MASTER

Two-echelon replenishment policy with perodic review, lot sizing and integral information for the region of UK & Ireland at Office Depot

Vargas Suavita, J.A.

Award date:
2012

Eindhoven, August 2012

Two-echelon Replenishment Policy with Periodic review, Lot sizing and Integral information for the region of UK & Ireland at Office Depot

by

J.A. Vargas Suavita

BSc Industrial Engineering – ITESM 2009

Student identity number 0757739

In partial fulfillment of the requirements for the degree of

Master of Science in
Operations Management and Logistics

Supervisors:
Dr. K. van Donselaar, TU/e, OPAC
Dr. Z. Atan, TU/e, OPAC
M. Ophelders, Office Depot, Supply Chain Europe

TUE. Department Industrial Engineering & Innovation Sciences

Series Master Theses Operations Management and Logistics

Subject Headings: Two-echelon Supply Chain, Replenishment policy, Integral Control, Divergent system, Periodic Review, Lot Sizing, Simulation

I. ABSTRACT

This master thesis project presents the development of a replenishment strategy in a two-echelon supply chain with one Regional Distribution Center and three Local Distribution Centers at Office Depot in the UK & Ireland region. The replenishment strategy for the private brand products consists of a replenishment policy with periodic review and lot sizing. The supply chain has decentralized control, central stock function for most of the products and echelon-stock information. The optimal lot size for each product at each stockpoint is found with a total cost function. The optimal reorder points are computed with an approximation available in the literature; with a modification to accommodate a very high target service level and different review periods at both echelons. Policy results, derived analytically and with a simulation model, show that the policy provides satisfactory results in terms of service level and outperforms with respect to the actual supply chain in terms of inventory value.

DISCLAIMER:

All figures and confidential data of Office Depot have been masked for protection of the company's interests. Some appendices are also confidential and are not presented in this report.

II. PREFACE

This report is the result of a 6-month research project developed at the Supply Chain Planning department of Office Depot in Venlo. This master thesis completes the final requirement for obtaining the Master of Science degree in Operations Management and Logistics at Eindhoven University of Technology. The experience of working on my project at Office Depot has been highly enriching and challenging, and it has contributed immensely to my professional and personal development.

Firstly, I would like to thank Michel Ophelders, my supervisor at the company, who gave me the opportunity to be part of the company and supported me throughout the course of the project, providing me with feedback and useful suggestions whenever they were needed. I also want to thank my colleagues at the Supply Chain department, who were always helpful me and made me feel part of the team, despite the differences in culture and language. I thank Paul in particular for making this experience easier for me, for the encouraging words and all the discussions we had when travelling to work.

Secondly, I would like to thank my first supervisor from the TU/e, Karel van Donselaar for the constant support. His critical comments and clear guidance were key factors in the success of my project. I really appreciate all his efforts and time spent in the supervision of this Master Thesis Project. Furthermore, I would like to thank my second supervisor from the TU/e, Zumbul Atan, for sharing her knowledge and valuable feedback during our meetings.

Finally, I dedicate this project to my family. I thank them for all the support throughout my life as student, because despite the distance and the challenges we have faced, they have always believed in me and encouraged me. In addition, I thank all my fellow colleagues and friends in Eindhoven for all the experiences, adventures and fun we had together, I keep only great memories of my life in this country.

Andrea Vargas

Eindhoven, August 2012

III. MANAGEMENT SUMMARY

Introduction and Problem definition

This master thesis project is the result of a study held in Office Depot during one semester and it has been designed to fulfill the requirements of the Master Program in Operation Management and Logistics at Eindhoven University of Technology. The development of this study takes place in the Supply Chain and Planning Department in Office Depot. Office Depot is a company that sells various types of office supplies. Originally founded in North America, the company now has operations all over the world, including Europe.

The European supply chain is supported by operations in 17 Local Distribution Centers (LDCs). These are divided into six different regions with one Central Distribution Center (CDC) that is fully dedicated to Private Brand (PB) assortment. This project is focused on the development of a replenishment strategy for the Private Brand (PB) products in the UK & Ireland region. This region operates with one Regional Distribution Center (RDC) located in [redacted] and two LDCs located in [redacted] and [redacted]. In the current system, three distribution channels are available for placing the PB assortment at each LDC or RDC, these are: 'Direct shipping method to LDC or RDC', 'Direct shipping method through RDC' and 'Indirect shipping method through CDC'. Products are sourced mainly from Far East locations with long lead times (production plus transportation lead time) and from European vendors with shorter lead times.

Currently, this region uses mainly the 'Direct shipping method' to the RDC-[redacted] and to the LDC-[redacted]. Only 6% of the PB assortment follows an 'Indirect shipping method through CDC'. Office Depot is interested in the development of a replenishment strategy for the two-echelon, regional supply chain assuming a RDC approach (Direct shipping method through RDC) for almost the entire PB assortment, disregarding the use of the CDC. It is believed that this approach can lead to the reduction of the actual inventory levels in the distribution centers and potential savings from the use of the CDC with the operations outsourced to a 3PL company.

The regional supply chain is illustrated in the following figure:

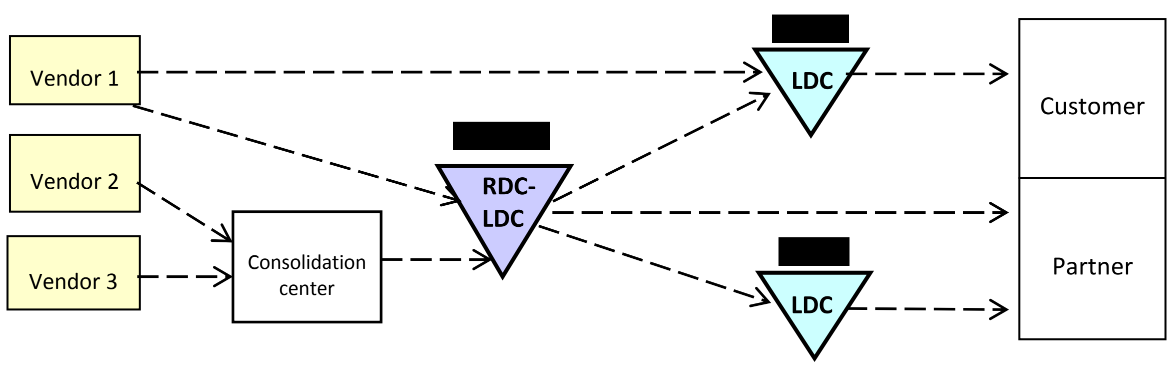


Figure i. Representation of the regional supply chain in the region UK & Ireland

The main research question is:

How to plan and control inventory in the two-echelon supply chain in the region of UK & Ireland?

The main research question is solved by providing answers to the following research sub-questions:

What replenishment policy to use?

What are the control parameters for each SKU at each location?

How to make replenishment decisions based on product and channel characteristics?

Analysis and Diagnosis

In order to provide an answer to the first research sub-question, four decisions need to be made: The degree of centralization in coordination, the need of a central stock function, the type of stock information and the type of reorder planning.

