Fast & Slow freight distribution in the Fast Moving Consumer Goods industry

by

Kris Radstok

Student identity number 0721962

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Supervisors:
Prof.dr. A.G. de Kok, TU/e, OPAC
dr. T. Tan, TU/e, OPAC
L. Deketele, P&G, SNIC
TUE. School of Industrial Engineering.
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ABSTRACT

In this paper, we consider an inventory system with two transportation modes; a fast mode (road transportation) and a slow mode (intermodal transportation). Furthermore, multiple products are considered with individual demand distributions. An allocation procedure is defined to split the volume among the two transportation modes. The slow mode will ship the (most) constant quantity, which is predetermined with a greedy algorithm. This fast mode is controlled with an order-up-to policy. The (individual) order-up-to levels of the products are determined with a service level constraint. Inventory theory is used to find the minimal Total Logistics Cost of the system, consisting of the Transportation cost, the Storage cost and the Cost of Capital. Based on a numerical study, conclusions follow about the conditions under which a combination of fast and slow transportation is more attractive than only fast transportation.
MANAGEMENT SUMMARY

In the past two decades, intermodal transportation emerged as an interesting alternative freight transportation method. It is more sustainable and can-with economies of scale and scope-be cheaper than the commonly used road transportation. However, road transportation is considered to be faster, more flexible and more reliable. The concept of floating stocks exploits all these transportation characteristics by combining both transportation methods and letting them operate in parallel. Through postponing the inventory allocation, this floating stock policy achieved faster response times and reduced both the storage costs and holding costs.

The concept of floating stocks is however not applied to the FMCG industry, which consists of many products with volatile demand. Therefore it is interesting to examine the conditions under which a combination of road- and intermodal freight for fast moving consumer goods distribution can achieve similar or better service and cost levels compared to unimodal road transportation.

This examination is performed for two different cases (Figure 1). The first case concerns the goods flow from a Central Stock (CS) location to a Regional Distribution Center (RDC), in which the shipment sizes are determined with a replenishment policy. The second case concerns the goods flow from a RDC to Retailer Distribution Centers (Retailer DCs), where a Crossdock DC is used to combine shipments from the two transportation modes.

First, a data analysis is performed to get an in-depth knowledge of the goods flow characteristics in the FMCG. This analysis is not available in the public version of this master thesis. Instead, it is assumed in this analysis that there is a high demand variation for the observed products, while the aggregated volume had a significantly low variation. This indicated that including multiple products in the analysis contributes to the practical usefulness of this research. Furthermore, the gamma distribution is considered to be the most appropriate demand distribution for these products.

Then, two mathematical models are designed to examine the cases. These models use inventory theory to find the minimal cost of the system. For this purpose, a Total Logistics Cost perspective is used to quantify the (qualitative) transportation characteristics. This perspective is considered to include three cost components; the Transportation cost, the Storage cost and the Cost of Capital.
Two transportation modes are available in these models; a fast mode (road transportation) and a slow mode (intermodal transportation). An allocation procedure is used to split the volume of the goods flow among these transportation modes in an efficient manner. The slow mode will ship a (predetermined) constant quantity, while the fast mode will ship the remaining (varying) volume. This fast mode is controlled with an order-up-to policy, based on product specific basestock levels. These basestock levels are sufficiently high to meet the service level restriction of the model.

A greedy algorithm is designed to select the (most) constant volume, which is allocated to the slow mode. This is done by analysing the individual demand distributions of the products.

The mathematical models are used by a simulation model to generate results. This simulation model determines the ‘optimal’ number of containers which should be allocated to the slow mode, in order to minimize the Total Logistics Cost.

A combination of road and intermodal freight transportation proved to be an attractive distribution method for the examined goods flow of the first case. The main reason for this success is the reduction of transportation cost, as intermodal transportation was considered to be significantly cheaper than unimodal road transportation. The use of intermodal transportation did however lead to additional Storage cost and Cost of Capital.

The examined goods flow for the second case, proved to be best served by unimodal road transportation. The distance between the RDC and the XDC was insufficiently far, for intermodal transportation to be cost-attractive.

Several parameters influence the transportation method decision and the Total Logistics Cost:

- The transportation prices for shipping a container with direct road and with the intermodal mode are considered to be the two most important parameters, by far. As the total Transportation cost represents a significant share of the Total Logistics Cost (70%), it is obvious that a change in the transportation prices will have a major impact. Basically, when the transportation cost of intermodal transportation is slightly cheaper than road transportation, a considerable volume (quickly >40%) will be allocated to this mode;
- The storage cost and the cost of capital per pallet, have only a small impact on the Total Logistics Cost. So, increasing these parameters will increase the Total Logistics Cost slightly;
- Finally, the lead times of the transportation modes are also influential. Logically, these lead times affect the Cost of Capital, as the lead times are directly related to the In-Transit inventory. Longer lead times imply more inventory In-Transit, so more Cost of Capital. Furthermore, the lead time of road transportation determines the required order-up-to level in the RDC (in the first case). A longer lead time of road transportation will result in higher order-up-to levels to cope with the demand uncertainty. Hence, both the Storage cost and the Cost of Capital will increase.
PREFACE

This thesis concludes my Master program at the department of industrial engineering and innovation sciences of Eindhoven University of Technology. Realizing that this thesis was possible with the help and guidance of others, I take this opportunity to thank some people.

This thesis was executed in Procter & Gamble’s Supply Network Innovation Center, located in Brussels. The graduation internship was a great experience, largely due to the enthusiastic support of Lieven Deketele. He gave me the opportunity to conduct my master thesis project at P&G and provided me with constant optimism and sharp observations. Thank you so much. Furthermore, I would like to thank all colleagues and fellow interns at P&G for the inspiring working atmosphere and the great time I have had.

Secondly, I would like to thank my supervisors at the TU/e, who have pointed me in the right direction several times. I would like to thank professor dr. Ton de Kok for the great suggestions throughout this project and dr. Tarkan Tan for his valuable feedback.

With an amazing feeling, I look back on my life as a student. In which I have fully enjoyed the challenges and experiences as a boardmember of Jong Logistiek Nederland. I have gain a great impression of the logistics industry in the Netherlands and most importantly, a fantastic network of young professionals. Furthermore, I really enjoyed the opportunity to experience South Africa during my international semester. This is already one of the most impressive moments of my life. This amazing student life was not possible without the help and support of my girlfriend Madeleine and my parents. Thank you!

Kris Radstok

Eindhoven, April 2013
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1. INTRODUCTION

We will first give a general introduction of this master thesis project (Chapter 1.1), after which we describe the organization where this project is conducted (Chapter 1.2). Finally, the outline of the remaining report is described in chapter 1.3.

1.1. GENERAL INTRODUCTION

Sustainability has become an important trend in the fast-moving consumer goods (FMCG) industry. It appears that the environmental awareness of the global society is recognized, whether this involves low temperature washing in laundry care or the commitment of tea brands to source all tea from sustainable farming practices. This development does also reflect itself in the field of freight transportation, in a way that more polluting modes such as road transportation are shifted to intermodal solutions.

Intermodal transportation is not only more sustainable than road transportation (Macharis et al., 2011), it can also be more attractive in terms of transportation costs, when sufficient distance is covered (Janic, 2008). Yet, intermodal transportation has very different characteristics. It uses multiple transportation modes, multiple decision makers and is oftentimes controlled by challenging timetables. These characteristics can affect the reliability, flexibility and speed of the supply chain in a negative way. Therefore, the challenge is to find a sustainable transportation set-up, able to cope with this. Reason enough to find out more about possibilities to use the strengths of both transportation methods:

Under which conditions can a combination of road- and intermodal freight for fast moving consumer goods distribution achieve similar or better service and cost levels compared to unimodal road transportation?

The concept of floating stocks is considered to be an interesting transportation set-up that can be used to answer this question. This concept makes use of the characteristics of intermodal transportation, by shipping a fraction of the inventory in the direction of the customers, before the demand is allocated. Road transportation is used in this concept to ship the remaining demand, so that the reliability, flexibility and speed of the supply chain are guaranteed (Dekker et al., 2009).

This master thesis contributes both to the existing scientific knowledge and to the business problem of the organization that is studied. It defines and uses applicable inventory-theoretic models to determine whether a combination of fast transportation (direct road) and slow transportation (intermodal) can be an attractive alternative opposed to only fast transportation. These models examine multiple products with individual demand characteristics and order up to levels. Furthermore, an effective greedy algorithm is defined to allocate the volume between the two transportation modes.

In order to determine which transportation set-up this most attractive, a total logistics cost perspective is used. This perspective implies particular attention to all costs in the supply chain that are affected by the choice of transport mode (Ballou, 1999).
1.2. COMPANY DESCRIPTION

The setting for this study is the multinational product manufacturer Procter & Gamble (P&G).

GENERAL INFORMATION

Established in 1837, P&G began as a small family-run candle and soap business in Cincinnati, Ohio. Today, P&G is the largest and most profitable consumer packaged goods company in the world. By marketing one of the strongest portfolios of trusted, quality, leadership brands, P&G is serving approximately 4.6 billion people around the world.

This global manufacturing company employs approximately 126,000 employees, working in about 75 countries worldwide. The products are sold in more than 180 countries, primarily through mass merchandisers, grocery stores, membership club stores, drug stores, department stores, salons and in high-frequency stores. Currently P&G is expanding its presence in other channels, including perfumeries, pharmacies and e-commerce (Procter & Gamble, 2012a). The business segments and the corresponding net sales in 2012 are given in Table 1 and Figure 2.

<table>
<thead>
<tr>
<th>Business Segment</th>
<th>Billion Dollar Brands</th>
<th>% of Net Sales</th>
<th>% of Net Earnings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beauty</td>
<td>Head &amp; Shoulders, Olay, Pantene, SK-II, Wella</td>
<td>24%</td>
<td>22%</td>
</tr>
<tr>
<td>Grooming</td>
<td>Braun, Fusion, Gillette, Mach3</td>
<td>10%</td>
<td>16%</td>
</tr>
<tr>
<td>Health care</td>
<td>Always, Crest, Oral-B, Vicks</td>
<td>15%</td>
<td>17%</td>
</tr>
<tr>
<td>Fabric care and home care</td>
<td>Ace, Ariel, Dawn, Downy, Duracel, Febreze, Gain, Iams, Tide</td>
<td>32%</td>
<td>26%</td>
</tr>
<tr>
<td>Baby care and family care</td>
<td>Bounty, Charmin, Pampers</td>
<td>19%</td>
<td>19%</td>
</tr>
</tbody>
</table>

2012 Net sales

The vision of P&G is to be, and be recognized as, the best consumer products and services company in the world. In order to achieve this, P&G has the mission is to provide products of superior quality and value that improve the lives of the consumers all over the world.

This project will be performed in cooperation with the department Supply Network Innovation Center (SNIC). SNIC is a multi-skilled team of P&G, based in Brussels, organized under the Research and Development section of the Global Business Unit and Supply Network Operations section of the Market Development Organization. The mission of this department is to inspire and innovate solutions for the Supply Network.
SUPPLY CHAIN
P&G is operating in a consumer driven supply chain with Retailer Distribution Centers (Retailer DCs) as their main clients. The products are delivered to these Retailer DCs by using several distribution methods, which are visualized in Figure 3.

![Figure 3 - Different Distribution Methods Supply Chain P&G](image)

The production facilities of P&G are geographically centralized and specialize in a specific category of products. The vast majority of these produced products are distributed via Regional DCs (RDC) of P&G, to make optimal use of consolidation advantages and to be able to meet the response times of the retailers. These response times vary from 18 up to 72 hours.

Regional DCs are often inventory points that need to respond to demand variation of the orders from the Retailer DCs. Upon customer order, pallets are prepared and delivered to the Retailer DCs by truck. These Retailer DCs are generally served by a single P&G RDC (rarely by two or three P&G RDCs) due to geographical- and product-category reasons.

P&G uses two additional distribution methods besides this previously mentioned flow (via the RDC). Some Retailer DCs order sufficiently large quantities, to be able to send full truck loads directly from a production facility, without going through a Regional DC of P&G. This distribution method is referred to as Direct Delivery in Figure 3. The last method is generally used for more expensive products such as perfumes. These smaller flows are distributed via the parcel and pallet distribution channel of a third party logistics provider.

SUSTAINABILITY TARGETS
As the largest consumer packaged Goods Company in the world, P&G recognizes its responsibility to operate sustainably. With a long-term environmental vision, P&G aims to be the leading global supply chain organization for end-to-end sustainability; from raw material suppliers through finished product logistics (Procter & Gamble, 2012b).

For P&G, sustainability is more than preserving the planet and improving the communities in which we live and work. It is also the way to grow the business, as it fuels innovation and strengthens results. Sustainability is therefore an important way to deliver cost savings.
This commitment is translated in multiple practical sustainability targets for 2020 which are summarized in the P&G Sustainability Report 2012 (Procter & Gamble, 2012b). Two of these targets are related to the research topic of this study, namely:

- Reduce the truck transportation by 20% per unit of production;
- Reduce the Energy Usage and Total CO₂ Emissions by 20% per unit of production.

One of P&G’s most recent sustainable operational innovations is the redesign of the transportation capability to deliver fewer and friendlier miles reducing CO₂ emissions. The European inter-modal transportation program, called TINA “Trains, Inter-modality... a New Approach”, aims to increase the use of rail and inter-modal transportation to 30% by 2015, with no trade-off on service and cost. P&G is one of the pioneers in the consumer goods industry to include inter-modality in its distribution network on such a large scale (European Intermodal Association, 2009).

The total TINA program proved to be feasible to reach 30% modal shift without compromising service and cost between point to point travel connections. This is one of the main reasons to initiate this master thesis project. Other reasons will be described in chapter 3.1.
1.3. REPORT OUTLINE

This report outline uses the logic of the reflective cycle of van Aken et al. (2007). This cycle aims to examine and solve a business problem by following the embedded Regulative Cycle of van Strien (1997). This reflective cycle is visualized in Figure 4.

