendix H.1-H.3 shows the inflation rates per country and the corresponding adapted supply chain network costs in 2020.

**Scenario 5: Optimal situation regarding current capacity in 2020**

……………..

…………….. Appendix G.2 shows an overview of the customer allocation decision outcome of scenario 5.

---

**Figure 6.7: Production plant throughput scenario 1, 5**  **Figure 6.8: Production plant throughput scenario 3, 5**

……………..

**Scenario 6: Optimal situation 2020 if expansion at existing plants only**

……………..…………….. Compared to the previous scenario, the only difference is that this scenario focuses on the additional demand in 2020, and considers only the reference lines of each plant which are assumed to be unconstraint in capacity. These reference lines are representative (in terms of costs and capacity) for new production lines at the same production plant (see appendix D.11). The performance of scenario 6 is presented in table 6.7.

<table>
<thead>
<tr>
<th>Performance indicator</th>
<th>Scenario 6</th>
<th>% of total costs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 6.7: Performance of scenario 6*

……………..
Figure 6.9: Production plant throughput per year in scenario 6

.................

Figure 6.10: Performance of scenario 6 regarding two different future sourcing strategies of PA6 P MV

.................

Sensitivity analysis
The results of scenario 6 show ........................................

Scenario 7: Optimal situation 2020 if external expansion is possible

.............

In this scenario it is assumed that all ......................

<table>
<thead>
<tr>
<th>Performance indicator</th>
<th>Scenario 6</th>
<th>Scenario 7</th>
<th>Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.8: Difference in performance between scenario 6 and 7

The difference in total costs is small between scenario 6 and 7. However, production costs are higher, and transportation costs are lower in scenario 7. The reason for this can be explained by figure 6.10, which shows the production and warehouse decision of scenario 7.
Figure 6.11: Production plant and warehouse throughput in scenario 7

Sensitivity analysis

Conclusion of future situation
6.3. Implementation

The implementation phase is the fourth phase of the regulative cycle (Van Strien, 1997), described in chapter 1. With regard to this project, implementation concerns on the one hand implementation of a strategic redesign direction discussed in the previous section, and on the other hand implementation of the SCN model in the organization. This section focuses on both types of implementation. However, the scope of this project excludes a detailed implementation plan and further execution of the proposed improvement opportunities. This section therefore only encompasses the starting point from which further follow-up actions can be taken.

Implementation of redesign direction: change management

Before implementation of one of the redesign directions regarding the future supply chain network, different in-depth analyses are required. As already said in chapter 2, strategic network decisions cannot be purely based on quantitative SCN model results. Some other quantitative and qualitative analyses need to be done in order to make a final strategic decision (see also the recommendations in chapter 7). Therefore, to fully execute the follow up of this project, which include additional analyses and the total change management (i.e. implementation), a project team must be composed. This project team must consist of experienced people who have been employed within DEP (Akulon Compound). People from Business (i.e. Business Unit Director, Business Manager), Technical Marketing (TM), Sourcing, Supply Chain Management, Sales, Finance, and Research & Development must be involved in this project.

Implementation of SCN model (LogicNet): software implementation

By the implementation of the SCN model is meant the implementation of the SCN model in combination with the software tool LogicNet. This is due to the fact that solving the SCN model is hard and less useful in practice without the software tool LogicNet. LogicNet is highly specialized in solving complex supply chain network design questions and is broadly used in practice (see section 5.5). The SCN model can be used for other BUs and other product lines as well. This makes it an interesting tool to implement in the organization. However, support for the model and program and willingness to use the program within DEP is required. During the project, much attention is paid to create commitment and confidence. In a series of presentations where people from several hierarchical levels and departments were present, the model and the results are demonstrated and discussed. In addition, also a small work instruction on the use of the software tool is presented already. These sessions have created, next to involvement and understanding, also confidence in the performance of the SCN model. In order to create more support for the implementation of the SCN model in the organization, the following actions should be considered:

- The first important step is creating confidence within DEP in the performance and usefulness of the SCN model. This first implementation step is already covered by this project, as the results of this project described in chapter 6 show the applicability, validity and performance of the SCN model.
- The second step is to determine the exact use of LogicNet (i.e. scope of use, frequency of use). It has been shown that LogicNet provides insight on a strategic level only. Due to this, it is recommendable to use the SCN model for these strategic purposes (e.g. strategic network analyses and optimization). As a lot of dynamic input data is necessary, it is recommendable to update the input data once a year. At any time it is possible to adapt data and to run scenarios, as loading and changing data in LogicNet is very easy and takes just a few seconds. Also the running time of scenarios in LogicNet is very short (at maximum 60 seconds). Finally, only for those who are involved in strategic processes the software tool needs to be accessible (e.g. managers, internal consultants).
An important last step is to make sure that LogicNet users understand the basics, aim, scope and results of the program. This report is the starting point in creating this required insight, of which chapter 4, and chapter 6 in particular. However, this project does not describe how to prepare for executing scenario analyses in LogicNet. Chapter 5 only explains what is taken into account by the SCN model. Therefore, in order to simplify this implementation step, in appendix I.1 the SCN model preparation in LogicNet is outlined.
State of affairs
The first part of the implementation is already realized; creating commitment from people at different hierarchical levels within DEP, and confidence in the results of the SCN model. Thereupon, the process of purchasing the software tool LogicNet is already started up. The next step is to assign a project owner who coordinates further actions regarding further analyses and implementation after this research project is finished.

6.4. Summary of redesign
The aim of this chapter was to create insights in both the current and future optimal supply chain network design of PA6 C. Table 6.10 and 6.11, summarizes the results of the main scenarios which are executed.

<table>
<thead>
<tr>
<th>2011</th>
<th>Base Case (as-is)</th>
<th>Scenario 1 (transport time and capacity constraint)</th>
<th>Scenario 2 (no transport time constraint)</th>
<th>Scenario 3 (no capacity constraint)</th>
<th>Scenario 4 (no capacity, no transport time constraint)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>Scenario 6 (expansion at current production plants only)</td>
<td>Scenario 7 (expansion at external locations)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.9: Summary results current situation scenarios

..........  

Table 6.10: Summary results future scenarios

..........  


7. CONCLUSIONS & RECOMMENDATIONS

This chapter concludes the report by outlining the most important conclusions and recommendations for DSM in section 1 and 2 respectively. Finally, in the last section areas for future research are outlined.

7.1. Conclusions

This project is focused on answering below mentioned research assignment:

"Develop a strategic global supply chain network model which is able to design the cost optimal supply chain network of PA6 C for both the current and future situation (i.e. in 2020). Apply the model such that the effect of market changes (e.g. cost changes) on the total performance (i.e. total costs, working capital, and customer service level) of the supply chain network can be measured”.

In order to design the global SCN model, a good understanding of the current situation regarding the supply chain network of PA6 C is required. The global supply chain network characteristics of PA6 C are analyzed, which lead to clear model requirements.

The SCN model which is developed is classified as a MILP model and is solved by using the mathematical optimization tool LogicNet. Different current situation and future scenarios are evaluated to answer the overall research assignment. The main conclusions of the design phase are stated below:

- .........
- .........
- .........
- Regarding the mid-term, if capacity must be expanded, ...............
- .........
- Towards 2020, ..............
- The SCN model in LogicNet is a broadly applicable, appropriate tool for supporting strategic supply chain network design decision. It can be therefore used for other product lines or BUs as well. As this project ignores local grades, which are about 13% of total demand and thus a significant amount, the SCN model can be also applied to these local grades. Furthermore, LogicNet is fully specialized in strategic supply chain network problems, is broadly used in practice, corresponds with findings in literature, is generally applicable, is easy to use, has a very short data loading and model running time, and finally is able to view, compare and export results to tables and graphs for further analyses.

7.2. Recommendations

Recommendations are based on the results obtained throughout this project. The advice to DEP is to focus on the following points of interest:

.................
7.3. Further research

- Although many studies focus on strategic supply chain network design models (also called facility location models), none of them focuses on the high-quality plastics industry where production costs play a significant role. In almost all production-allocation models, transportation and routing decisions play the main role. However, most companies outsource transport which means that routing decisions are out of scope. For further research it is interesting to focus on the role of production and sourcing decisions in the design of the supply chain network in industries that focus on high-quality products. Sourcing costs of RMs cannot be ignored in these industries. In other words, it would be valuable to extend the literature concerning three-echelon models where sourcing decisions regarding the main RM(s) are included.