Based on the current ownership of responsibilities within the company, a decentralized coordination (pull system) was selected. This meant that the RDC determines the order quantities to the suppliers and the proportion of stock allocated to each LDCs in case of stock-out. Thus, each LDC defined whether an order was placed and the quantity to be ordered.

With regard to the central stock function, it was decided to keep stock centrally in the RDC for the entire assortment in LDC-[redacted] and for 80% of the assortment in LDC-[redacted]. Central stock function was avoided in LDC-[redacted], for voluminous products (chairs from Far East) with high demand rates. This was also the case for fast-moving products with high product value and short replenishment cycles (part of the assortment of European toners).

The status of information selected is the echelon-stock information. Due to this, the upper echelon (RDC) has complete visibility of the inventory levels and backorders at every LDC at any moment in time. This information is used to make the replenishment decisions for the RDC. Finally, given the current IT capacities, the diversity of the assortment and the lack of strong patterns in demand, the type of reorder planning selected is a reactive logic in which orders are placed to the upper echelon based on an order quantity and a reorder point.

Finally, the replenishment policy selected is a ***(R,s,nQ)*** policy at both echelons, meaning that every review period ***R***, the echelon-inventory position (*All stock in transit to this stockpoint + physical stock + stock in transit to and/or hand in its downstream stockpoints – all backorders at the end stockpoints*) is reviewed. If this is equal or below the reorder point ***s***, a quantity equal to ***nQ*** is placed such that the echelon-inventory position is raised above the reorder point.

Plan of Action

The second research sub-question triggered the development of two approaches to find the optimal parameters. The first approach involves of the design of a total-cost function in order to find the lot size (Q) at every stockpoint such that the sum of the annual relevant cost is the minimum. The relevant costs included are: capital costs, handling costs and storage costs. Detailed description of the formulation of each cost factor based on local information is provided in this report.

The second approach is the use of an approximation found in Donselaar (1990) with certain variations to accommodate very high service levels and different review periods at both echelons. The approximation is used to find the optimal reorder points at every stockpoint given the lot size found with the first approach and a target service level of 99.5% at all LDCs for all SKUs.

Intervention

In this phase of the project the two approaches to find the policy parameters are applied to all SKUs of PB within the scope of this study.

The outcome of the total cost calculation showed that at both echelons, the most significant cost is the handling cost, incurred in all activities related to unloading containers or trucks, storing items in the warehouse and expediting orders to the LDCs. It was found that handling costs are lower when ordering pallets rather than layers and cartons. However, with slow-moving products, ordering large lot sizes also implies high capital and storage cost. In such cases, a smaller lot size is preferred.

The results of the lot size determination showed that at LDCs, more than [redacted]% of the assortment should be ordered in multiples of cartons, while at the RDC, [redacted]% of the assortment should be ordered in larger lot sizes. The analysis order cycles indicates that long order cycles at LDCs are mainly caused by low demand rates combined with the amount of selling units contained in the smallest lot size. The estimated annual cost when using the lot sizes proposed is € [redacted]. However because the company currently does not perform any allocation of logistic costs to activities, this cost could not be compared with the actual situation.

The outcome of the second approach is the reorder levels for each SKU at every stockpoint. The service level provided with this solution is computed analytically and the overall performance of each LDC results in a service level above the target. In terms of inventory value, the RDC approach operates with an inventory value of approximately € [redacted] less than the current inventory value, representing around [redacted]% of savings. The LDC-[redacted] can reduce the average days of inventory by approximately [redacted]% but the LDC-[redacted] requires about [redacted]% more days of inventory in order to meet the service level. The LDC/RDC [redacted] can operate with [redacted]% less inventory than with the current situation.

The replenishment parameters are also being evaluated using a simulation model in which an allocation rule developed by the author of the reorder point approximations was tested. The allocation rule is needed in order to determine the proportion of inventory to allocate to the LDCs in case the RDC is not able to meet all demand entirely. It is assumed that the RDC is allowed to send partial shipments to the LDC; thus, allowing for less than the optimal lot size. Simulation results indicate that the replenishment policy performs with a service level above 99% at all stockpoints with no indication of impact from the differences in lot sizes, the demand variability or the supply lead time. Moreover, the results showed that out of 1200 orders, the RDC would expedite less than 14 partial orders to each LDC. This indicates that in most of the cases, the RDC will be able to meet the entire requirements of the downstream echelon.

With regard to the final research sub-question, one type of replenishment strategy has been selected in this study for the whole assortment. However, this master thesis provides theoretical findings about different distribution and inventory control decisions suggested in a replenishment strategy depending on a set of product, market and channel characteristics.

Evaluation

The findings presented in this study provide the company with a better insight about the allocation of relevant cost to the replenishment activities. The total cost functions can be used to find the cost-optimal lot size for any product in the regional supply chain. The same methodology could also be applied to other regions subject to similarities in the handling activities and information of local labor rates and storage rates.

Furthermore, the policy parameters presented can be used at each stockpoint in case the company decides to use the RDC approach with integral information in UK & Ireland. The analytical and simulated performance indicates that the policy performs with an overall service level within an acceptable boundary.

IV. TABLE OF CONTENTS

Contents

Part I: Introduction

1. INTRODUCTION

1.1. Office Depot

Office Depot is founded in 1986, with headquarters located in Boca Raton, Florida. It is one of the world's largest sellers of office products and an industry leader in every distribution channel, including stores, direct mail, contract delivery, internet and business-to-business electronic commerce. Office Depot has three business units: North American Retail Division, North American Business Solutions Division and International Division.

Office Depot markets in 53 countries throughout North America, Europe, Asia and Latin America. It operates wholly-owned entities, majority-owned entities, participates in other ventures covering 41 countries and has alliances in an additional 19 countries. In 2011, Office Depot generated sales of over US$11.5 billion, with approximately 39,000 employees worldwide. The International Division sells office products and services through direct mail catalogs, contract sales forces, internet sites and retail stores, using a mix of company-owned operations, joint ventures, licensing and franchise agreements, alliances and other arrangements. Office Depot maintains DCs and call centers throughout Europe and Asia to support these operations. (Annual Report, 2011).

1.2. Office Depot Europe

The international direct channel was launched in 1990 with the start-up of operations in the United Kingdom. Now, the company has catalogue offerings in 15 countries outside of North America. In March 1999, the first international public internet site was introduced for consumers and businesses in the UK. Today, over 40 separate web sites operate in the International Division.

The annual sales of the International Division represented 29% of the total sales in 2010. As part of the International Division, Office Depot Europe and Middle East is the number one reseller with 8,500 associates. It has retail activities, both directly operated and in partnership, in France, Hungary, Israel, Sweden, Saudi-Arabia, Dubai and Kuwait. During 2011, additional operations in Sweden were acquired, adding customers to both the contract and the retail distribution channels. The corporate headquarters of Office Depot in Europe and the Middle East are located in Venlo, The Netherlands.