![Reflective Cycle Diagram]

The generic business problem of the organization where this research is conducted is already mentioned in the general introduction (chapter 1.1). The next chapter (chapter 2) describes relevant scientific knowledge to get a better understanding of the research topic. Afterwards, the regulative cycle of van Strien (1997) starts with defining underlying problems for this business problem (Chapter 3.1). This problem background is followed by a scoping process, in which the research questions (chapter 3.2), methodology (chapter 3.3) and problem scope (chapter 3.4) are defined. The next step is the Analysis phase in Chapter 4, where we get in-depth knowledge of goods flow characteristics in the FMCG industry. Chapter 5 will then design two mathematical models which can be used to answer the research questions. The mathematical models are used by a simulation tool, described in chapter 6, to generate results. These results are given and described in chapter 7. Chapter 8 represents the evaluation phase of the regulative cycle, in which the findings of this project are discussed (chapter 8.1). Finally a reflection is done, in which the limitations (chapter 8.2) and several issues for further research (chapter 8.3) are mentioned.
2. **THEORETICAL BACKGROUND**

*In order to acquire the relevant state-of-the-art scientific knowledge on unimodal and intermodal transportation, we did a literature review. One of the most important findings was the concept of ‘floating stocks’ we mentioned briefly before. We report the main findings in the following subchapter (chapter 2.1) and will describe additional, frequently used articles in the last part of this chapter (chapter 2.2).*

2.1. **FINDINGS LITERATURE REVIEW**

In the past two decades, intermodal transportation emerged as an interesting alternative freight transportation method. Several trends lay at the root of the emergence:

- An increasing recognition of the external effects of transportation, urges organizations to go towards more sustainable freight transportation modes, including as trains and barges (Macharis et al., 2011);
- Increasing traffic congestions on the roads are considered to be a serious problem among the managers of shipping companies (Golob & Regan, 2001), therefore non-road transportation modes have become more and more popular;
- There is an increasing need for consolidating goods to achieve competitive logistics advantages. This leads to an increasing development of hub-and-spoke networks (Caris et al., 2008). These networks provide sufficient volume to make intermodal solutions cost attractive.

Intermodal transportation has its own characteristics compared to unimodal road transportation. These characteristics are qualitatively compared in the literature review (Radstok, 2012) and visualized in Figure 5.

![Figure 5 - Qualitative Comparison of Transportation Modes and Methods](image-url)
On the left side of Figure 5, the transportation attributes of three transportation modes are rated. Road transportation is marked more reliable by shippers, compared to train and barge, despite the increasing traffic congestions. Moreover, road transportation is also considered to be more frequent, faster and more flexible. However, train and barge transportation are considered far more sustainable (Macharis, Caris, et al., 2011) and generally cheaper per km.

The right side of Figure 5 indicates the transportation attributes for the two distribution methods. The ratings for unimodal road transportation and intermodal transportation correspond with the transportation modes. Note that the cost characteristic is not included. It is not possible to make a clear cost indication because the transportation prices of these methods are dependent on the door-to-door distance. The average transportation costs for intermodal transportation decreases more than proportionally, compared to unimodal road transportation, as the door-to-door distance increases (Janic, 2008). The main haulage cost for intermodal transportation modes is namely generally cheaper compared to road transportation. However, the transportation cost of intermodal transportation is also subject to (expensive) drayage costs and transhipment costs.

These transportation attributes can be quantitatively compared by using a total logistics cost perspective (Blauwens et al., 2006). This perspective includes the transportation cost, the cost for holding the inventory in transit and the cost for storing both the cycle and safety stock. From this perspective, it is not possible to determine which transportation method is in general cheaper, since that is very dependent on the situation. Key determinants are hereby the value of the goods and the distance. High value goods will favour a fast transportation method, as slower modes generally lead to additional inventory in-transit and safety stock. The distance affects mainly the transportation prices. Longer distances will generally favour intermodal modes, as the transportation price of intermodal transportation will increase less than proportionally compared to unimodal road transportation.

An interesting concept identified in literature is the concept of floating stocks (Ochtman et al., 2004). This concept exploits the characteristics of unimodal road- and intermodal transportation. It uses a slower transportation mode to ship a fraction of the inventory from the central stock to a terminal in the direction of the customers, before the demand is allocated. When demand arrives, it will be fulfilled from that terminal if sufficient inventory is available. In the case that insufficient inventory is available, direct road transportation is used to fulfil the order with inventory from the central stock.

With this concept, it is theoretically possible to reduce the response times to the customer, reduce the total storage costs, to obtain pooling advantages and to stay flexible towards the customers. However, the increasing in-transit stock might lead to higher cost of capital and will decrease some flexibility in terms of inventory allocation.

The concept of floating stocks can be applied with different distribution methods, each having their own strengths and weaknesses. An interesting observation is that by using this concept, the use of a relatively slow mode does not automatically mean that the lead time increases. However, a major challenge for this policy is the demand volatility of the individual products, especially in the FMCG industry.
2.2. ADDITIONAL LITERATURE

The literature review focused only on scientific articles which were directly related to intermodal transportation. As this focus was considered too specific, additional literature was examined to get a more complete overview of the existing scientific knowledge. Several articles concerning multiple transportation modes and multiple suppliers were studied, of which two are frequently used in this master thesis project. These two articles are briefly introduced and described below.

The first article is written by Janssen & De Kok (1999). This article considers an inventory model with two suppliers. One of the suppliers delivers a fixed quantity, while the other supplier is governed with a replenishment policy. In this article, an algorithm is developed for the determination of the decision parameters S (order-up-to level) and Q (fixed order quantity) such that the long-run expected average costs per time unit are minimized, subject to a service level constraint. The costs are defined as the sum of the holding, purchasing, and ordering costs.

The second frequently used article is from Combes (2011). This article uses inventory theory to design a logistic policy, involving the simultaneous use of two freight transport modes. A heavy mode carries a constant amount of commodities to the retail center each day, while a light mode is used to address the unexpected variations of the destination inventory, using an order-up-to policy. Combes (2011) investigates this mode choice analytically, in order to explain under which circumstances a shipper would use two transport modes for a single commodity flow.
3. **RESEARCH PLAN AND METHODOLOGY**

In this chapter, we will formulate the research questions of this study (chapter 3.2) based on the problem background within the observed organization (Chapter 3.1). After the research questions, we will describe the used research methodology (Chapter 3.3) and the project scope (Chapter 3.4).

3.1. **PROBLEM BACKGROUND**

The underlying reasons (i.e. the set of problems) for initiating this project were derived in a preliminary investigation. Orientating interviews with employees of P&G and several related documents indicated several issues, which are visualized in Figure 6. These issues will be addressed below.

![Figure 6 - Problem Mess](image)

An important first motive concerns the sustainability goals from P&G. As described in chapter 1.2, P&G recognized its responsibility to operate sustainable and puts this into action by formulating several challenging sustainability targets for the next years. Two of these targets relate directly to the trade-off between intermodal and unimodal transportation:

- Reduce truck transportation by 20% per unit of production by 2020;
- Reduce 20% CO₂ and energy per unit of production by 2020.

As intermodal transportation modes prove to require significantly less CO₂ (Macharis, Caris, et al., 2011), it is certainly worth examining when this option is attractive.
Furthermore, academic literature has proven several promising features from the floating stock policy. This policy combines direct road transportation with intermodal transportation in a similar way as the formulated problem definition. Ochtman et al. (2004) demonstrated that this floating stock policy can achieve considerable faster response times (-35%) in contrast to the currently used direct road transportation, through postponing the inventory allocation. The same study indicated that also the storage (-32%) and holding costs (-7%) can be reduced. These achievements have been realized by assuming that all the demand could be aggregated to one ‘unit’, leading to a relatively constant demand. However, this assumption is considered to have a significant impact on the practical usefulness of the research. In the FMCG industry, good flows generally consist of the opposite: many products with a high volatility (Seiler, 2012).

Finally, there are several gaps in the literature concerning this research topic in the context of the FMCG industry. These gaps are in line with the just mentioned shortcomings of the concept of floating stocks. The literature review (Radstok, 2012) indicated that none of the observed articles included multiple products in their models. Furthermore, the high demand volatility, which is common for products in the FMCG industry (Seiler, 2012), is not coped with. Only two articles mentioned some demand volatility. Ochtman et al. (2004) included a volatility with 0.5 as Coefficient of Variation (CV), while Groothedde et al. (2005) visualized an example with an even lower CV.

3.2. RESEARCH QUESTION AND SUB QUESTIONS

The Problem Background (chapter 3.1) described that the floating stock policy might be an interesting alternative to unimodal road transportation in terms of response time, costs and sustainability. However, there seems to be a lack of knowledge about the attractiveness of this policy, when it is applied in the FMCG industry.

This master thesis project will fill these blanks. It will examine the conditions under which a combination of direct road and intermodal freight transportation can be more attractive in terms of costs, compared to unimodal road transportation.

As the service levels (towards customers) should not be negatively affected while examining these distribution methods, the research question is formulated as:

Under which conditions can a combination of road- and intermodal freight for fast moving consumer goods distribution achieve similar or better service and cost levels compared to unimodal road transportation?

The main research question can be split up in several sub questions:

- Is a combination of road and intermodal freight distribution in the FMCG industry an interesting alternative in the current situation, as opposed to unimodal road transportation? If it is;
- To which extend should intermodal distribution be used to obtain the optimal Total Logistics Cost? What is the corresponding saving in terms of the sustainability targets?
• Which main parameters determine the trade-off between these two distribution methods in the FMCG industry?
• What is the sensitivity of these parameters in terms of the optimal Total Logistics Cost?
• What is the sensitivity of these parameters in terms of the used fraction of intermodal transportation?

3.3. METHODOLOGY

In order to answer the research questions, four methods have been used. These methods are visualized in Figure 7 and described below.

First, a data analysis is performed, as it is important to get a thorough understanding of the characteristics and complexities of the FMCG industry. This data analysis will analyse the demand of interesting goods flows.

Next, a representation of a FMCG supply chain is required in which two transportation modes can be used; intermodal transportation and (direct) road transportation. For this purpose, a mathematical model is considered to be exactly what is needed. A mathematical model is “a representation of the essential aspects of an existing system (or a system to be constructed) which presents knowledge of that system in usable form” (Eykhoff, 1974). This model should be able to measure the impact of relevant parameters and variables, on the preferred distribution method and the Total Logistics Cost.

A simulation can then be used to analyse the behaviour of the modelled system (Shannon, 1998), when changing the distribution method or influencing parameters. The main objective of this simulation is to gain structured and quantitative insights. A sensitivity analysis is then performed with the results from the simulation model, to examine the impact of influencing parameters on the Total Logistics Cost and the best possible transportation set-up.

3.4. PROBLEM SCOPE

This research will confine itself to a part of the FMCG supply chain, from the Central Stock location to the Customer DCs. Furthermore, the focus of this master thesis project is on the trade-off between the two distribution methods. Hence, during the modelling and simulating phase, only the influencing factors are examined. Factors which are not affected by the distribution method choice are not taken into account.

The Problem Background (chapter 3.1) mentioned that none of the studied articles in the literature review (Radstok, 2012) included multiple products and products with high demand volatilities in their research. As these characteristics are assumed to represent the FMCG industry, it is considered important to include them in the mathematical model. Adding these characteristics can provide practical usefulness and make a relevant contribution to the academic literature.
4. ANALYSIS FMCG GOODS FLOWS

The goal of this chapter is to get in-depth knowledge of the goods flows in the FMCG industry. Furthermore, this chapter will select goods flows that can be analysed by the models developed in chapter 5.

This chapter will start by describing a FMCG supply chain (Chapter 4.1), after which the characteristics of the used numerical study will be explained (chapter 4.2).

4.1. FMCG SUPPLY CHAIN

The frequently used distribution method makes use of Regional DCs to cope with the generally short order response times of Retailer DCs (Chapter 1.2). A simplistic representation of such a supply chain is visualized in Figure 8. In this representation, the concept Customer Order Decoupling Point (CODP) is introduced, located at the Regional DC. This decoupling point separates the order-driven activities from the forecast-driven activities (Hoekstra et al., 1992). This requires a different approach in the way that the goods flow is planned and controlled.

![Figure 8 - Simplistic Representation FMCG Supply Chain](image)

The case studies performed in the research of Ochtman et al. (2004) and Dekker et al. (2009) concerned the latter part of the supply chain (in the figure from the RDC towards the Customer DCs). However, since the FMCG supplier P&G is fully controlling the upstream segment, it is also considered interesting to include this part of the supply chain in the analysis. Hence it is intended to examine two cases, one in which the two distribution methods are available before the CODP, and one where these are available after the CODP (Figure 9).

![Figure 9 - Two Models to be Analysed](image)
4.2. GOODS FLOWS

When selecting the goods flows for this analysis, we take two prerequisites into account for cost-attractive intermodal transportation set-ups:

- It is concluded in the literature review that intermodal transportation might be an attractive solution in terms of costs, if the door-to-door distance is sufficiently long (Radstok, 2012). The main reason is that the average transportation cost decreases more than proportionally for intermodal transportation, compared to unimodal road transportation, as the door-to-door distance increases (Janic, 2008);
- Economies of scale are also preferred for cost-effective intermodal transportation. Intermodal modes can be beneficial in terms of transportation costs if sufficient volume is distributed (Groothedde et al., 2005).

While taking these prerequisites into account, a meeting is conducted with a senior distribution masterplanner of P&G. The goal of this meeting was to select an interesting goods flow within P&G for these two case studies.