- The SCN model does not incorporate inventory control decisions and corresponding distinction between MTF and MTO products. The mathematical optimization tool LogicNet did not allow these flexibilities regarding integration with other decisions, as is described in literature (e.g. location-inventory models). If a distinction can be made between MTO and MTF products, also a better evaluation of transport times toward customers (i.e. customer service level) is possible. Therefore, a SCN model which integrates these inventory decisions would be an interesting research topic.

- As transportation costs play an important role in the optimal design of the supply chain network, it is interesting to expand the SCN model such that transportation costs are calculated in more detail (i.e. aggregated on city level instead of country, different carriers etc.). Thereupon, including the distinction between FTL and LTL transport would give a better representation of reality in terms of costs.
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READING GUIDES

In order to provide a reading guide, both a list of figures and a list of tables are given below. Besides, the abbreviations throughout the report are defined.

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<td>AP</td>
<td>Asia Pacific</td>
</tr>
<tr>
<td>BG</td>
<td>Business Group</td>
</tr>
<tr>
<td>BSD</td>
<td>Business Strategy Document</td>
</tr>
<tr>
<td>CAP</td>
<td>Caprolactam</td>
</tr>
<tr>
<td>CORC</td>
<td>Corporate Operations &amp; Responsible Care</td>
</tr>
<tr>
<td>DAS</td>
<td>DSM Advanced Services</td>
</tr>
<tr>
<td>DD</td>
<td>DSM Dyneema</td>
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<tr>
<td>DEP</td>
<td>DSM Engineering Plastics</td>
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<tr>
<td>DB</td>
<td>DSM Biomedical</td>
</tr>
<tr>
<td>DBPS</td>
<td>DSM Bio-based Products &amp; Services</td>
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<tr>
<td>DFI</td>
<td>DSM Fiber Intermediates</td>
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<tr>
<td>DFS</td>
<td>DSM Food Specialties</td>
</tr>
<tr>
<td>DNP</td>
<td>DSM Nutritional Products</td>
</tr>
<tr>
<td>DPP</td>
<td>DSM Pharmaceutical Products</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------------------------------------------------</td>
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<tr>
<td>DRF</td>
<td>DSM Resins &amp; Functional Materials</td>
</tr>
<tr>
<td>DSP</td>
<td>DSM Sinochem Pharmaceuticals</td>
</tr>
<tr>
<td>EBIT</td>
<td>Earnings Before Interest and Taxes</td>
</tr>
<tr>
<td>E&amp;E</td>
<td>Electrical &amp; Electronics</td>
</tr>
<tr>
<td>EU</td>
<td>Europe</td>
</tr>
<tr>
<td>FTE</td>
<td>Full Time Equivalent</td>
</tr>
<tr>
<td>FTL</td>
<td>Full Truck Load</td>
</tr>
<tr>
<td>FCL</td>
<td>Full Container Load</td>
</tr>
<tr>
<td>HRR</td>
<td>Heat resistant resins</td>
</tr>
<tr>
<td>HV</td>
<td>High Viscose</td>
</tr>
<tr>
<td>IP</td>
<td>Intellectual Property</td>
</tr>
<tr>
<td>JV</td>
<td>Joint Venture</td>
</tr>
<tr>
<td>KPI</td>
<td>Key Performance Indicator</td>
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<tr>
<td>LCL</td>
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<td>MIP</td>
<td>Mixed Integer Program</td>
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<td>MILP</td>
<td>Mixed Integer Linear Program</td>
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<tr>
<td>MTF</td>
<td>Make To Forecast</td>
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<tr>
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<tr>
<td>MV</td>
<td>Mid Viscose</td>
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<tr>
<td>OWC</td>
<td>Operating Working Capital</td>
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<tr>
<td>PA6/66 P</td>
<td>Polyamide 6/66 Poly</td>
</tr>
<tr>
<td>PA6/66 C</td>
<td>Polyamide 6/66 Compound</td>
</tr>
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<td>RM</td>
<td>Raw Material</td>
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<td>SCM</td>
<td>Supply Chain Management</td>
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<td>SCN model</td>
<td>Supply Chain Network model</td>
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<tr>
<td>SKU</td>
<td>Stock Keeping Unit</td>
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<tr>
<td>S&amp;OP</td>
<td>Sales &amp; Operations Plan</td>
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<tr>
<td>TM</td>
<td>Technical Marketing</td>
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<tr>
<td>US</td>
<td>United States</td>
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<tr>
<td>WACC</td>
<td>Weighted Average Cost of Capital</td>
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