The company provides products and services directly to large businesses thorough its delivery operations in Europe. Business Solution Division sells branded and private brand products and services by means of a dedicated sales force through catalogues and internet sites. Telephone account management is also used for outbound sales contacts. Small/medium sized customers and consumers also can shop at *Viking Direct*. (www.officedepot.com.uk). *Viking Direct* is an Office Depot company that sells office supplies with e-stores for both personal and business customers. The wide range of products includes office items, paper supplies, art and craft tools, ink and toner, janitorial goods, and office machines from photocopiers to laptops.

1.3. Private brand at Office Depot

Original Equipment Manufacturer (OEM) and Private Brand products are classified into three categories: (1) supplies, (2) technology, and (3) furniture and other. The supplies category includes products such as paper, binders, writing instruments, school supplies, ink and toner. The technology category includes products such as desktop and laptop computers, printers, software, digital cameras, and wireless communications products. The furniture and other category include products such as desks, chairs, luggage and print centers, as well as other miscellaneous items.

Private Brand (hereafter referred as PB) is purchased directly from manufacturers and other primary suppliers, including direct sourcing of own brand products from domestic and offshore sources. The company also enters into arrangements with vendors that can lower the unit product costs if certain volume thresholds or other criteria are met. Each merchandising group in North America, Europe and Asia is responsible for selecting, purchasing and pricing merchandise as well as managing the inventory lifecycle. (Annual Report, 2011)

The selection of own brand products has increased in variety and level of sophistication. In Europe, around [redacted]% of the assortment belongs to Private Brand. The selection of PB office supplies includes general office supplies, computer supplies, business machines and related supplies, and office furniture under various labels, including Depot®, Viking Office Products®, Foray®, and Ativa®.

Private Brands of Office Depot	
ativa	*Ativa* offers a wide range of products to work. These include computer accessories, electronic devices, storage devices, telecommunications accessories, etc.
FORAY	The Foray brand is about all kind of writing instruments with a unique design in a nice packaging.
everyday value niceday	One of Europe's most familiar office product brands. It has over 1000 highly competitive choices that enable customers to benefit from a real alternative for their basic office needs.
Office DEPOT	Office Depot the global private brand, available in 63 countries around the world. It is priced below the OEM products, to offer considerable savings to the customers.
realspace	Real Space is the Office Depot furniture umbrella brand which covers both products and solutions. The RS product range consists of three sub-brands: *RS Soho, RS to-go, and RS PRO*
VIKING	All Viking products are produced according to Office Depot's demanding specifications and working together with manufacturers allow reducing costs. A range of over 1000 products is offered.

Table 1. Exclusive and private brands of Office Depot

In the past, importing PB was managed through decentralization in each country. This consisted in local procurement in which the vendors deliver with high service levels and low lead times. However, the introduction of PB in Europe around 4 years ago implied new supply chain planning challenges.

Therefore, a new Central Distribution Center (hereafter referred as CDC) was opened to support the PB supply chain activities in Europe. The CDC located in Turnout, Belgium; is managed by the 3PL company [redacted]. It started operations in January 2008 with the first shipment received in December 2007. It is fully used for PB, acting as a distribution channel and safety stock for the Local Distribution Centers in Europe (hereafter referred as LDCs)

1.4. PB Supply Chain at Office Depot

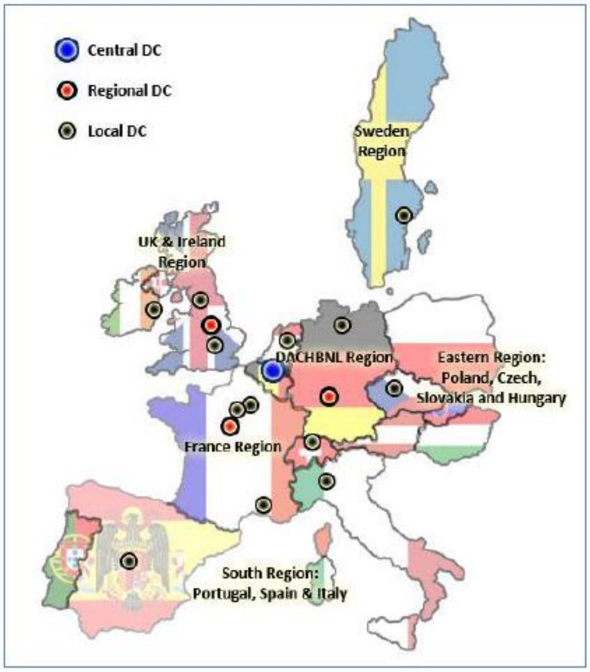


Figure 1. Regional presence of Office Depot in Europe

The European supply chain supports its activities by means of a variety of distribution and sales channels. With presence in over 12 countries, each location of Office Depot in Europe can act as a site for contract sales, direct sales, multi-channel (Direct and Contract) or as a Combo (including Retail). The company operates with 17 LCDs which are classified into six different regions: DACHBNL (Germany, BENELUX, Switzerland and Austria), UK & Ireland, France & Southern Europe, Eastern Europe and Sweden.

From all the DCs in Europe, 3 DCs are identified as Regional Distribution Centers (hereafter referred as RDC), that can expedite orders to other LDCs or serve as a cross dock facility. The RDCs are located in [redacted], UK; [redacted], Germany; and [redacted], France.

Shipments of PB can pass through different distribution channels in order to reach each LDC, which is the final location before the delivery to the customer, except for the countries with retail locations. These 3 channels are 'Direct Shipping to LDCs or RDCs', 'Direct Shipping through RDC' and 'Indirect Shipping'. The selection of one of these channels depends on certain aspects such physical volume, demand rate, order frequency and lead time of each vendor. In the current situation, the logistic channel used by a LDC has been determined for each individual product. It is possible that two items from the same vendor reaches the LDC through different logistics channels. In the following sections each channel is described in detail.

1.4.1. Direct Shipping to LDCs or RDCs

Direct shipments from the vendor (or from the consolidation center) are preferred when the demand of the region in particular is high enough that a full container load (hereafter referred as FCL) is ordered. This is the case for Far East Vendors. In the case of European vendors, the direct shipping is selected when demand volumes are equal to Full Truck Loads (hereafter referred as FTL) which in most of the cases is the aggregated requirement of a European vendor. The direct shipment is also feasible for those vendors whose purchase price already includes transportation fee to any of the DCs in Europe.

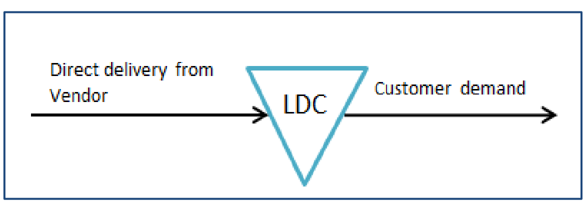


Figure 2. Direct shipping to LDC/RDC

When ordering from Far East vendors, each LDC places an order with a review period of 4 weeks based on a demand forecast. Thus each LDC must have enough safety stock to ensure the target customer level. The lead times (time from the moment of ordering until the delivery) are in average 10 weeks, including the production lead time and the transportation time.