The remaining part of this goods flow analysis is not included in the public version of this master thesis. Instead, the characteristics of the used numerical study will be explained. This numerical study considers 50 products, with a high demand volatility as assumed in chapter 3.1. The demand of the products is assumed to follow gamma distributions with varying demand parameters. The average demand of the products is 13 pallets per day, with a minimum of 5 pallets and a maximum of 20 pallets. The demand volatility is measured with the Coefficient of Variation (CV). The CV of the products varies between 0.75 and 1.12, with an average of 0.9.

The aggregated demand is 665 pallets per day. The demand variation of this volume is (logically) significantly lower, with a CV of 0.35. This strengthens the need to include multiple products in the models, as it contributes to the practical usefulness of this research.
5. **Modelling**

*In this chapter, we design two inventory-theoretic models which can be used to answer the research questions (chapter 3.2). First, a brief description is given concerning the used type of model (chapter 5.1), after which the key elements of the models are explained (Chapter 5.2). Then, before describing and specifying the models (chapter 5.4 and 5.5), several assumptions are clarified (chapter 5.3).*

5.1. **Inventory Theory**

It is assumed in the previous chapter (Chapter 4), that the examined FMCG-goods flows consisted of many products, with much demand variation and individual demand distributions. A suitable method to model these analytically complex phenomena is by using inventory theory. Inventory theory is the sub-specialty within operations research that is concerned with the design of production/inventory systems in order to minimize costs (Arrow, 1958).

The literature review (Chapter 2.1) described that the Total Logistics Cost perspective can be used to quantify the (qualitative) transportation attributes. Therefore, the objective function of the models is to minimize the Total Logistics Costs. It is considered very appropriate, as it implies attention to all costs in the supply chain that are affected by the choice of transport mode (Ballou, 1999). The TLC is considered to have three cost components; the Transportation cost, the Storage cost and the Cost of Capital.

These cost components are inspired by the framework used by Blauwens et al. (2006). These authors used the components transportation costs, cycle stock costs, inventory in-transit cost and the safety-stock cost. The main reason to deviate from this framework, is that the ‘holding cost’-parameter was used to calculate the last three cost components. This ‘holding cost’-parameter represented the opportunity cost of capital tied in stock, inventory service and handling charges, storage space costs and risk related costs (Sheffi et al., 1988). It is considered incorrect that storage costs are charged for inventory which is in-transit. This property affects the models in this master thesis, as intermodal transportation will generally have a longer transit time compared to direct road transportation. Hence, a disproportionate amount of holding costs will be assigned to this slower mode, making this mode less attractive. Therefore, these holding costs are separated into two cost components: the Storage cost and the Cost of Capital. The Storage cost component will represent the storage related costs (cycle stock and safety-stock cost), while the Cost of Capital will represent the interest on the inventory in the supply chain (inventory in-transit cost).

The Transportation cost is determined with the expected number of shipped containers, by the fast and by the slow mode. The utilization of these containers is hereby not taken into account, so a partly filled container is charged similarly as a full container. The Storage cost is logically determined with the expected On-Hand inventory in the storage location(s). Finally, the Cost of Capital is affected by the expected inventory in the pipeline. This implies both the inventory stored in the observed storage location(s) and the inventory In-Transit. This is visualized in Figure 10.
5.2. **Key elements**

**Demand**
The demand analysis of the considered goods flow (chapter 4.2), indicated that the demand for individual products was very volatile and was following gamma distributions. These findings are matching with the studied literature. Vernimmen et al. (2008) described that a gamma distribution has received wide attention in the academic literature for modelling fast moving demand. These authors mentioned several characteristics which make this distribution ideally suited to model period demand. First of all, a gamma distribution can be used for generating non-negative values (contrary to a normal distribution). Furthermore, the gamma distribution can take a wide number of shapes, ranging from an exponential distribution to a (slightly skewed) normal distribution. Finally, a gamma distribution is mathematically (relatively) easy to use.

Therefore, it is preferred to use these data-points exclusively for finding suitable gamma distributions, which can be used for generating the demand in the mathematical models. This implies that this historical data is not used directly for the demand generation.

It is assumed in the mathematical models that the demand of Retailer DCs will occur each replenishment cycle $R$. For the ease of use, this replenishment cycle is considered to be one day in the remainder of this analysis ($R = 1$). Furthermore, the demands for the products are independent and identically distributed (i.i.d.) random variables. Also the demands for different products are assumed independent. Lastly, it is assumed that the occurred demand should be shipped the same day. If there is insufficient demand available, the demand will be backlogged.

Therefore, the base unit of this analysis is considered to be a (full) pallet, while the demand will be rounded to the nearest integer. This implies that stacking of pallets is not allowed for both transportation and storage.

The procedure for generating the demand is given in chapter 6.1.
**ALLOCATION PROCEDURE**

With two transportation modes available for one goods flow, an allocation procedure is needed to split the volume in a clever manner.

Before determining an allocation procedure, the difference between the two distribution methods will be described. It is concluded in the literature review that unimodal road transportation has a significant advantage over intermodal transportation in terms of its transit-time (Woxenius, 2006). This characteristic is used to make a clear distinction. In these models, road transportation will be assumed to be the fast mode, while intermodal transportation will be assumed to be the slow mode. So basically, unimodal road transportation will use only the fast transportation method. While the combination of intermodal- and direct road transportation will use both the fast and the slow mode.

It is assumed that these transportation modes operate in parallel, with a daily frequency \( R \). Besides that, it is assumed that agreements are made with the shipper of the intermodal mode (or slow mode), regarding a constant number of pallets which are shipped on a daily basis. This means in more general terms, that a predetermined quantity will be allocated to the slow mode. This is considered to be a reasonable assumption without losing much practical usefulness. Besides that, this assumption is comparable to the assumptions made by Janssen & De Kok (1999) and Combes (2011).

However, in contrast to these authors, we have to be more specific. Multiple products are examined with different demand characteristics, so we might have to distinguish between products when determining this shipment size of the slow mode. We have to determine for each product, the number of pallets should be allocated to the slow mode; given the predetermined number of available pallet-spots. A logical method is to send the constant demand with the slow mode, while the fast mode will ship the remaining (varying) volume. This method is in line with the application of parallel transportation in the study of Groothedde et al. (2005).

In order to determine which portion of the products is (most) constant, the demand distributions will be analysed. These demand distributions can indicate the probability that the daily demand will be equal or larger than a specified number (let's say \( x \)). An example is given in Figure 11. This probability is considered to be the best method to find the (most) constant demand.

![Probability demand vs Daily demand](image)
When these probabilities are determined for all the products in the goods flow, a greedy algorithm can be used to select iteratively the ‘most’ constant demand. The operation of this algorithm will be explained with an example, supported by Table 2 and Table 3.

**TABLE 2 - EXAMPLE OF PROBABILITIES THAT THE DEMAND IS EQUAL OR LARGER**

<table>
<thead>
<tr>
<th>Demand</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product 1</td>
<td>100%</td>
<td>82%</td>
<td>54%</td>
<td>33%</td>
<td>19%</td>
<td>10%</td>
</tr>
<tr>
<td>Product 2</td>
<td>100%</td>
<td>83%</td>
<td>61%</td>
<td>44%</td>
<td>30%</td>
<td>21%</td>
</tr>
<tr>
<td>Product 3</td>
<td>100%</td>
<td>74%</td>
<td>58%</td>
<td>47%</td>
<td>38%</td>
<td>31%</td>
</tr>
</tbody>
</table>

This example is based on three products with relatively low demand, named Product 1, Product 2 and Product 3. The allocation of pallets is denoted as \( x^i \), indicating the number of allocated pallets for product \( i \). The starting point of this algorithm is by allocating zero pallets to all the products; so \( x^i = \{0,0,0\} \). Each iteration, this procedure will compare the probabilities that the demand (denoted with \( D^i_1 \)) will be increased by an additional pallet; \( P(D^i_1 > x^i + 1) \). So the first iteration of this algorithm will compare the probabilities that the demand of the products is equal or larger than 1. As the probability for product 2 is largest, one (additional) pallet will be allocated: \( x^i = \{0,1,0\} \). The allocations of the following iterations are given in Table 3.

**TABLE 3 - ALLOCATED QUANTITY AFTER ITERATIONS GREEDY ALGORITHM, BASED ON EXAMPLE IN TABLE 2**

<table>
<thead>
<tr>
<th>Iteration</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product 1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Product 2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Product 3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

This algorithm is formally described in chapter 6.1.

**ORDER-UP-TO LEVEL**

As the slow mode will ship the constant demand, the remaining (volatile) demand will be shipped by the fast mode. This is done with a replenishment policy.

Similar to the articles from Janssen & De Kok (1999) and Combes (2011), a basestock policy will be used with the order-up-to level \( S^i \) for product \( i \) and replenishment period \( R \). When the current inventory position of the RDC is below this order-up-to level, a shipment will be sent by the fast mode.

This order-up-to level is directly related to the service level restriction of the model. This service level restriction measures whether there is sufficient on hand inventory to deliver the occurred demand. As the customers should not be negatively affected by the transportation method choice, a service level restriction is defined which will guarantee a certain performance of the models. To be more specific, a quantity-oriented performance measure is used, which describes the proportion of total demand that is delivered directly (so without delay) from the On-Hand inventory. This restriction should be applicable to each product separately.
5.3. ASSUMPTIONS

Several relevant assumptions were made during the design of Model 1 (chapter 5.4) and Model 2 (chapter 5.5). These assumptions are listed and briefly explained below:

- It is assumed that there are no other products in the system, which can affect the order-up-to levels or transportation cost. Additional products will not influence the order-up-to levels, as these are product specific. However, these products might have an impact on the transportation costs when the utilization of the transportation modes is affected;
- The demand characteristics, the distribution-type and its corresponding parameters, are assumed to be known in advance. Furthermore, the demand does not have an upward or downward trend;
- The influence of the day-of-the-week is assumed to be non-existing. This assumption might have impact on the practical usefulness of the managerial insight;
- The product life times are not taken into account, so it is assumed that the demand for the products will continuously be following the predetermined demand distribution;
- It is assumed that the occurred demand should be fulfilled the same day. So the order lead time of the customer demand is equal to or longer than the transportation lead time from the RDC to the customers. If the order lead time is longer, the order is released on the last possible moment.

5.4. MODEL 1

DESCRIPTION

Consider a supply chain with one Central Stock location (CS) and one Regional Distribution Centre (RDC). Customer orders arrive at the RDC each day ($R = 1$). These customer orders (the demand) will be fulfilled directly from the available inventory in the RDC. If insufficient inventory of a product is available, the remaining demand is backlogged. The backlogged demand will be fulfilled when the inventory of the product is replenished. Since waiting for the goods is regarded as a discomfort, a service level restriction will guarantee a specified performance level of the model.

There are two distribution-methods available between the CS and the RDC, a fast mode ($m = 1$) with the deterministic lead time $l_1$ and a slow mode ($m = 2$) with the deterministic lead time $l_2$. These methods work in parallel, with a daily frequency ($R$). An effective heuristic is used to allocate the volume of the products amongst these distribution methods. Similar to Combes (2011) and comparable to Janssen & De Kok (1999), a fixed quantity will be allocated to the slow mode. In practical terms; it is assumed that agreements are made with the shipper of the slow mode, regarding a constant number of Full Container Loads (FCLs) which are distributed by the slow modality on a daily basis.
The problem for the organization in this supply chain is to determine this number of FCLs with the slow modality that should be sent each day, so as to minimize the transport and inventory costs. Note that when the optimal number of FCLs is zero, only the fast transportation mode is used. While, if this optimal number of FCLs is larger than zero, a combination of fast and slow transportation is preferred.

**MODEL SPECIFICATION**

This model will consider a pallet-spot as the base unit as explained in chapter 5.2, so stacking pallets is not possible for both transportation and storage. Furthermore, $I$ products are observed in this model, which are denoted as $i \in \{1, 2, \ldots, I - 1, I\}$. During each time period $t \geq 0$, the Customer DCs order a total of $D_i^t$ pallets of product $i$. The expected value of $D_i^t$ for product $i$ is denoted as $\mu_i$. For each $i$, the random variables $D_i^t$ are independent and identically distributed (i.i.d.) random variables. Demands for different products are assumed independent.

The inventory level in the RDC for product $i$ at time $t$ is denoted as $IL_i^t$. When this inventory level is positive, it represents the amount of on-hand inventory in pallets $(OH_i^t)$. $IL_i^t$ can also be negative, in which case it stands for the amount of backorders $(BO_i^t)$. Note in the following equations that $y^+ = \max\{y, 0\}$.

\[
OH_i^t = (IL_i^t)^+ \tag{1.1}
\]

\[
BO_i^t = (-IL_i^t)^+ \tag{1.2}
\]

The inventory level at the beginning of time period $t + 1$, is the inventory level at time $t$ plus the arrived shipments at time $t$, minus the occurred demand at time $t$ (Equation 1.3). These arrived shipment sizes are represented by the summation $\sum_{m=1}^{2}(s_{m,t-i_m})$, in which $s_{m,t}$ denotes the shipment size of product $i$ by mode $m$, at time $t$. It is assumed that these shipments will arrive early enough in the day, so that they can be used to fulfill the daily demand.

\[
IL_{t+1}^i = IL_t^i + \sum_{m=1}^{2}(s_{m,t-i_m}) - D_i^t \tag{1.3}
\]

The inventory in transit for product $i$ at time $t$ can be denoted as $IT_i^t$ (Equation 1.4):

\[
IT_i^t = \sum_{m=1}^{2}\sum_{j=t-i_m}^{t-1}(s_{m,j}) \tag{1.4}
\]

The shipment size of product $i$ on the slow mode is determined with the allocation procedure which is described in chapter 5.2. This constant shipment size is represented as $x_i$, where $x_i \geq 0$. Note that it is possible to change the constant quantity ($x_i$) into a time-dependent variable, without losing the correctness of the other equations.

\[
s_{2,t}^i = x_i \tag{1.5}
\]

The shipment size of product $i$ at time $t$ with the fast mode $(s_{1,t}^i)$, is determined with an order-up-to policy. So each day, the inventory position ($IP_i^t$) will be compared with the order-up-to level of product $i$ ($S_i^t$). When the inventory position is less than the order-up-to level, a shipment will be sent of size $S_i^t-IP_i^t$ from the CS. This order-up-to level should be sufficiently high to satisfy the service level restriction (Equation 15) of this model. The procedure for finding these order-up-to levels is described in chapter 6.1.
The inventory position is considered to be the inventory On-Hand in the RDC \((IL_t^i)\) plus the inventory In-Transit which will arrive within the lead time of the fast mode \((l_1)\). This inventory In-Transit concerns both the shipments from the fast mode and the slow mode. To be more specific; for the slow mode, it concerns the volume shipped in time \(t - l_2\) up to (and including) time \(t - l_2 + l_1\). While for the fast modality, it concerns the shipments from time \(t - l_1\) up to time \(t - 1\). Note that the shipment of the fast mode in time \(t\) is not included as this shipment size is yet to be determined.