The number of TEUs (twenty-foot equivalent units) delivered to all DCs in Europe during the year 2011 of PB was [redacted]. From these, [redacted]% of all TEUs purchased had two LDCs in the region of UK & Ireland as a final destination.

1.4.2. Direct Shipping through RDC

This logistic channel is currently available for the UK & Ireland, DACHBNL and France regions. Each of these regions has a RDC that can function as a cross-dock facility or as stockpoint for the other LDCs in the region. The use of this channel is applicable only when goods for one region are consolidated at the port of origin before shipping (buyer consolidation).

Consolidated orders arrive to the RDC, where they are unloaded and stored. Orders are placed with a review period of four weeks for Far East suppliers and between one and nine weeks to European suppliers. The RDC holds the safety stock necessary to cover the demand of the region during the long lead time. The Supply Chain Team in Venlo is responsible for placing the orders that will eventually arrive to the RDC each month. These are planned according to the sales forecast provided by the inventory managers of each region.

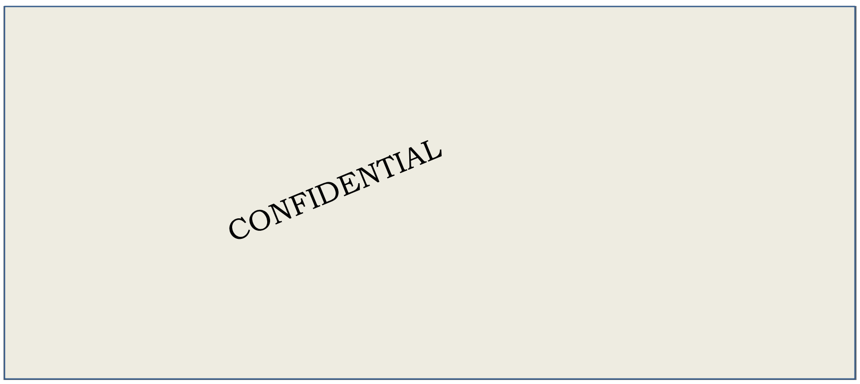


Figure 3.Direct shipment through RDC (UK & Ireland)

The LDCs are able to request inventory to the RDC in a daily basis with a lead time of one or two days. The RDC also faces customer demand that must be satisfied.

Figure 3 represents this logistic channel for the region of UK & Ireland. During the year 2011 a total of [redacted] TEUs of PB ([redacted]% of all TEUs shipped from Far East) were sent to the RDC-[redacted]

1.4.3. Indirect Shipping

The indirect shipping to a LDC is used in cases when the demand is not sufficient to order with the 'Direct shipment' and when the RDC is unable to supply the LDC. In this channel, consolidated and non-consolidated goods are shipped to the CDC that only acts as a stockpoint (there is no customer demand at the CDC) to supply the requirements of PB products of all DCs in Europe. The outsourced operations at the CDC must guarantee a target service level towards LDCs of 98%. Similar to the Direct Shipment through RDC, orders are placed to vendors by the Supply Chain team at the headquarters. It is responsibility of each LDC to place orders to the CDC on a weekly basis. Figure 4 represents the indirect shipping method in which the CDC located in [redacted] satisfies orders from any LDC in Europe. During the year 2011, a total of [redacted] TEUs of PB were shipped to the CDC, representing [redacted]% of all TEUs purchased.

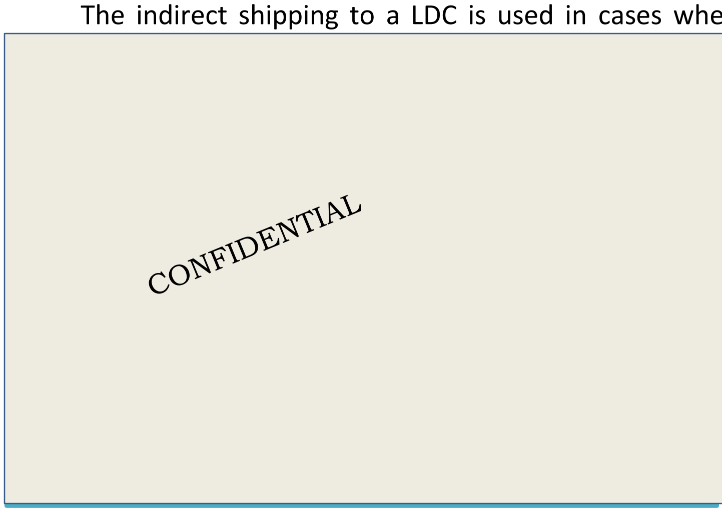


Figure 4. Indirect shipment through CDC

1.5. Regional Supply Chain in United Kingdom & Ireland

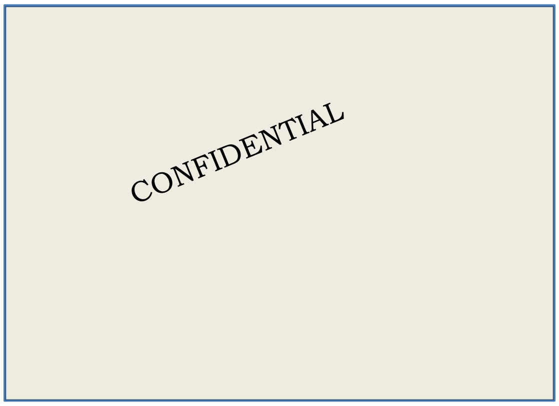


Figure 5. Regional presence in UK & Ireland

Office Depot entered the UK & Ireland stationery market in 1998 under the Viking brand. In 2011 the revenues of the region reached $960 million, making it a region that accounts for a large part of the European profit. During 2011, Office Depot started to expand the stationery market, including Managed Print Services and Facilities Management Supplies. It also started offering furniture.

Some of the regional customers include companies in the retailing, banking and food industries. Office Depot is also supplier of stationery, office furniture and printed stationery to Buckingham Palace, among other Royal customers. The region has around 2,200 employees, deployed in Office sites in [redacted], [redacted], [redacted], [redacted], [redacted] and [redacted]. Currently, the supply chain is supported by operations in 3 Local Distribution Centers and 1 Regional Distribution Center showed in figure 5. This project will not include LDC-[redacted], which is only specialized in furniture.

As mentioned in the previous section, this region has access to three different shipping methods for the distribution of PB assortment. During the last two years, the region has experienced a shift from the *Indirect shipping method* to the *Direct shipping to LDCs* because the sales of PB have increased in a way such that consolidated FCL and FTL can be sent directly to the region. In 2010 a total of [redacted] TEUs of PB were sent to the region from Far East, while in 2011 a total of [redacted] TEUs were shipped to the region. Therefore, many of the items that had an indirect flow through the CDC currently have a direct shipping method. During this transition, the region was able to order the same item to the CDC (in order to use the remaining inventory) and with a direct flow.