So the equation can be written as:

\[
IP_t^i = IL_t^i + \sum_{j=t-l_1}^{t-1} \left(s_{1,j}^i\right) + \sum_{j=t-l_2}^{t-l_1+l_2} \left(s_{2,j}^i\right) \tag{1.6}
\]

This shipment size is always equal or larger than zero, as it is assumed that only volume is shipped from the CS to the RDC and not the other way around (there is no back haulage). Therefore, the equation for the shipment size of the fast mode can be formulated as:

\[
s_{1,t}^i = \left(S^i - IP_t^i\right)^+ \tag{1.7}
\]

Note that it is assumed that there is always sufficient inventory available in the CS. If this is not the case, a restriction can be included in this equation.

Given the two previous equations (Equation 1.6 and 1.7), the basestock level can also be formulated as:

\[
S^i = IL_t^i + \sum_{j=t-l_1}^{t} \left(s_{1,j}^i\right) + \sum_{j=t-l_2}^{t-l_1+l_2} \left(s_{2,j}^i\right) \tag{1.8}
\]

The used order-up-to level is similar to the standing order policy used by Janssen & De Kok (1999), who calculate the order-up-to level analytically. However, in this study, the order-up-to levels are found by simulation. The main reason is the use of several rounding-functions in the equations, which make the calculations more complex. As mentioned, the used simulation procedure is described in chapter 6.1.

Combes (2011) applied the order-up-to policy differently. Instead of using an order-up-to level, this author used a desired inventory level \((DIL_t^i)\). In this paper, a replenishment decision is made based on the desired inventory level of product \(i\) \((DIL_t^i)\), its current inventory level at the RDC \((IL_t^i)\), the expected demand of product \(i\) for \((l_1 + 1)\) days, while considering the shipments which will arrive beforehand. As the expected demand for product \(i\) might have a non-integer value, it is rounded up to the nearest integer with the expression 
\[
\lceil x \rceil
\]

The shipment size according to Combes (2011) is formulated in the following equation:

\[
s_{1,t}^i = \left(DIL_t^i + \lceil \mu(l_1 + 1) \rceil - \sum_{j=t-l_1}^{t-1} \left(s_{1,j}^i\right) - \sum_{j=t-l_2}^{t-l_1+l_2} \left(s_{2,j}^i\right) - IL_t^i\right)^+ \tag{1.9}
\]

Note that the desired inventory level can be defined in terms of the order-up-to level:

\[
S^i = DIL_t^i + \lceil \mu(l_1 + 1) \rceil \tag{1.10}
\]

This desired inventory level can be used to validate the outcome of the simulation.
The cost function \( C \) for this model is constructed from the perspective of the Total Logistics Cost (described in chapter 5.1). We include three cost components; the Transportation cost \( C_{Tr} \), the Storage cost \( C_S \) and the Cost of Capital \( C_C \). The cost function can therefore be written as:

\[
C = C_{Tr} + C_S + C_C \tag{1.11}
\]

The Transportation cost \( C_{Tr} \) is determined with the number of shipped containers between the CS and the RDC. It is assumed that the containers shipped by both modes carry always the same quantity, denoted with \( Q \). The cost for shipping one container with transportation mode \( m \) is denoted with the parameter \( a_{Tr,m} \). Shipping a container for a specific mode is presumed to be a constant cost, regardless of its utilization. This property is included in the equation with the function \( \lceil \frac{\sum_{i=1}^{l} (s_{m,i})}{Q} \rceil \), which will round the shipped volume on mode \( m \) up to the nearest integer. The Transportation cost can therefore be written as:

\[
C_{Tr} = \frac{1}{T} \sum_{t=1}^{T} \sum_{m=1}^{M} \left( a_{Tr,m} \times \left\lceil \frac{\sum_{i=1}^{l} (s_{m,i})}{Q} \right\rceil \right) \tag{1.12}
\]

The Storage cost \( C_S \) in this model are applicable to the inventory in the RDC. These costs are assumed to be similar for each pallet and are denoted with \( a_S \). The equation is given below:

\[
C_S = \frac{1}{T} \sum_{t=1}^{T} \sum_{i=1}^{l} (a_S \times OH_t^i) \tag{1.13}
\]

Note that it is implicitly assumed that the used transportation method does not influence the volume stored in the Central Stock location.

The last cost component, Cost of Capital \( C_C \), concerns all the goods in the system, both in transit as stored in the RDC. All these goods experience a determined Cost of Capital for each time unit \( t \), dependent on its value. These daily costs are represented as \( a_C^i \) and the equation is given below (Equation 1.14).

\[
C_C = \frac{1}{T} \sum_{t=1}^{T} \sum_{i=1}^{l} \left( a_C^i \times (OH_t^i + IT_t^i) \right) \tag{1.14}
\]

The service level restriction of this model will guarantee a certain performance of this model, as described in chapter 5.2. Each product \( i \) has an individual minimum desired service level, denoted as \( \alpha^i \). The expected service level is determined with the number of occurred backorders \( \left( \sum_{t=1}^{T} (BO_t^i) \right) \) divided by the occurred demand \( \left( \sum_{t=1}^{T} (D_t^i) \right) \).

\[
1 - \frac{\sum_{t=1}^{T} (BO_t^i)}{\sum_{t=1}^{T} (D_t^i)} \geq \alpha^i \text{ for } i \in \{1,2,\ldots,l\} \tag{1.15}
\]

Another restriction guarantees that the fast mode is faster than the slow mode (Equation 1.13). Note that this restriction is also required for a correct Equation 1.6.

\[
l_1 < l_2 \tag{1.16}
\]
5.5. MODEL 2

Model 2 is fundamentally different from Model 1, so these models cannot be compared one-on-one. There are two main differences; First of all, the fast mode is controlled with actual demand instead of expected demand. And secondly, an additional (inventory-) location is included in the model (the Crossdock DC).

DESCRIPTION

Consider a supply chain with one Regional Distribution Centre (RDC) and a Crossdock DC (XDC). Similar to Model 1, there are two distribution-methods available between these locations, a fast mode \((m = 1)\) with the deterministic lead time \(l_1\) and a slow mode \((m = 2)\) with the deterministic lead time \(l_2\). These distribution methods work in parallel, with a daily frequency \((R)\).

A similar heuristic is used to allocate the constant volume of the products to the slow mode, while the irregular demand will be distributed by the fast mode. However, in this model, there is a considerable difference. The slow mode will distribute unallocated demand to the XDC, while the fast mode contains the remaining allocated demand. This concept is similar as the one used by Ochtman et al. (2004).

The daily demand of Retailer DCs arrives at the RDC. From this location, it is first examined which part of the demand is (on-time) available in the XDC. This part of the demand is then ‘allocated’. After which the remaining demand is directly fulfilled by the fast mode (if sufficient inventory is available).

Just like Model 1, an order-up-to level is determined in the RDC, in order to fulfil the service level restriction. If insufficient inventory of a product is available, the remaining demand is backlogged. The backlogged demand can be fulfilled in the following time-units, preferably from the arriving shipments at the XDC, or else from the RDC.

All the demand is shipped through the XDC, where the shipments of both modalities are combined. The XDC will preferably hold no inventory. However, as the demand might follow a volatile distribution (Seiler, 2012), it is possible that the (constant) shipment size of the slow mode will be more than the occurred demand. In these cases, the remaining volume should be stored until it can be allocated to the demand of the following day(s).

Model 2 includes variable transportation prices \((a_{Tr,m,K})\), which are dependent on the distance \((K > 0)\) from the RDC to the XDC.

Again, the problem for the organization in this supply chain is to determine the number of FCLs with the slow modality that should be sent each day, so as to minimize the Total Logistics Cost.
MODEL SPECIFICATION
This model specification will primarily focus the differences between Model 1 and Model 2, to avoid being repetitive.

The first main difference concerns fulfilling the demand. As mentioned, the daily demand arrives at the RDC. From this location, it is examined which part of the demand is (on-time) available in the XDC. Note that this implies the available inventory at time \( t + l_1 \). The inventory that can be fulfilled from the XDC is then allocated. This volume is denoted with \( All_{t+l_1}^i \), indicating the allocated demand for product \( i \) which is fulfilled from the XDC at time \( t + l_2 \).

The equation for this variable takes into account the total volume that should be fulfilled at time \( t \), including the demand (\( D_t^i \)) and the remaining backorders (\( BO_t^i \)). Besides that, this equation will also check the available on-hand inventory (\( OH_{XDC,t+l_1}^i \)) and the arriving shipment (\( s_{2,t+l_1-l_2}^i \)) in the XDC, since it is presumed not possible to allocate more than the available inventory. The equation for the allocated demand in the XDC is therefore:

\[
All_{t+l_1}^i = M \min \left( OH_{XDC,t+l_1}^i + s_{2,t+l_1-l_2}^i, D_t^i + BO_t^i \right)
\] (2.1)

When this allocated demand is defined, it is possible to determine the On-Hand inventory in the XDC:

\[
OH_{XDC,t+1}^i = OH_{XDC,t}^i + s_{2,t-l_2}^i - All_t^i
\] (2.2)

Also, knowing the allocated demand in the XDC makes it possible to determine the inventory level in the RDC. For convenience in the explanation, the inventory level in the beginning of time \( t \) (\( II_t^i \)) is constructed from the On-Hand inventory in the RDC (\( OH_{RDC,t}^i \)) and the Backorders (\( BO_t^i \)):

\[
II_t^i = OH_{RDC,t}^i - BO_t^i
\] (2.3)

The On-Hand inventory in the RDC for the next day (\( OH_{RDC,t+1}^i \)) is determined with the current On-Hand inventory (\( OH_{RDC,t}^i \)), the arrived shipments (\( s_{0,t-l_0}^i \)) and the departed shipments (\( s_{1,t}^i \& s_{2,t}^i \)):

\[
OH_{RDC,t+1}^i = OH_{RDC,t}^i + s_{0,t-l_0}^i - s_{1,t}^i - s_{2,t}^i
\] (2.4)

The backordered inventory for the next day (\( BO_{t+1}^i \)) is determined with the current backorders (\( BO_t^i \)), the remaining demand for the RDC (\( D_t^i - All_{t+l_1}^i \)) minus the fulfilled volume by the RDC (\( s_{1,t}^i \)).

\[
BO_{t+1}^i = BO_t^i + D_t^i - All_{t+l_1}^i - s_{1,t}^i
\] (2.5)
Knowing these equations, it is possible to formulate the equation of the inventory level in the RDC (\( IL_t^i \)):

\[
\begin{align*}
IL_t^i &= OH_{RDC,t}^i - BO_t^i \\
IL_t^i &= (OH_{RDC,t-1}^i + s_{0,t-1}^i - s_{1,t-1}^i - s_{2,t}^i) - (D_{t-1}^i + BO_{t-1}^i - All_{t+1}^i - s_{1,t-1}^i) \\
IL_t^i &= IL_{t-1}^i + s_{0,t-1}^i - s_{2,t}^i - D_{t-1}^i + All_{t+1}^i
\end{align*}
\]

Hence

\[
IL_{t+1}^i = IL_t^i + s_{0,t}^i - s_{2,t}^i - D_t^i + All_{t+1}^i
\] \hspace{1cm} (2.6)

This equation (Equation 2.6) expresses the iterative inventory level, which is composed of the shipment volumes of the supplying mode \((s_{0,t}^i)\), the slow mode \((s_{2,t}^i)\) and the remaining demand for the RDC \((D_t^i - All_{t+1}^i)\). As the shipment volumes of the supplying- and the slow mode are assumed to be strictly positive, backorders are determined based on the ability to fulfill \(D_t^i - All_{t+1}^i\) from the current On-Hand inventory by the fast mode. This is in line with Equation 2.5. Note that the shipments of this fast mode are not included in the equation or in its variables.

Model 2 does also have some different equations for the shipment volumes. It is assumed that the RDC is replenished from the CS locations by a single transportation mode \((m = 0)\). This supplying transportation mode is not within the perspective of this model, but is required for determining the order-up-to level \(S^i\) in the RDC. In order to reduce the complexity of the model, it is presumed possible to make three simplifying assumptions:

- A product is only delivered by one CS location;
- All supplying CS locations have a similar delivery lead time;
- There is always sufficient inventory available in the CS locations.