The current ordering method for Far East assortment with direct flow is the following: each month inventory planners at [redacted] and [redacted] place an order taking into account the supplier lead time. Orders are received at the Headquarters where all European requirements are consolidated to place one order to the supplier. After the production lead time has elapsed, in the consolidation center, FCLs are arranged such that items with [redacted] and [redacted] as final destination are sent in separate containers. When the volume is not enough, the container can also contain mixed orders. Upon arrival to the UK, containers are unloaded by a 3PL company and the stock is shipped to the corresponding destination (containers with chairs are usually unloaded at [redacted]). On the other hand, currently [redacted] is being refilled with stock held at any of the other two LDCs. The region has a fixed cost of transportation between LDCs. This consists of a daily shuttle runs from [redacted] to [redacted] and then to [redacted].

With regard to European suppliers of PB with direct flow, the same procedure is followed, in which the orders placed by the LDCs are received at the Headquarters, with a review period that varies for each vendor. The orders are then consolidated and sent to the supplier taking into account that a FTL is achieved with the regional requirements. Upon arrival, stock is offloaded (by the 3PL or at [redacted]) and sent to the corresponding destination.

Finally, items with an indirect flow are ordered by the LDCs ([redacted] and [redacted]) to the CDC with a review period of one week. These orders are then shipped to the region and received at the corresponding LDC.

1.5.1 Distribution Centers

In order to have a better overview of the DCs that are included in this study a brief description of each facility is provided in the following paragraphs.

Regional Distribution Center (RDC): The regional distribution center in [redacted] was opened in 2007 due to the continuously increasing order figures in e-commerce. Today, the sophisticated high-tech system technology of the location allows for a significantly contribution to the company's profit and is relied on an efficient order processing. The RDC is able to handle up to [redacted] orders per day with a current operating capacity of [redacted]% and a physical capacity of [redacted] mt^2. As all DCs are predominately a 'next day delivery service', the start of operations is driven by customers placing orders and ends with the delivery to customer. Moreover, the RDC is able to serve as a cross-dock facility or stock point for other LDCs in the region.

Local Distribution Centers (LDCs): LDC-[redacted] is similar in technology characteristics as the RDC. This facility is able to handle up to [redacted] orders per day with a current operating capacity of [redacted]% and a physical capacity of [redacted] mt^2. On the other hand, LDC-[redacted] is a smaller warehouse with automation limited to a conveyor belt. This location is able to fulfill up to [redacted] orders per day with a current operating capacity of [redacted]% and a physical capacity of [redacted] mt^2.

2. METHODOLOGY

The purpose of this section is to present a methodology that will guide the course of the project. In their book, van Aken et al (2007), describe the nature of a Business Problem-solving Project and presents a set of guidelines for students to solve these type of projects. The setup of this project will follow a *regulative cycle* proposed by Van Strien (1997). It presents all the elements that should be taken into account in a research project. The regulative cycle consists of five phases: Problem definition, Analysis and diagnosis, Plan of Action, Intervention and Evaluation.

2.1. Problem definition

The first step is based on the identification of a problem and an agreement between the company and the student. The problem is analyzed and accurately formulated, leading to the formulation of the research objectives. Chapter 3 is dedicated to this phase of the methodology.

2.2. Analysis and Diagnosis

In the second step, quantitative and/or qualitative methods will be used to produce specific knowledge on the context and nature of the problem. In this phase the current process of replenishment is investigated and a quantitiative approach is used to explore the characteristics of the system. The outcome of this phase is the selection of a replenishment policy that fits the characteristics of the regional supply chain. Chapter 4 presents a literature review concerned to the problem and chapter 5 presentes the analysis and diagnosis of the current inventory system providing answer to the first research sub-question.

2.3. Plan of action

In this phase, the selection of a method to solve the second research sub-question based on the outcome of the analysis and diagnosis is described. This includes a detailed solution based on concepts found in the literature. Chapter 6 and 7 present the methodology carried to find the optimal parameters for the replenishment policy selected, this includes the determination of the optimal lot size (chapter 6) and the calculation of the optimal reorder points (chapter 7). Alongside, in chapter 8 a plan of action for the evaluation of the replenishment policy is described, it includes a description of the simulation model used to evaluate the customer service level at the LDCs.

2.4. Intervention

During the intervention, the analytical model is implemented and the results are analyzed, providing answer to the second research sub-question. Chapters 9 and 10 provide details about the results of the analytical model and the simulation model correspondingly.

2.5. Evaluation

The objetive of this phase is to evaluate whether the outcome of the solution provides the desired results. The application of the findings and the limitations are available in chapter 11, followed by the general conclusions, recommendations and contribution to literature presented in chapter 12. The answer to the third reseach sub-question, regarding replenishment decicions and product characteristics is provided at the end of the report. These theoretical findings were used to select the replenishment and distribution decisions of the inventory system of this project, explained in the Analysis and Diagnosis section.

Part II: Problem Analysis

3. PROBLEM DEFINITION

This research project will focus on the development of an optimal replenishment policy for the two-echelon supply chain in the region of UK and Ireland. According to the characteristics of inventory planning and control process in the company, the final objective is to present a procedure to obtain the policy parameters that will optimize the inventory levels and meet the target service level.

3.1. Definition of the problem

The Supply Chain Planning Department at Office Depot has identified that one of the main problems is the current levels of stock at the LDCs and CDC. It is believed that one reason is the low demand responsiveness to some PB products that are sourced mainly from Far East locations. In addition, the high target service level causes the necessity of keeping high amounts of inventory in all locations.

Previous analysis performed by the company showed that in average, a PB product spends around [redacted] days in a LDC and [redacted] days in the CDC. [redacted]. It is believed that the excess inventory was originated due to a lack of trust from the inventory planners at the LDCs towards the vendors, including the CDC, regarding item availability and lead times. This lack of trust causes the inflation of order quantities, manual overwriting, setting of multiple safety stocks and an increase in the order frequency.

Goods are negotiated and purchased from vendors in Europe, China and other locations in the Far East based on the aggregated forecasts of all regions. These purchases and distribution logistics are planned at the European Headquarters in Venlo.

One of the regions that represent a large portion of the yearly profits in Office Depot Europe is UK and Ireland. In 2011, this region accounted for approximately [redacted]**%** of total European Cost of COGS of PB. Therefore, at the moment there is an increasing number of direct shipments to this region using both shipping methods, direct through the RDC and direct to LDC. In addition, the technology and capacity at the RDC – [redacted] allows unloading of containers, storing goods and shipping stock to other LDCs in the same region. In order to reduce stock and operations in the CDC, which are expensive; this study is aimed at investigating a replenishment policy focused only in the regional supply chain of UK & Ireland. It will be assumed that all the PB assortment planned by supply planners in Venlo has a Direct shipping through RDC or a Direct shipping flow to LDC, disregarding the use of the Indirect shipment (through the CDC)

It is expected that the total regionalization of inventories using the RDCs in each region, instead of the central warehouse, will significantly reduce the inventory levels, ensure the high customer service levels and improve the coordination and communication between the parties involved. An important reason for the selection of this study is the country-specific assortment of PB. Approximately [redacted]% of the SKUs stored in the CDC are used in all regions. The regionalization is then regarded as a solution to improve and simplify the inventory replenishment process.

The following figure 6 represents the two-echelon supply chain and the distribution channels that will be the focus of this study.