With these assumptions, it is possible to determine the shipment size of the supplying mode with almost similar equations compared to Model 1. The inventory position of the RDC is formulated in Equation 2.7, after which the shipment size is formulated in two different equations; 2.8 & 2.9. The second shipment size equation uses the desired inventory level \((DIL^i)\), which can be related to the order-up-to level \((S^i)\), see equation 2.10.

\[
\begin{align*}
IP_t^i &= IL_t^i + \sum_{j=t-1}^{t-1} s_{0,j}^i \\
S_{0,t}^i &= (S^i - IP_t^i)^+ \hspace{1cm} (2.7)
\end{align*}
\]

\[
\begin{align*}
s_{0,t}^i &= (DIP^i + Round(\mu(l_0 + 1) - \sum_{j=t-1}^{t-1} s_{0,j}^i - IL_{1,t}^i))^+ \hspace{1cm} (2.8)
\end{align*}
\]

\[
\begin{align*}
S^i &= DIL^i + \left\lfloor \mu(l_0 + 1) \right\rfloor \hspace{1cm} (2.9)
\end{align*}
\]
The fast mode should ship all the remaining demand at the RDC \((D^i_t + BO^i_t - All^{i,t}_{t+t_1})\). However, it is dependent on the available inventory, consisting of the On-Hand inventory in the RDC \((OH^i_{RDC,t})\) plus the arrived shipment from the CS \((s^i_{0,t-t_0})\) minus the constant shipped quantity by the slow mode \((s^i_{2})\). Hence:

\[
s^i_{1,t} = \left(\text{Min}(D^i_t + BO^i_t - All^{i,t}_{t+t_1}, OH^i_{RDC,t}, s^i_{0,t-t_0} - s^i_{2})\right)^+
\]  

(2.11)

The shipment size of the slow mode \((s^i_{2})\), is determined with the same procedure as in Model 1. This procedure is described in chapter 6.1.

\[
s^i_{2,t} = x^i
\]  

(2.12)

It is assumed in Equation 2.11 and Equation 2.12 that the shipment size of the slow mode is constant and secured, regardless the available inventory. Note that in the unlikely occasion when \(OH^i_{RDC,t} + s^i_{0,t-t_0} < s^i_{2,t}\), a backorder will arise of (at least) the size \(s^i_{2,t} - \left(OH^i_{RDC,t} + s^i_{0,t-t_0}\right)\).

The equations for the inventory In-Transit (\(IT^i_t\)) and the cost function (\(C\), are similar to Model 1:

\[
IT^i_t = \sum_{m=1}^{2} \sum_{j=t-t_m}^{t-1} (s^i_{m,j})
\]  

(2.13)

\[
C = C_{TR} + C_S + C_C
\]  

(2.14)

It is assumed in the cost function that the handling costs in the XDC are not affected by the modal choice. This is only possible if all the volume is shipped through the XDC.

In this model, the Transportation cost is dependent on the distance \(K\). These transportation costs \((a_{TR,m,K})\) are assumed to follow a simple linear function with an intercept \((int_m)\) and a slope \((sl_m)\) for mode \(m\) (Equation 2.15). Besides that, the transportation cost for supplying the goods from the CS to the RDC are considered constant and can therefore be omitted.

\[
a_{TR,m,K} = int_m + (K \times sl_m)
\]  

(2.15)

\[
C_{TR} = \frac{1}{T} \Sigma_{t=1}^{T} \sum_{m=1}^{2} \left( a_{TR,m,K} \times \left[ \frac{\Sigma_{i=1}^{t}(s^i_{i,t})}{q} \right] \right)
\]  

(2.16)

The equations for the Storage cost (\(C_S\)) and the Cost of Capital (\(C_C\)) are almost similar to the ones in Model 1. The only differences are the introduction of the On-Hand inventory in the XDC \((OH^i_{2,t})\) and the more specific storage cost parameters.

\[
C_S = \frac{1}{T} \Sigma_{t=1}^{T} \Sigma_{i=1}^{t} \left( a_{S,RDC} \times OH^i_{RDC,t} + a_{XDC,t} \times OH^i_{XDC,t} \right)
\]  

(2.17)

\[
C_C = \frac{1}{T} \Sigma_{t=1}^{T} \Sigma_{i=1}^{t} \left( a^i_t \times \left(OH^i_{RDC,t} + OH^i_{XDC,t} + IT^i_t\right) \right)
\]  

(2.18)
The first two restrictions of Model 2 are similar to Model 1. There is however an additional restriction introduced. The storage cost per pallet in the XDC should be equal or more expensive than the storage cost per pallet in the RDC, since it is preferred to fulfil the backorders from the XDC. When the storage cost in the RDC is cheaper, the used equations might lead to a suboptimal outcome.

\[ 1 - \frac{\sum_{t=1}^{T} (b_{i,t})}{\sum_{t=1}^{T} (\rho_{i,t})} \geq \alpha^i \text{ for } i \in \{1,2, ..., l\} \]  
\[ l_1 < l_2 \]  
\[ a_{S,RDC} \leq a_{S,XDC} \]
6. SIMULATION

In this chapter, we will first describe the simulation procedures which are needed in addition to the mathematical models (chapter 6.1). Then, we describe briefly the used simulation program (chapter 6.2) and the chosen values for the input parameters (chapter 6.3). Finally, the output of the simulation model is verified in chapter 6.4.

6.1. SIMULATION PROCEDURES

In addition to the mathematical equations in chapter 5, several procedures are needed to simulate the model. The first procedures will generate the demand ($D^i_t$) and determine the shipment size of the slow mode ($x^i$). After which the procedures are given for performing the simulation runs of the models.

DEMAND GENERATION

The demand for product $i$ at each time-unit $t$ ($D^i_t$) is assumed to follow a gamma distribution (chapter 5.2), of which the demand parameters ($\text{Alpha}^i$ & $\text{Beta}^i$) are assumed to be known in advance. The following procedure uses these parameters to determine the mean and to generate the demand.

Three functions are introduced for this procedure:

- $\text{GammaInv}(v, \text{Alpha}^i, \text{Beta}^i)$, this function returns the inverse of the gamma cumulative distribution, with the parameters $v$, $\text{Alpha}^i$ and $\text{Beta}^i$. The parameter $v$ represents a probability, with $0 > v > 1$;
- $\text{Random}()$, this function generates a random value between 0 and 1;
- $\lfloor y + 0.5 \rfloor$, this function rounds the value $y$ to the nearest integer;

Procedure Demand_Generation

01 For $i = 1$ to $l$ do
02  $\mu^i = \text{Alpha}^i \times \text{Beta}^i$;
03 For $t = 1$ to $T$ do
04  $D^i_t = \lfloor \text{GammaInv(} \text{Random}(), \text{Alpha}^i, \text{Beta}^i) + 0.5 \rfloor$;
05 End for;
06 End for;

Note that the demand for product $i$ at time $t$, is rounded to the nearest integer, since full pallets are considered to be the base-unit in this model.

SHIEMENT SIZE

The shipment size on the slow mode is determined with a greedy procedure as described in chapter 5.2. This procedure will allocate pallets to the slow mode until a predetermined number of pallets is reached. Basically, the ‘most constant’ demand will be allocated. The main decision variable is the probability that the demand of product $i$, is larger than $x^i$ pallets; $P(D^i_t > x^i)$. These probabilities are found with the function $\text{GamCDF}$, in the procedure Demand_Probabilities. The procedure Volume_Slow_mode measures and compares this probability for each product $i$, in the case that 1 additional pallet will be sent; $P(D^i_t > x^i + 1)$. 

- 27 -
For the first procedure: Demand_Probabilities, a new index is introduced; the demand size \( ds \in \{1, 2, ..., dsMax\} \). The variable \( dsMax \) indicates the maximum possible demand for all products, to be shipped by the slow mode. This variable is introduced to find the maximum matrix length of the matrix \( DemProb(ds, i) \). This maximum length can be determined, by presuming that it is inconvenient to send more volume of product \( i \) with the slow modality, than its corresponding mean. Hence, \( dsMax \) is the maximum mean of all the products.

The matrix \( DemProb(ds, i) \) will indicate the probability that the demand of product \( i \) is equal or larger than \( ds \). As explained, this matrix will be used in the procedure Volume_Slow_mode. In order to determine the values in this matrix, two new functions are introduced:

- \( \text{GamCDF}(ds, \text{Alpha}^i, \text{Beta}^i) \), this function returns the cumulative probability function of a gamma distribution for the demand \( ds \) with the parameters \( \text{Alpha}^i \) and \( \text{Beta}^i \);
- \( \lfloor y \rfloor \), this function will round the value \( y \) down to the nearest integer.

Procedure Demand_Probabilities

```plaintext
01 \( dsMax = 0 \);
02 \textbf{For} i = 1 to iMax \textbf{do}
03 \quad \textbf{If} \lfloor \mu^i \rfloor < dsMax \textbf{do}
04 \quad \quad \lfloor \mu^i \rfloor = dsMax;
05 \quad \textbf{End if};
06 \textbf{End for};
07 \textbf{For} i = 1 to iMax \textbf{do}
08 \quad \textbf{For} ds = 1 to dsMax \textbf{do}
09 \quad \quad DemProb(ds, i) = 1 - \text{GamCDF}(ds, \text{Alpha}^i, \text{Beta}^i);
10 \quad \textbf{End for};
11 \textbf{End for};
```

After determining the matrix \( DemProb(ds, i) \), we can allocate the predetermined number of pallets \( pMax \) to the slow mode. These pallets are indicated by the index \( p \in \{1, 2, ..., pMax\} \). The allocation is done with a greedy algorithm, which selects iteratively the optimal \( P(D^i_p > x^i + 1) \) for a product. The corresponding product is indicated by the variable \( i^* \).
Procedure Volume_Slow_mode

01 For $i = 1$ to $I$ do
02 $x^i = 0$;
03 End for;
04 For $p = 1$ to $pMax$ do
05 $i^* = 0$;
06 For $i = 1$ to $I$ do
07 If $DemProb(x^i + 1, i) > DemProb(x^{i^*} + 1, i^*)$ and $(x^i + 1) < \mu^i$ do
08 $i^* = i$;
09 End if;
10 End for;
11 $x^{i^*} = x^{i^*} + 1$
12 End for;

Note that it is not possible to allocate more pallets of product $i$ to the slow mode, than the corresponding mean $\mu^i$. Note also that this procedure will become invalid if $pMax > \sum_{i=1}^I |\mu^i|$. In that case, the maximum allowed number of allocated pallets is exceeded.

SIMULATION RUN

Two variables are still to be determined for finding the minimal Total Logistics Cost for each simulation run:

- $pMax$, the number of pallets to be shipped by the slow mode;
- $S^i$, the order-up-to level of product $i$ in the RDC.

The characteristics of the relationships between these two parameters ($pMax$ and $S^i$) and the cost function ($C$) will be examined below. These characteristics can then be used to make an efficient simulation run for finding the optimal TLC without loss of generality.

The relationship between the shipment size of the slow mode ($pMax$) and the objective function ($C$) is difficult to estimate and describe, because of several influencing variables. The main influencers are the lead times, the transportation prices, the demand variation and the utilization of both transport modes. A complete enumeration analysis (with the default settings) is performed to visualize this complex relationship (Figure 14).

![Figure 14 - Relationship between PMAX and Total Logistics Cost](image-url)
The shipment size of the slow mode proves to have a periodic relation with the objective function, with the length $Q$ (in this case 26). Looking more closely will verify that local optima exist for each full container. This is logical in the case that the transportation cost is accountable for a significant share of the total logistics cost, as it is non-optimal to send partly filled container loads with the slow mode. It can therefore be accepted that (without loss of generality) the parameter $p_{Max}$ can be set to multitudes of $Q$ to find the optimal TLC.

The order-up-to levels ($S^i$) in the RDC have a clear positive relation with the Total Logistics Cost. In other words; when $S^i$ increases, the total logistics cost will increase. This is logical as increasing the order-up-to level, will increase the On-Hand stock in the RDC, leading to additional Storage cost ($C_S$) and Cost of Capital ($C_C$). So from the perspective of the objective function, $S^i$ should be kept as low as possible. Yet $S^i$ has a significant impact on the service level restrictions of the models (Equation 1.15 and 2.19), since the order-up-to level of product $i$ should be high enough to meet the required minimal service level ($\alpha^i$). This relationship is visualized in Figure 15 for a random product.

An interesting characteristic of these models is that changing the order-up-to levels $S^i$ will not influence the shipment quantity of the fast mode (or in Model 2 the supplying mode). The reason is that the Inventory Position ($IP^i$) is levelled with the order-up-to level ($S^i$), each time period. So basically, the replenishment decision is based on the changes which occur in the Inventory Level of the RDC ($IL^i$). This characteristic is also observed by Janssen & De Kok (1999). It is used to make the simulation more efficient.

Based on the inventory levels ($IL^i$), is it possible to determine the minimal required order-up-to levels ($S^i$) for fulfilling the service restrictions with a bi-section algorithm. This is a robust algorithm which can find these optimal levels by repeatedly bisecting an interval and selecting the relevant subinterval. When this algorithm is applied to the example in Figure 15, only 9 iterations are needed to find the optimal order-up-to level.

For both models, the objective of the simulation is similar; to find the optimal order-up-to levels ($S^i$) for a range of predetermined number of (full) container loads, denoted as $FCL \in \{0,1,...,FCL_{Max}\}$. After finding these order-up-to levels, it is possible to find the corresponding Total Logistics Costs ($C$). The minimal Total Logistics Cost will then indicate the optimal $FCL$. 

![FIGURE 15 - RELATIONSHIP BETWEEN ORDER-UP-TO LEVEL AND TOTAL LOGISTICS COST FOR A RANDOM PRODUCT](image-url)
The maximal allowed number of container loads \( (FCLMax) \) is dependent on the mean \( (\mu_i) \) of the Products, as explained in the paragraph Shipment Size. This is the case because it is assumed that stacking pallets is not allowed. Hence, this maximum can be found with the Equation 3.1. Note that the function \( \lfloor y \rfloor \) rounds the value \( y \) down to the nearest integer.

\[
FCLMax = \frac{\sum_{i=1}^{l} (\lfloor \mu_i \rfloor)}{q} \quad (3.1)
\]

The output variables of the simulation runs can be determined by studying the cost functions of the models. For Model 1, the cost equations can be turned into Equation 3.2. For Model 2, the cost equations can be turned into Equation 3.3.