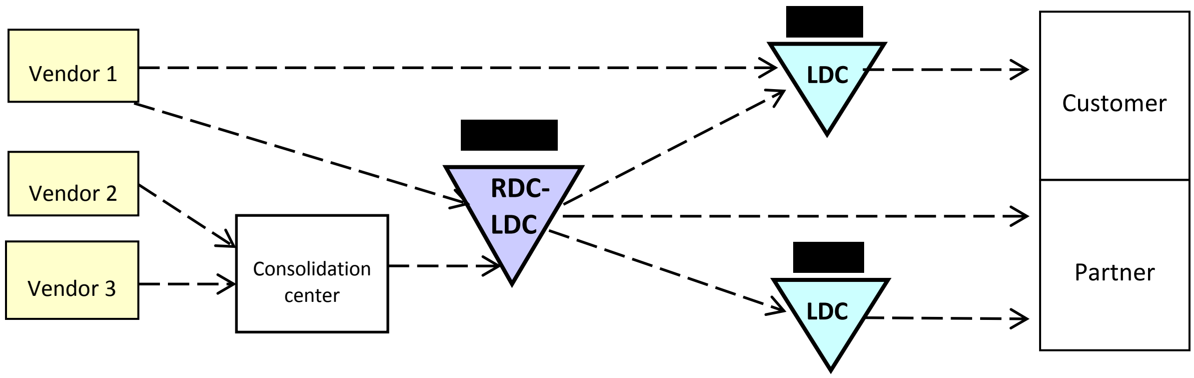


Figure 6. Regional supply chain in the region UK & Ireland

As seen in the figure, goods from the Far East can be consolidated by origin port before they are shipped to the RDC. It is also the case that the vendor sends stock directly to the RDC. This is the case of European vendors and some Far East vendors that do not use the consolidation center. Once the goods are stored in the RDC, orders from the LDCs at [redacted] and [redacted] are received and shipped each week. At the same time, the RDC also experiences customer demand. For a limited set of products the direct delivery to the LDC- [redacted] is possible. The selection of the distribution channel for each product will be defined beforehand and used as input in the model.

Given the context described, the problem is related to the inventory management in a two-echelon supply chain that consists of one central depot (RDC - [redacted]) and three LDCs: [redacted] (from hereafter, [redacted] is defined also as a LDC due to the existence of customer demand). Specifically, Office Depot is interested in developing an inventory strategy to plan and control the inventory at both echelons, taking into account the satisfaction of a target customer service. The ultimate goal is to analyze the performance of such system from the customer service level point of view and provide the company with recommendations that can support future managerial decisions in case of regionalization of inventories.

3.2. Research Questions and Objectives

The objective of this research project is to develop an inventory replenishment strategy for the reconstruction of the distribution network in the UK & Ireland, in such a way that the costs related to inventory are minimized. The main research question is

How to plan and control inventory in the two-echelon supply chain in the region of UK & Ireland?

Next to the main research question, the following sub-questions are identified:

What replenishment policy to use?

What are the control parameters for each SKU at each location?

How to make replenishment decisions based on product and channel characteristics?

The first research sub-question will be answered based on an analysis and diagnosis of the current system and the literature study. Once the replenishment policy has been established, the methodology to find the optimal control parameters of the replenishment policy is described. Then, the performance of the policy is tested analytically and with simulation. The purpose of the last research sub-question is to provide managers with a theoretical perspective regarding replenishment and distribution decisions for individual items or subset of items based on their characteristics and the distribution channel characteristics. Since the project is focused on one replenishment policy with its own characteristics and assumptions for the PB assortment, it is implied that one set of decisions has been selected from the other possible decisions.

3.3. Scope of the research project

This research project is focused on those products that would be sourced and planned in the headquarters, no matter whether the product is shipped thorough the RDC or direct to LDC. The selection of vendors and SKUs was based on only active items with at least one demand occurrence in the year 2011. Appendix A presents an overview of the vendors, the number of SKUs per vendor, the category of products, the percentage of the total COGS, the total lead time (including production lead time consolidation and transportation) and the port of origin. The list consists of [redacted]. Table 2 shows the number of SKUs per warehouse, distribution channel and origin.

CONFIDENTIAL

Table 2. Selection of SKUs for the project

The scope of the project is the determination of a replenishment strategy for the items indicated. It is important to clarify that only one type of policy will be analyzed for all products. The input information is based on the three DCs in the region: [redacted], [redacted] and [redacted]. Since the supply chain in this study does not involve the use of CDC anymore, the study is not aimed to improve the current situation but to analyze the two-echelon regional supply chain. Then, propose a replenishment strategy and evaluate the performance in terms of inventory value and service level. In order to check whether the solution can provide better results in terms of inventory level, the current inventory value is also presented in the results and confronted with the solution.

Part III: Analysis and Diagnosis

The following chapters provide the literature review related to the problem and the research questions. The findings in the literature and the diagnosis of the characteristics of the inventory system in Office Depot, will guide the determination of a set of distribution control decisions and the selection of a replenishment policy, providing answer to the first research sub-question: "*What replenishment policy to use?*"

4. LITERATURE REVIEW

The literature review is based on the techniques available to control a distribution system. Next to the decisions on *how* to control the distribution systems, the decision techniques on *how much* and *when* to order are investigated. Finally, an overview of the literature about policies in two-echelon divergent supply chain is summarized.

4.1. Distribution Control Decisions

Distribution control may be defined as "*All the activities taking place to coordinate the place and timing of demand over a finite horizon with the supply of products and capacities, in such a way that the objectives of the distribution process are met, given the characteristics of the product and the requirements of the market*" (De Leeuw et al., 1999). These control techniques are divided into certain control decisions that are: Allocation Coordination, Central stock function, Status of information and Type of reorder planning.

4.1.1. Allocation coordination

The decision of the degree of centralization of the allocation coordination. In a decentralized coordination the allocation quantities need to be determned by the LDCs, so locally each planner decides on their requirements. In a decentralized coordination, allocation quantities are determined by a local authority which can be the RDC. In terms of costs, the central control has advantages, however, this coordination is naturally more difficult to apply.

4.1.2. Central stock function

The decision about the stock position of inventory in the distribution system. This is whether inventory is stored in the central DC for the needs of LDCs or whether it is possible to use the central DC as a cross-docking point only or to totally avoid the use of a central DF. According to De Leew et al., (1999), having a central stock is beneficial for high value products, for products with high fluctuating demand, for long supply lead times and for high probability of imbalance.

4.1.3. Status of information

Status information consists of the type of information about demand and stock levels in the distribution system. The status of information that is used in the replenishment decisions can be either local or integral. Local status information (also called installation-stock) refers to the information about demand of the next downstream location and local inventory levels only. Integral information (also called echeon-stock) is information about the end-stockpoint demand (or customer demand) and the inventory levels at all downstream locations.

The question whether integral or local information should be used in the replenishment of items is closely related to the topic of stock imbalance. Stock imbalance is related to demand uncertainty and lot sizing. (De Leeuw et al.,1999). The imbalance affects the performance in a system with a central DC when there are considerable long order cycles due to large lot sizes and variation of demand.

4.1.4. Type of reorder planning

The type of reorder planning is categorized as the planning of independent and dependent demand. Independent demand is the demand of the final customer and dependent demand consists of the requirements from the LDCs as faced by the central DC. (De Leeuw et al., 1999). The planning technique of independent demand or in other words, the selection of the forecast technique, is out of the scope of this project. With regard to dependent demand from the LDCs, two possibilities are idenfitied. The first, the **time phased planning technique** is aimed at predicting the moment which a new order is generated by the lower echelon and the order is planned in such a way that the stock is avaialble just before it is needed. The second, is a **reactive logic** in which the pattern of reorders over time is discarded and the LDCs are replenished up to a specific level based on the stock norms of the LDCs.

The most common time phased technique is the Distribution Requirements Planning (DRP) in which the demand requirements of each product and each LDC are projected in a schedule. Schedules for the same product are integrated to determine the overall requirements for replenishing the central warehouse. The schedules are developed using weekly, daily or monthly time increments or buckets, in which one period of activity is projected. According to De Leeuw et al., (1999), time phased dependent demand calculation is beneficial if there are strong and stable patterns in the demand from the LDC at the CDC. These patterns may be the result of large distribution batch sizes or of large customer orders. In addition, this logic requires accurate and coordinated forecasts. In general, any type of uncertainty and variability such in supply lead times, vendor delivery reliability, and order cycles causes system nervousness and frequent re-scheduling of the planning strategy, leading to higher amounts of safety stocks.

On the other hand, as the name implies, in a reactive system each member reacts to its own inventory needs by placing a replenishment order to the immediate predecessor when the available stock levels reach a reorder point. Usually, each LDC makes replenishment decisions locally and the CDC also orders independently to the suppliers. According to Bowersox & Closs (1996), in this type of system, it can be difficult to coordinate the inventory requirements across multiple retailers, due to independency of replenishment orders. In addition, using the correct parameters is fundamental; overestimating the policy parameters can lead to overstock, while underestimating the parameters can lead to a propagation of backorders through the supply chain and the reduction of customer service level.

4.2. Inventory Control Decisions

Inventory control decisions are perhaps one of the most complex problems in supply chain management. The conflicting objective is to meet the target customer service while keeping inventory levels as low as possible. The important decisions in inventory control are: (1) the review time of inventory stock, (2) the reorder point that triggers an order and (3) the quantity to order.

The classic inventory control methods are based on the decisions of the order quantity and the time when orders are placed. They are also used when demand and supply lead time are deterministic or stochastic. Table 3 summarizes four classic control systems.

	Continuous review	Periodic review
Fixed lot size (Q)	(s,Q)	(R,s,Q)
Variable lot size	(s,S)	(R,s,S)

Table 3. Classic inventory control systems

In the continuous review, with fixed lot size (**s,Q**), the inventory position is continuously tracked, and when it is equal or below the reorder point (***s*),** an order equal to the fixed lot size (**Q**). In a (**s,S**) system the order is placed to raise inventory position to a certain order up to level (**S**). The time between placements of orders may fluctuate given variable demand.

In the periodic review with lot size **(R,s,Q**) every (**R**) units of time the inventory position is compared with the reorder point (**s**)and an order lot size (**Q**) is ordered only if the inventory position is equal or below the reorder point. The (**R,s,S**) follows the same logic but the order placed is equal to the difference between the actual inventory position and the order up to level (**S**).

4.2.1. Inventory Control in a two-echelon divergent supply chain

The motivation for using a multi-echelon inventory system rather than a single-echelon approach in each location, is that single-echelon approaches can lead to a poor coordination, delays and/or information distortion between suppliers and customers. All these aspects are translated into the so-called *bullwhip effect* or the increase in demand distortion that moves upstream towards the manufacturers, causing inefficient use of resources and high transportation and inventory holding costs, (de Kok, 2003).

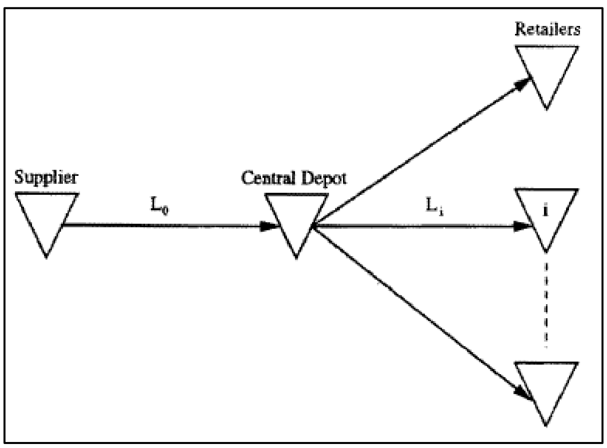


Figure 7. Representation of a 2-echelon divergent

There are several authors who have approached this type of inventory systems. These can be categorized by the type of information used: *installation-stock* policies and *echelon-stock* policies (or integral information).

In the first type, Axsater (2003) and Ganeshan (1999) have studied continuous review policies with lot sizing. Regarding periodic review policies, Seifbarghy & Jokar (2006) and Cachon (2001) provide analytic models to find the exact solution for a divergent system with lot-sizing. Finally, Rosenbaum (1981) presents a heuristic for placement of safety stocks assuming lot sizing at the LDCs and an 'order-up-to' policy at the central depot.

In the second type, authors focusing in echelon-stock policies include Giannoccaro & Pontrandolfo (2002) who provide a solution for the continuous review system without lot sizing. With regard to echelon-stock policies with periodic review, Van der Heijden (2000) and De Kok & Fransoo (2003) have extensively studied heuristics and optimal solutions of such policies without lot sizing. Research of policies with lot sizing and echelon-stock is more limited due to the large effect of lot sizes in the risk of imbalance. Van Donselaar (1990) provides an approximation of integral stock parameters for all locations with lot-sizing and assuming identical retailers with respect to their lead time, review period and demand characteristics.

The selection of the literature that will guide the determination of the policy parameters depends on the type of policy selected for this project and the characteristics of the inventory system. Next chapter is dedicated to this analysis.

5. REPLENISHMENT POLICY SELECTION

In order to define the distribution control decisions and the inventory control decisions it is necessary to explore the nature of the inventory system. The characteristics analyzed include demand variability, lead times, existence of demand patterns, ownership of replenishment decisions and current IT capabilities.

5.1. Distribution control decisions

Allocation coordination: The decision on the degree of centralization depends on the way the replenishment decisions are owned by the different actors within the supply chain. Although, the regional supply chain belongs to the same company, the decisions of when to order and how much to order to suppliers are taken by the supply chain department in the headquarters. The department has a yearly budget which is used to cover all expenses related to transportation, storage and handling of inventory from the point of purchase until the delivery to the LDC. On the other hand, locally, each inventory planner makes the replenishment decisions based on the local requirements. Given these facts, the allocation coordination for the inventory system is a *decentralized coordination* in which allocation of quantities is not determined by a central authority, but it is locally determined.