Model 1:

\[
C = \frac{1}{T} \sum_{t=1}^{T} \left( \sum_{m=1}^{2} \left( a_{TR,m} \times \frac{\sum_{i=1}^{l} (s_{m,t})}{q} \right) + \sum_{i=1}^{l} \left( OH_i^t \times (a_S + a_C^i + IT_i^t \times a_c^i) \right) \right) \quad (3.2)
\]

Model 2:

\[
C = \frac{1}{T} \sum_{t=1}^{T} \left( \sum_{m=1}^{2} \left( a_{TR,m,K} \times \frac{\sum_{i=1}^{l} (s_{m,t})}{q} \right) + \sum_{i=1}^{l} \left( OH_{RDC,t}^i \times (a_C^i + a_{S,RDC}) + OH_{XDC,t}^i \times (a_C^i + a_{S,XDC}) + IT_i^t \times a_c^i \right) \right) \quad (3.3)
\]

Since many parameters in the equations 3.2 and 3.3 are fixed, only several variables are needed to find the TLC \( (C) \) and the optimal number of container loads for the slow mode \( (FCL) \). These variables are: the shipment sizes of the fast \( (s_{1,t}) \) and the slow mode \( (s_{2,t}) \), the On-Hand inventory levels \( (OH_{RDC,t}^i \text{ and } OH_{XDC,t}^i) \) and the inventory In-Transit \( (IT_i^t) \).

After determining these output variables, we can describe the simulation procedure. In order to do so, several variables are introduced for performing the simulation runs:

- \( \tilde{a}^t \), the service level of the model for product \( i \);
- \( SMin^t \), the (temporary) lower bound for finding the order-up-to level \( s^t \);
- \( SMax^t \), the (temporary) upper bound for finding the order-up-to level \( s^t \);
- \( TotBO^i \), The total number of occurred Backorders for product \( i \);
- \( TotDem^i \), The total number of occurred demand of product \( i \);

The simulation procedure is visualized in Figure 16 as a process diagram. This simulation procedure is elaborated in two more formal procedures in Appendix 3 - Simulation Procedures.
After loading the predetermined parameters, it is possible to use the procedures Demand_Generation and Demand_Probabilities to find $D_i^1$ and $DemProb(d, i)$. Then, for each possible number of containers on the slow mode ($FCL \in \{0,1, \ldots, FCLMax\}$), a loop is used to find the optimal order-up-to levels for the products ($S^i$). The optimal order-up-to levels are found with a bi-section algorithm, using the upper and lower bounds $SM_{ax}^i$ and $SM_{in}^i$ respectively. The initial values for these bounds are determined by increasing the order-up-to level with $\lceil \mu^i + 0.5 \rceil$, until the required performance level is exceeded. When the order-up-to level ($S^i$) equals the upper-bound ($SM_{ax}^i$), the bi-section procedure is stopped and the optimal order-up-to level is stored. After finding the order-up-to levels of all the products, the output variables can be determined and stored. Then, this procedure can be repeated for the remaining values of the Full Container Loads ($FCL$).

The saved output variables are used to determine the Total Logistics Cost for each possible number of allocated containers to the slow mode (Equations 3.2 and 3.3). The number of allocated containers with the smallest Total Logistics Cost is considered to be the ‘optimal’ number.

The procedure Find_Performance is called in the simulation procedure, to find the performance $\hat{\alpha}^i$ given an order-up-to level $S^i$. This procedure divides the total number of backorders for product $i$ ($TotBO_i^1$) by the total occurred demand ($TotDem_i^1$), similar to the service restrictions of the models (Equations 1.15 and 2.19). Note that the product $i$ is already known when this procedure is called.
Procedure Find_Performance
01    \( \text{TotBO}_i = 0; \)
02    \( \text{TotDem}_i = 0; \)
03    \( \text{For } t = 1 \text{ to } T \text{ do} \)
04    \( \text{TotBO}^i = \text{TotBO}^i + BO^i_t; \)
05    \( \text{TotDem}^i = \text{TotDem}^i + D^i_t; \)
06    \( \text{End for;} \)
07    \( \hat{a}^i = \frac{\text{TotBO}^i}{\text{TotDem}^i} \)

6.2. SIMULATION PROGRAM

The mathematical models (chapter 5) and the corresponding procedures (chapter 6.1) are elaborated in the program Visual Basic for Applications (VBA) from Microsoft. This program is used as it is capable of simulating the two models efficiently. Moreover, VBA is easy to learn and widely available and is therefore very accessible to make adjustments (Plant & Murrell, 2007). Finally, this program can use Microsoft Excel for both loading the input parameters, as storing the output of the simulation.

6.3. INPUT PARAMETERS

Several parameters have to be decided upon, before it is possible to start simulating. In order to answer the research questions, the parameters are based upon the characteristics and costs of direct road transportation (for the fast mode) and intermodal transportation (for the slow mode). These parameters are listed in Table 4 and will be briefly explained further below.

**TABLE 4 - INPUT PARAMETERS MODELS**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Model 1</th>
<th>Model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha^i ) - Minimum allowed service level</td>
<td>99%</td>
<td>99%</td>
</tr>
<tr>
<td>( l_0 ) - Fixed lead time of supplying mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( l_1 ) - Fixed lead time of fast mode</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>( l_2 ) - Fixed lead time of slow mode</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>( Q ) - Max. number of pallets per container</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>( FCL_{Max} ) - Max. allowed FCLs on slow modality</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>( a_{Tr,1} ) - Transportation cost fast mode</td>
<td>€1000</td>
<td>Eq. 2.12</td>
</tr>
<tr>
<td>( a_{Tr,2} ) - Transportation cost slow mode</td>
<td>€900</td>
<td>Eq. 2.12</td>
</tr>
<tr>
<td>( a_c ) - Cost of Capital per pallet</td>
<td>€1.00</td>
<td>€1.00</td>
</tr>
<tr>
<td>( a_s / a_{s,RDC} ) - Storage cost per pallet at RDC</td>
<td>€1.00</td>
<td>€1.00</td>
</tr>
<tr>
<td>( a_{s,XDC} ) - Storage cost per pallet at XDC</td>
<td>€2.50</td>
<td></td>
</tr>
<tr>
<td>( K ) - Distance between RDC and XDC (km)</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>( int_1 ) - Intercept of transp. cost fast mode</td>
<td>€0</td>
<td></td>
</tr>
<tr>
<td>( sl_1 ) - Slope of transp. cost fast mode</td>
<td>€1.00</td>
<td></td>
</tr>
<tr>
<td>( int_2 ) - Intercept of transp. cost slow mode</td>
<td>€150</td>
<td></td>
</tr>
<tr>
<td>( sl_2 ) - Slope of transp. cost slow mode</td>
<td>€0.65</td>
<td></td>
</tr>
</tbody>
</table>
The service restriction of the models will use the ‘minimum allowed service level’ $\alpha^i$ of 99% for each product. This indicates that minimal 99% of the demand of product $i$ should be directly delivered from the On-Hand stock.

The lead time to get from the CS to the RDC in Model 1, is assumed to be 2 days for the fast mode ($l_1$) and 4 days for the slow mode ($l_2$). For Model 2, this part is referred to as the supplying mode ($l_0$), which is set to 1 day. The determined lead times from the RDC to the XDC are 2 days for the fast mode and 4 days for the slow mode.

For Model 1, the transportation cost for shipping one container from the CS to the RDC is assumed to be €1000 for the fast mode ($a_{TR,1}$), while intermodal transportation is assumed to be cheaper with a transportation cost of €900 ($a_{TR,2}$).

The storage cost of the RDC ($a_S / a_{S,RDC}$) are €1.00 per pallet per day. For Model 2, the storage cost in the Crossdock DC ($a_{S,XDC}$) is assumed to be significantly more expensive as the RDC; €2.50 per pallet per day.

The cost of capital per pallet can be determined by estimating the Weighted Average Cost Of Capital (WACC). This cost is assumed to be similar for all products in a model. In both models, these costs are estimated to be €1.00 per pallet per day.

The last parameters of Table 4 concern the intercepts and slopes of the transportation cost formulas for both modes (Equation 2.15). The fast mode is presumed to operate without fixed cost ($int_1 = 0$) and is relatively expensive per km ($SL_1 = €1$). While the slow mode is assumed to have a higher fixed cost ($int_2 = 150$) and is cheaper per km ($SL_2 = €0.65$). Note that the fixed cost for the slow mode represents in this case the pre- and end-haulage of intermodal transportation and the transhipments. These values are deducted from an online search for similar practical case studies.

The parameters of the used demand-distributions of the products are listed in 'Appendix 4 - Demand distributions simulation models'.
The shipped volumes in the simulations are on average 20.1 FCLs for both models, while assuming that a container can ship 33 pallets ($Q$). With the known demand characteristics it is possible to determine the $FCL_{\text{Max}}$ (Equation 3.1), the maximal allowed FCLs on the slow mode. This maximum is 19 FCLs for both models.

A simulation length of 50,050 time-units ($T$) was considered more than sufficient, as the variations of the output-variables were almost neglectable ($<0.001$). The first 50 time-units of the simulation length were not included in the analysis, as this period was considered the warming-up period.

6.4. Verification
This subchapter will verify two important output variables from the simulations, to be sure that the model is working properly.

**In-Transit Inventory**
The expected In-Transit inventory level from the simulation, can be verified with the following equation:

$$\frac{1}{T} \sum_{t=1}^{T} \sum_{i=1}^{I} (\text{IT}_i^t) = l_1 \times (\sum_{i=1}^{I} (\mu^i) - FCL \times Q) + (l_2 \times FCL \times Q)$$ (4.1)

The expected In-Transit inventory in the slow mode can be found easily, as the number of allocated pallets to the slow mode ($FCL \times Q$) times the lead time ($l_2$). The remaining demand ($\sum_{i=1}^{I} (\mu^i) - FCL \times Q$) is delivered with the fast mode, with the lead time $l_1$.

This equation proved to be valid for the output of the simulation, with a very small standard deviation ($< 0.001$).

**Order-Up-To Levels**
It is difficult to find a method to verify (precisely) whether the order-up-to levels of the simulation are correct, since none of the observed articles has a similar allocation procedure. However, it is important to verify these order-up-to levels, as they are a key element of the models. Hence, a relatively rough verification method is used.

The stand-alone tool ChainScope is used, which can generate the control parameters for complex operational planning systems (de Kok, 2008). This tool can find the expected On-Hand inventory assuming a normal distribution; which is roughly similar to the expected Desired Inventory Levels ($DIL$). Note that the Desired Inventory Levels can be denoted as the order-up-to levels with the Equations 1.10 and 2.10.
The following assumptions are made:

- The ‘Allocated stock’ in ChainScope represents the desired inventory level ($DIL$), as used in the models;
- All the volume is shipped by the fast mode, since it is not possible to verify the On-Hand inventory when the slow mode is used (assuming a volatile demand). The reason is that the shipment size of the slow mode can then exceed the occurred demand of a product, which might lead to more On-Hand inventory than the ‘normal’ variation around the desired inventory level;

The Desired Inventory Levels of the simulation proved to be almost similar as the allocated stock in the tool ChainScope, for both models.
7. RESULTS

The results of the simulations will be visualized and described in this chapter.

7.1. MODEL 1

GENERAL RESULTS

For the goods flow between the CS and the RDC, it proved to be attractive to use a combination of fast and slow transportation. The minimal TLC was found when 12 FCLs were send by the slow mode, which is 62% of the observed volume. This is visualized in Figure 18 and the corresponding Table 5.

![Graph showing the total logistics cost as a function of the FCLs allocated to the slow mode (Model 1)](image)

**FIGURE 18 - TOTAL LOGISTICS COST AS A FUNCTION OF THE FCLS ALLOCATED TO THE SLOW MODE (MODEL 1)**

**TABLE 5 - CORRESPONDING VALUES FOR COST-COMPONENTS, ILLUSTRATED IN FIGURE 18 (VALUES × €1000).**

<table>
<thead>
<tr>
<th>FCL</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>% vol.</td>
<td>0%</td>
<td>5%</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>25%</td>
<td>30%</td>
<td>34%</td>
<td>39%</td>
<td>44%</td>
<td>49%</td>
<td>54%</td>
<td>59%</td>
<td>64%</td>
<td>69%</td>
<td>74%</td>
<td>79%</td>
<td>84%</td>
<td>89%</td>
<td>94%</td>
<td>0%</td>
</tr>
<tr>
<td>$C_g$</td>
<td>3,1</td>
<td>3,1</td>
<td>3,1</td>
<td>3,1</td>
<td>3,1</td>
<td>3,1</td>
<td>3,2</td>
<td>3,2</td>
<td>3,2</td>
<td>3,2</td>
<td>3,3</td>
<td>3,3</td>
<td>3,4</td>
<td>3,4</td>
<td>3,5</td>
<td>3,8</td>
<td>4,6</td>
<td>9,5</td>
<td>3,1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_c$</td>
<td>4,5</td>
<td>4,5</td>
<td>4,5</td>
<td>4,6</td>
<td>4,6</td>
<td>4,7</td>
<td>4,7</td>
<td>4,7</td>
<td>4,8</td>
<td>4,8</td>
<td>4,9</td>
<td>4,9</td>
<td>5,0</td>
<td>5,0</td>
<td>5,1</td>
<td>5,1</td>
<td>5,3</td>
<td>5,4</td>
<td>5,8</td>
<td>6,6</td>
<td>12</td>
</tr>
<tr>
<td>$C_{tr,2}$</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$C_{tr,1}$</td>
<td>21</td>
<td>20</td>
<td>19</td>
<td>18</td>
<td>17</td>
<td>16</td>
<td>15</td>
<td>14</td>
<td>13</td>
<td>12</td>
<td>11</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>21</td>
</tr>
<tr>
<td>TLC</td>
<td>28,3</td>
<td>28,2</td>
<td>28,1</td>
<td>28,1</td>
<td>28,0</td>
<td>28,0</td>
<td>27,9</td>
<td>27,8</td>
<td>27,7</td>
<td>27,7</td>
<td>27,7</td>
<td>27,6</td>
<td>27,6</td>
<td>27,6</td>
<td>27,6</td>
<td>27,6</td>
<td>27,6</td>
<td>27,8</td>
<td>28,0</td>
<td>28,5</td>
<td>30,1</td>
</tr>
</tbody>
</table>

It can be observed that the Total Logistics Cost is a sum of four cost components; the transportation cost for the fast mode (denoted as $C_{tr,1}$), -for the slow mode (denoted as $C_{tr,2}$), the cost of capital ($C_c$) and the storage cost ($C_g$). The two transportation cost components represent the majority of the TLC (70%). Obviously, the transportation cost for the fast mode reduces when more FCLs are allocated to the slow mode, while the transportation cost for the slow mode increases. It is also obvious that the Cost of Capital increases, as the lead time of the slow mode is longer.

The behaviour of the storage cost in the RDC is more interesting. These storage costs remain almost similar when 0 to 10 FCLs are allocated to the slow mode, after which the storage cost increases (seemingly) exponentially when additional FCLs are allocated. This is visualized in Figure 19.
The shares of the cost-components from the Total Logistics Cost, for the optimal number of allocated FCLs on the slow mode (18), are visualized in Figure 20.

**Sensitivity Transportation Costs**

The transportation costs components proved to be responsible for the largest share of the Total Logistics Cost. These cost-components are examined in this chapter, by changing the initial values from -50% up to +50%. Values outside this range are considered to be less likely.

Figure 21 illustrates the optimal number of allocated FCLs to the slow modality, as a function of the transportation costs $a_{Tr,1}$ and $a_{Tr,2}$. 
Logically, the optimal number of FTLs on the slow mode will change when the transportation cost of the fast mode becomes cheaper; in other words if: $a_{Tr,1} < a_{Tr,2}$. However, it is interesting to see that this change occurs quite abruptly. When the transportation cost of the fast mode is decreased by 5% ($a_{Tr,1} = €950$), still 9 FCLs are allocated, which is 44% of the volume. But when this cost is decreased by 7.5% ($a_{Tr,1} = €925$) suddenly 0 FCLs are allocated. This illustrates the large impact of the transportation costs on the Total Logistics Cost. Obviously, a similar reaction is observed when the transportation cost of intermodal transportation is increased by 7.5% ($a_{Tr,2} = €975$).

Figure 22 illustrates the change in the optimal TLC, as a function of the transportation costs $a_{Tr,1}$ and $a_{Tr,2}$.

When the transportation cost of the fast mode is reduced by 5% ($a_{Tr,1} = 950$), a bent is visible, after which a decrease in this transportation cost has a larger impact on the optimal TLC. As explained, this is the moment that the transportation cost for the fast mode is cheaper than the transportation cost for the slow mode, after which all the volume is allocated to the fast mode.

Figure 23 visualized the cost saving (in terms of TLC) of switching from only fast transportation to a combination of fast- and slow transportation. This cost saving is hereby called the option value, and is defined as the daily value (in terms of TLC) of having the option to change from only fast transportation ($FCL = 0$) to a combination of fast- and slow transportation ($FCL > 0$).
It can be observed that this option value is currently about €630 per day. This means that the optimal combination of fast- and slow transportation (with 12 allocated FCLs), is €630 per day cheaper than only fast transportation ($FCL = 0$). Logically, this value will increase when the transportation cost of the fast mode increases. On the other hand, if the transportation cost of the slow mode reaches €975, the option value is €0.

The previous results revealed that there is a significant gap of allocated FCLs to the slow mode (e.g. from 0 to 9 FCLs), when the transportation costs of the modalities meet each other. This is examined more closely by performing a sensitivity analysis with both variables in a three dimensional graph, with a small increment (Figure 24).

![Figure 24 - Optimal Allocated FCLs per Combination Transportation Costs (Model 1)](image)

Figure 24 confirms the abrupt change in the optimal allocated FCLs to the slow mode. Given the values in this figure ($900 \leq a_{Tr,m} \leq 1100$), it can be observed that:

- When $a_{Tr,1} + \varepsilon30 \leq a_{Tr,2}$, 0 FCLs are allocated to the slow mode;
- When $a_{Tr,1} + \varepsilon40 = a_{Tr,2}$, 1 FCL is allocated to the slow mode;
- When $a_{Tr,1} + \varepsilon50 = a_{Tr,2}$, 9 FCLs are allocated to the slow mode;
- When $a_{Tr,1} + \varepsilon60 = a_{Tr,2}$, 11 FCLs are allocated to the slow mode;
- When $a_{Tr,1} + \varepsilon90 = a_{Tr,2}$, 12 FCLs are allocated to the slow mode;
- When $a_{Tr,1} + \varepsilon110 = a_{Tr,2}$, 13 FCLs are allocated to the slow mode;
- When $a_{Tr,1} + \varepsilon130 = a_{Tr,2}$, 14 FCLs are allocated to the slow mode;
SENSITIVITY LEAD TIMES
The sensitivity of the lead times in respect to the cost-components and the TLC is captured in Figure 25.

Changing the lead time of the fast mode to 1 day provides some insights. Changing this lead time leads to changes in all the cost components. The main reason is that a longer lead time for the fast mode changed the optimal amount of allocated FCLs to the slow mode from 12 to 11. This change in the allocated quantity had a moderating effect on all the cost components. Besides that, the lead time of the fast mode also has a direct (positive) relation with both the Storage Costs and the Cost of Capital.

Changing the lead time of the slow mode did also influence the optimal FCLs allocated to the slow mode. The main reason is the impact on the total Cost of Capital.

COST OF CAPITAL AND STORAGE COST
The last two interesting influencing parameters are the Cost of Capital per pallet ($\alpha_C$) and the Storage cost per pallet at the RDC ($\alpha_S$). It is already observed that these two parameters have much less impact than the transportation cost parameters. Therefore, the sensitivity analysis is performed for a larger interval, from -100% up to +200% (Figure 26).
The parameters for the Cost of Capital and the Storage cost prove to have a positive and almost linear relationship with the optimal TLC. When the Cost of Capital per pallet is doubled, the TLC will increase by 17.9%, while if the storage cost per pallet in the RDC is doubled, the TLC will increase by 11.5%.

Changing these parameters slightly will have a minor impact on the optimal number of allocated FCLs for the slow mode (Figure 27). Increasing these parameters has only significant impact on the allocated quantity of containers, when the default value of the Cost of Capital is increased by more than 150%.

![FIGURE 27 - COST OF CAPITAL AND STORAGE COST VS OPTIMAL FCLS SLOW MODE (MODEL 1)]
7.2. MODEL 2

GENERAL RESULTS
The observed goods flow between the RDC and the XDC proves to be cost-optimal when only the fast mode is used. This is visualized in Figure 28 and described in Table 6.

FIGURE 28 - TOTAL LOGISTICS COST AS A FUNCTION OF THE FCLS ALLOCATED TO THE SLOW MODE (MODEL 2)

TABLE 6 - CORRESPONDING VALUES FOR COST-COMPONENTS, ILLUSTRATED IN FIGURE 28 (VALUES × €1000).

| FCL | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| % vol.| 0% | 5% | 10% | 15% | 20% | 25% | 30% | 34% | 39% | 44% | 49% | 54% | 59% | 64% | 69% | 74% | 79% | 84% | 89% | 94% |
| T_{x,XDC} | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.7 | 1.0 | 1.4 | 2.0 | 3.1 | 5.7 | 19.0 |
| T_{c,RDC} | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.0 | 3.0 | 3.0 | 3.0 | 2.9 | 2.8 | 2.8 | 2.7 | 2.5 | 2.3 | 1.8 |
| C_C | 4.4 | 4.5 | 4.5 | 4.6 | 4.6 | 4.6 | 4.7 | 4.7 | 4.8 | 4.8 | 4.8 | 4.8 | 4.9 | 4.9 | 5.0 | 5.1 | 5.2 | 5.4 | 5.7 | 6.6 | 12.0 |
| C_{T_{r,1}} | 0.0 | 0.4 | 0.8 | 1.2 | 1.6 | 2.1 | 2.5 | 2.9 | 3.3 | 3.7 | 4.1 | 4.5 | 4.9 | 5.3 | 5.7 | 6.2 | 6.6 | 7.0 | 7.4 | 7.8 | 12.0 |
| C_{T_{r,2}} | 8.3 | 7.9 | 7.5 | 7.1 | 6.7 | 6.3 | 5.9 | 5.5 | 5.1 | 4.7 | 4.3 | 3.9 | 3.5 | 3.1 | 2.7 | 2.3 | 1.9 | 1.5 | 1.1 | 0.7 | 12.0 |
| TLC | 15.8 | 15.9 | 15.9 | 16.0 | 16.0 | 16.1 | 16.2 | 16.2 | 16.3 | 16.4 | 16.5 | 16.6 | 16.6 | 16.8 | 17.0 | 17.3 | 17.8 | 18.5 | 19.8 | 23.0 | 40.8 |

Compared to Model 1, the transportation costs ($a_{T_{r,1}}$ and $a_{T_{r,2}}$) are significantly lower. However, the total transportation cost does still contribute for the largest share of the TLC (53%). The Cost of Capital is now representing 28% of the TLC, while the total storage cost represents 20%.

It is interesting to observe that there is almost no inventory stored in the XDC, until 9 or more FCLs are allocated to the slow mode. From that moment on, the expected stored quantity increases significantly (Figure 29). The volume stored in the RDC, on the other hand, showed a modest decline.
SENSITIVITY TRANSPORTATION COSTS

The transportation costs in Model 2 are determined with a linear equation (Equation 2.12). Three parameters have a large impact in these transportation costs, if it is assumed that the fixed costs \((\text{int}_1 \text{ and } \text{int}_2)\) are secured; the cost per km for the fast mode \((s_{l1})\), the cost per km of the slow mode \((s_{l2})\), and the distance \((K)\). A sensitivity analysis is performed for these parameters (Figure 30).

Two parameters appear to have a (almost) linear relationship with the optimal TLC. Logically, as the distance \((K)\) increases, the TLC will increase. But changing the price per km for the slow mode \((s_{l2})\) will not influence the optimal TLC at all, as this mode is too expensive compared to the fast mode. The price per km for the fast mode \((s_{l1})\) proved to have a deflection. It will behave similar as the distance parameter \(K\), until it becomes too expensive. From that moment on, the increase deflects gradually.

Figure 31 visualizes the reasons for the deflection. This graph illustrates the optimal number of allocated FCLs to the slow mode, after changing the default value of the examined parameter from -50% to 50%.
With the initial values, zero FCLs are allocated. The trade-off points for using both fast and slow transportation prove to vary for two parameters. When all other parameters are fixed, the distance \( (K) \) should be increased by at least 45% \((K \geq 580)\), while the cost per km of the fast mode should be increased by at least 12.5% \((s_{1} \geq €1.25)\). These values are obviously also the points in which the option value of using a combination of fast and slow transportation, becomes larger than zero.

It is interesting to observe that also in this model, an abrupt change of allocated FCLs to the slow mode takes place, similar to Model 1 (Figure 21). However, this change is less extreme. This is examined more closely in the following analysis. So again, a three-dimensional sensitivity graph is made which gives the optimal number of allocated FCLs to the slow mode, for a combination of the two transportation cost parameters \((a_{TR,1,K} \text{ and } a_{TR,2,K})\). The thick white line follows the €400 line for both parameters:
Given the values in this figure (300 ≤ a_{Tr,m,K} ≤ 500), it can be observed that:

- When a_{Tr,1,K} + €30 ≤ a_{Tr,2,K}, 0 FCLs are allocated to the slow mode;
- When a_{Tr,1,K} + €40 = a_{Tr,2,K}, 1 FCL is allocated to the slow mode;
- When a_{Tr,1,K} + €50 = a_{Tr,2,K}, 5 FCLs are allocated to the slow mode;
- When a_{Tr,1,K} + €70 = a_{Tr,2,K}, 7 FCLs are allocated to the slow mode;
- When a_{Tr,1,K} + €80 = a_{Tr,2,K}, 9 FCLs are allocated to the slow mode;
- When a_{Tr,1,K} + €110 = a_{Tr,2,K}, 10 FCLs are allocated to the slow mode;
- When a_{Tr,1,K} + €120 = a_{Tr,2,K}, 11 FCLs are allocated to the slow mode;
- When a_{Tr,1,K} + €170 = a_{Tr,2,K}, 12 FCLs are allocated to the slow mode.

**SENSITIVITY LEAD TIMES**

With the initial parameter-values, it is not interesting to examine the sensitivity of the lead time from the slow mode. This is logical as this transportation mode is not used. The sensitivity of the lead time of the fast mode, on the other hand, is captured in Figure 33.

Changing the lead time of the fast mode will only affect the Cost of Capital, by 11%. Interestingly, the Storage costs are not affected (contrary to the finding of Model 1).
SENSITIVITY COST OF CAPITAL AND STORAGE COST

The sensitivity of the storage cost and cost of capital parameters are visualized in Figure 34.

The storage costs of the XDC are not included in this sensitivity analysis, as the slow model is not used. Hence, none of the goods need to be stored at the XDC (all demand is allocated). The other parameters, the Storage cost at the RDC and the Cost of Capital, are linear related with the TLC. Changing both parameters did not influence the optimal number of allocated FCLs to the slow mode, in the interval from -100% up to +200%.
8. CONCLUSIONS

This master thesis project examines under which conditions, a combination of road and intermodal freight distribution might be an attractive alternative opposed to unimodal road transportation, for the distribution of fast moving consumer goods.

By analysing the demand of a FMCG manufacturer, two interesting goods flows are selected. The first goods flow examined these distribution methods in an upstream segment of the FMCG supply chain, while the second goods flow examined these distribution methods in a more downstream segment (Figure 9). Then, two mathematical models are constructed, able to simulate a goods flow with a fast and slow transportation mode, with several complexities of the FMCG industry. A decisive element of these models is a greedy algorithm, which allocates a constant quantity of the demand to the slow transportation method. Finally, a simulation tool is used to give quantitative insights in expected Total Logistics Costs and the corresponding use of the distribution methods.

This chapter will use the results of this simulation tool to discuss and answer the research questions (chapter 8.1). Furthermore, the limitations of this study will be mentioned (Chapter 8.2), followed by a suggestion for further research (Chapter 8.3).

8.1. DISCUSSION

This discussion will address all the sub questions which were defined in chapter 3.2, in order to answer the main research question.

AN INTERESTING ALTERNATIVE

For the first goods flow (Model 1), a combination of road and intermodal freight distribution proved to be an attractive distribution method, as opposed to unimodal road transportation. This goods flow contained 50 products with a high demand volatility. While making several assumptions, a combination of road and intermodal freight distribution is estimated to save €630 per day, i.e. 230,000 euros a year. The main reason is the significant difference between the transportation cost of direct road transportation and intermodal transportation.

Shipping a container with the intermodal transportation mode, instead of road transportation, requires more storage space in the RDC and additional Cost of Capital. However, the cost-saving in terms of transportation cost is considerably more. Hence, it proved to be attractive to send a large quantity (60% of the demand) with the intermodal transportation method. This obviously leads to less truck transportation and hence a reduction of CO₂. Unfortunately, there is insufficient information available (such as the percentage of pre-and end haulage and the used modes) to give a more specific answer.

The second observed goods flow (Model 2) proved to be best served by unimodal road transportation. This goods flow consisted of the similar 50 products, shipped on a shorter distance. The distance was insufficiently far for intermodal transportation to be cost-attractive, which made direct road transportation both cheaper and faster.
INFLUENCING PARAMETERS
Several parameters are influencing the distribution method decision (Table 4), of which the most important parameters are described below. The sensitivity graphs of these parameters, in terms of the minimal Total Logistics Cost and the corresponding number of allocated FCLs to the intermodal mode, can be found in chapter 7.

The transportation costs for shipping a container by direct road and by the intermodal mode are considered to be the two most important parameters. The analysis of both models indicated that if the transportation cost of intermodal transportation is at least €40 cheaper, it is preferred to use a combination of direct road and intermodal transportation. If this is the case, a significant share of the volume will be allocated to the intermodal mode.

Another influencing parameter is the storage cost per pallet. Increasing this storage cost will favour direct road transportation, as allocating volume to the intermodal mode proved to result in more stored inventory. The impact of this parameter was relatively small in the two models, as the total storage cost was only representing 12-20% of the Total Logistics Cost.

The value of the products is also influencing the distribution method decision. This value is included in the models as the Cost of Capital per pallet per day. The total Cost of Capital is dependent on the total volume of products in-transit and stored. The use of a fast distribution method is therefore preferred, as this reduces the required order-up-to level at the RDC and the total inventory In-Transit. The behaviour of this parameter is similar to the storage cost, when it is assumed that direct road transportation is faster than intermodal transportation. Increasing this parameter will favour direct road transportation.

Finally, the lead times of the transportation modes will also influence the distribution method decision. Generally, when the lead time of road transportation is increased, more volume will be allocated to the intermodal mode. This is logical, as the total Cost of Capital becomes higher due to the increasing inventory In-Transit. Furthermore, in the first model, the order-up-to level is dependent on the lead time of the fastest mode. When direct road transportation takes longer (e.g. due to congestions), a higher order-up-to level is required to satisfy the service restriction to Retailer DCs. This implies more Storage cost and Cost of Capital.

A change in the lead time of the intermodal transportation mode, on the other hand, will only affect the Cost of Capital. Increasing this lead time sufficiently high, will obviously favour direct road transportation.
8.2. LIMITATIONS

This study has several limitations which might affect the managerial insights which were discussed in the previous sub-chapter (chapter 8.1):

- Several simplifying assumptions were made regarding the demand from Retailer DCs. It is assumed that the distribution of the demand is known in advance; that the demand has no upward or downward trend; and that the observed products will not have an ending lifetime. In practice there will be more uncertainties, which might affect service level of the supply chain. Therefore, in practice, a higher basestock level may be required;
- In Model 2, it is assumed that all the observed products will pass by the Crossdock DC. Logically, it may be more attractive to ship the demand directly to Retailer DCs if there is no inventory to be allocated in the XDC. This will save handling cost at the XDC and might prevent a detour;
- In this study, it is assumed that only full pallets are stored and shipped. However, it might be more attractive to stack multiple partly-filled pallets when the demand of products is relatively low. This can decrease the required storage capacity in the Regional DC.

8.3. FURTHER RESEARCH

The following recommendations can be made for further scientific research:

- The allocation algorithm determines the constant shipment size of the slow modality with a greedy procedure, in which the ‘most constant’ demand is selected. It might be interesting to improve this algorithm, by including the value of the products. Hence, more expensive products may be allocated more to the faster mode, while less expensive products may be allocated more to the slower mode. This might decrease the Cost of Capital in the system. Including this logic is especially interesting when the value between products varies;
- In both models, the fast mode (direct road transportation) is used to ship a measured amount of pallets to either the RDC (Model 1) or the XDC (Model 2). This measured amount is determined from an inventory-cost perspective, but not from a transportation-cost perspective. It might be cost-optimal to also take into account the utilization of this transportation mode, while determining the shipment size of the fast mode. This can reduce the expected transportation cost.
- The models assumed a daily frequency of both transportation methods. It can be interesting to relax this assumption and to use the intermodal mode less frequent. By doing so, it is possible to accumulate the volume of several days, so that economies of scale can be achieved.
9. BIBLIOGRAPHY


European Intermodal Association. (2009). Application Form; The “Intermodal Award for best practices.”


APPENDIX 1 - SELECTED LOCATIONS

This Appendix described which and how the selected locations of the goods flows are chosen. This appendix is however not available in the Public version of the Master thesis.
APPENDIX 2 – NOTATION IN MATHEMATICAL MODELS

INDICES

\( t \)  
Time unit;  \( t \in \{1, 2, ..., T\} \)

\( i \)  
Product;  \( i \in \{1, 2, ..., I\} \)

\( k \)  
Transportation distance in km;  \( k \in \{1, 2, ..., K\} \)

\( m \)  
Transportation mode

   Model 1:  \( m = \begin{cases} 
1 & \text{Fast mode} \\
2 & \text{Slow mode} \\
0 & \text{Supply} 
\end{cases} \)

   Model 2:  \( m = \begin{cases} 
1 & \text{Fast mode} \\
2 & \text{Slow mode} 
\end{cases} \)

VARIABLES

\( D_{it} \)  
Aggregated demand of Customer DCs for product \( i \) at time \( t \) in pallets;

\( \mu_{it} \)  
The mean demand of product \( i \) in pallets;

\( IIL_{it} \)  
Inventory level of product \( i \) at the RDC at time \( t \) in pallets;

\( IP_{it} \)  
Inventory Position of the RDC of product \( i \) at time \( t \) in pallets;

\( IT_{it} \)  
Inventory In-Transit of product \( i \) at time \( t \) in pallets;

\( OHI_{it} \)  
Inventory of product \( i \) On-Hand in the RDC at time \( t \) in pallets;

\( OHI_{RDC,t} \)  
Inventory of product \( i \) On-Hand in the RDC at time \( t \) in pallets;

\( OHI_{XDC,t} \)  
Inventory of product \( i \) On-Hand in the XDC at time \( t \) in pallets;

\( All_{it} \)  
Allocated demand of product \( i \) from available inventory in the Crossdock DC;

\( BO_{it} \)  
Backordered demand of product \( i \) at time \( t \) in pallets;

\( s_{im,t} \)  
Shipment size of product \( i \), sent by transportation mode \( m \) at time \( t \) in pallets;

\( DIL_{it} \)  
The desired inventory level in the RDC for product \( i \);

\( R \)  
The replenishment period;

DECISION VARIABLES

\( l_{m} \)  
Fixed transport lead time for transport modality \( m \);

\( x^{i} \)  
A predetermined distributed quantity of product \( i \) for each time unit in pallets by the slow mode;

\( \alpha^{i} \)  
The minimum allowed service level of the model for product \( i \);

\( S_{i} \)  
Order-up-to level of product \( i \) in the RDC in pallets;

\( K \)  
The distance from the RDC to the XDC in km;

\( Q \)  
Maximum number of pallets in a container.

COST PARAMETERS

\( C \)  
Total logistics cost;

\( C_{TR} \)  
Transportation cost;

\( a_{TR,m} \)  
Transportation cost per Container, for transportation mode \( m \);

\( a_{TR,m,K} \)  
Transportation cost per Container, for transportation mode \( m \), for distance \( K \);

\( C_{S} \)  
Storage cost;

\( a_{S} \)  
Storage cost per pallet per day in the RDC;

\( a_{S,RDC} \)  
Storage cost per pallet per day in the RDC;

\( a_{S,XDC} \)  
Storage cost per pallet per day in the XDC;

\( C_{C} \)  
Cost of capital in the pipeline;

\( a_{C} \)  
Cost of capital per pallet per day for product \( i \).
APPENDIX 3 - SIMULATION PROCEDURES

Procedure Simulation_Model_1

01 Call Procedure Load_Parameters
02 Call Procedure Demand_Generation
03 Call Procedure Demand_Probabilities
04 For FCL = 0 to FCLMax do
05 \[ p_{\text{Max}} = FCL \times Q; \]
06 Call Procedure Volume_Slow_mode
07 For \( i = 1 \) to \( l \)
08 \[ S^i = 0; \]
09 Find \( IL^t_i \) for \( i \in \{1,2,\ldots,l\}, \ t \in \{1,2,\ldots,T\}; \]
10 \[ \Delta = \text{Round}(2\mu^i); \]
11 \[ \hat{a}^i = 0; \]
12 While \( \hat{a}^i < a^i \) do
13 \[ S^i = S^i + \Delta; \]
14 Call Procedure Find_Performance
15 End While;
16 \[ S_{\text{Min}}^i = S^i - \Delta; \]
17 \[ S_{\text{Max}}^i = S^i; \]
18 \[ S^i = \text{Round}\left(\frac{S_{\text{Max}}^i + S_{\text{Min}}^i}{2}\right); \]
19 While \( S_{\text{Current}}^i \neq S_{\text{Max}}^i \) do
20 Call Procedure Find_Performance
21 If \( \hat{a}^i < a^i \) then
22 \[ S_{\text{Min}} = S^i; \]
23 Else
24 \[ S_{\text{Max}} = S^i; \]
25 End If;
26 \[ S^i = \text{Round}\left(\frac{S_{\text{Max}}^i + S_{\text{Min}}^i}{2}\right); \]
27 End While;
28 End for;
29 End for;
30 Call Procedure Store_Output
The procedure for simulating Model 2 is different, as the inventory levels \( (IL^t_i) \) cannot be determined solemnly before the order-up-to levels are determined.

Procedure Simulation_Model_2

01 Call Procedure Load_Parameters
02 Call Procedure Demand_Generation
03 Call Procedure Demand_Probabilities
04 For \( FCL = 0 \) to \( FCLMax \) do
05 \( pMax = FCL \times Q; \)
06 Call Procedure Volume_Slow_mode
07 For \( i = 1 \) to \( I \)
08 \( S^i = 0; \)
09 \( \Delta = \text{Round}(2\mu^i); \)
10 \( \hat{a}^i = 0; \)
11 While \( \hat{a}^i < a^i \) do
12 \( S^i = S^i + \Delta; \)
13 Find \( IL^t_i \) for \( i, \ t \in \{t_{wu}, t_{wu} + 1, ..., T\}; \)
14 Call Procedure Find_Performance
15 End While;
16 \( SMin^i = S^i - \Delta; \)
17 \( SMax^i = S^i; \)
18 \( S^i = \text{Round} \left( \frac{SMax^i + SMin^i}{2} \right); \)
19 While \( SCurrent^i < SMax^i \) do
20 Find \( IL^t_i \) for \( i, \ t \in \{t_{wu}, t_{wu} + 1, ..., T\}; \)
21 Call Procedure Find_Performance
22 If \( \hat{a}^i < a^i \) then
23 \( SMin = S^i; \)
24 Else
25 \( SMax = S^i; \)
26 End If;
27 \( S^i = \text{Round} \left( \frac{SMax^i + SMin^i}{2} \right); \)
28 End While;
29 End for;
30 End for;
31 Call Procedure Store_Output
APPENDIX 4 - DEMAND DISTRIBUTIONS SIMULATION MODELS

This appendix lists the demand parameters which were used during the simulation. It was assumed that the demand of the examined products follows a gamma distribution (chapter 5.2). The corresponding parameters $\text{Alpha}^i$ and $\text{Beta}^i$ for all products are listed below:

**TABLE 7 - GAMMA PARAMETERS DEMAND DISTRIBUTIONS**

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<tr>
<th>Prod</th>
<th>$\text{Alpha}^i$</th>
<th>$\text{Beta}^i$</th>
<th>Prod</th>
<th>$\text{Alpha}^i$</th>
<th>$\text{Beta}^i$</th>
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