Central stock function: As described in the literature review, a central stock function is beneficial for high value products, for products with fluctuating demand, products with long lead time and when the risk of imbalance is high. With respect to product value, the range of carton value is very large, with carton value that varies from € [redacted] to € [redacted]. The most expensive items belong to the categories of toners and chairs, with an average value of € [redacted] per selling unit, representing the largest portion of the turnover.

With regard to the lead times, [redacted]% of the assortment it is sourced from the Far East, with an average lead time of 70 days. According to De Leeuw (1999), if supply lead times are long, central stock is needed due to higher uncertainty.

An important characteristic is the demand variability. One of the most common measures of the variability is the coefficient of variation (CV) defined as the ratio of the standard deviation and the average demand. Items with CV greater than 1 are categorized as having a high variability. Table 4 presents the CVs of all SKUs over the three LDCs. The CV was measured with data of weekly demand during one year period from March 2011 until February 2012.

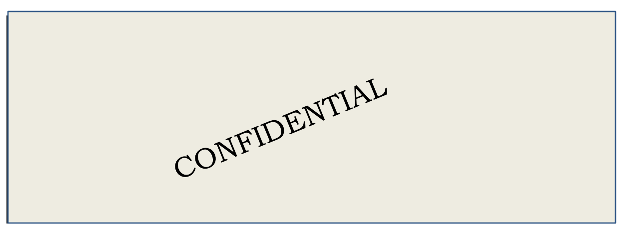


Table 4. Number of SKUs within the CV range

As seen in table 4, around [redacted]% of the assortment has a high variability in [redacted] and [redacted], while in [redacted], the demand fluctuates more, with more than [redacted]% of the items with high variability. Furthermore, figure 8 shows the distribution of the total demand in the region by the COGS incurred in the year 2011. In conclusion, the inventory system is composed of two warehouses with high demand rates and medium-small variability in most of the products, and the third warehouse with low demand rates and highly fluctuating demand. These findings suggest that risk of imbalance can be high, due to large differences in order cycles and so, central stock can also be beneficitial to correct this imbalance. The decision of a *central stock function* is chosen for all the assortment and vendors in the

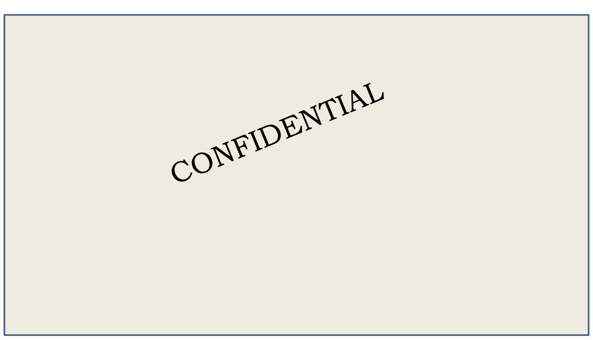


Figure 8. COGS in 2011 per LDC

warehouse of [redacted]. In the case of [redacted], additional aspects have been taken into consideration: the combination of high physical volume of items and the costs of transportation with the demand rates. In particular, this is the case of chairs sourced in the Far East, that have a high turnover with stable demand for which transportation costs are relatively high due to the number of FCL needed to satisfy the requirements per period plus additional transportation costs between RDC and LDC. Currently these items account for almost [redacted]% of the total sales in the region and the time between replenishments is two weeks shorter than for other products sourced from Far East.

It has been decided than in order to avoid inland transporation costs and storage costs at the RDC, the SKUs belonging to the two Far East vendors of chairs ([redacted]) will follow a direct flow to LDC-[redacted]

Moreover, attention is also paid to the European vendor of toners ([redacted]) that accounts for [redacted]% of the annual sales in the region. The number of SKUs of this vendor is [redacted] with high product value and sales that varies a lot from one model of toner to another. In addition, the purchase price paid to this vendor includes the freight charge to any of the DCs in the region. According to De Leeuw (1999) it is suggested to avoid the central stock function for products with stable demand and high order frequency as well as to keep centrally the high value products. Therefore, in accordance with the company supervisor, it has been decided to assume a direct flow to [redacted] only for the fast moving toners. The assumption is to have a direct flow of toners with order cycle shorter or equal to 2 weeks ([redacted] SKUs) and to keep a central stock function for the rest of the SKUs which have lower demand rate demand but high product value.

Status of Information: Whether local (installation-stock) or integral information (echelon-stock) will be used or not to take replenishment decisions depends mainly on the IT capabilities of the company and the visualization of all inventory levels throughout the supply chain.

When using **installation-stock** the inventory position of a stockpoint is defined as: *All planned orders at this stockpoint + Physical stock - backorders at this stockpoint*. On the other hand, when using **echelon-stock** the echelon inventory position of a stockpoint is defined as: *All stock in transit to this stockpoint + physical stock + stock in transit to and/or on hand in its downstream stockpoints – all backorders at the end-stockpoints.*

The advantage of the systems with installation stock is that there is no need for an exchange of information about stock levels between stockpoints. However, the upstream locations could be unable to react quickly to strong changes in demand due the delay in information reflected in the upcoming orders. Inventory systems using echelon stock have been proved to be more cost efficient, but determining optimal parameters is a difficult task. Furthermore, a rationing policy needs to be defined in order to allocate the available echelon stock at the depot over the retailers. When the echelon inventory is not balanced throughout the stockpoints, the system has a risk of “imbalance” or negative allocations of stock. Thus, echelon stock policies should also take the imbalance into account.

[redacted] For this reason and due to the advantages seen in using echelon-stock information, the inventory system studied in this project will use *integral information*.

Type of reorder planning: The selection of a reactive logic rather than a DRP system is also influenced by the IT capabilities of the company and the characteristics of the inventory system.

As described in the literature review, a DRP system is suitable when the demand can be accurately predicted; thus relying on the quality of the forecasts. It is also recommendable when demand has strong patterns as trends or seasonality. In addition, a time-phased planning logic is recommended in situations where the time between elapsed between the arrival of orders is rather long.

[redacted].

With regard to the existence of strong demand patterns in the overall demand, demand of 2010 and 2011 was plotted in the same chart for a random sample of 100 SKUs at the three LDCs. For the case of [redacted], a majority of the sample displayed random and unstable behavior that does not seem to be correlated with time. Even items within the same category showed different demand behaviors. Visual inspection for [redacted] and [redacted] showed that the overall, demand of 2011 follows a similar pattern as demand of 2010. Some of the SKUs have an increased demand in the first and last weeks of the year, while other items have the increase in the middle of the year. The difference in patterns differs for each category, and even more, for items within the same category. However, the overall increase in demand is not significantly greater than the average and so, the variability seems to have a stronger impact than seasonality patterns.

Finally, the IT system available for replenishment decisions in Office Depot does not currently support the application of a time-phased planning. In conclusion, due to the lack of strong and defined patterns in demand, the questionable quality of the sales forecast projected locally, the proportion of the assortment that display high coefficients of variations and the current IT capabilities, a *reactive logic* for all SKUs within the scope of this project is selected.

In summary, the inventory system of this study will have a decentralized decision making, with a central stock function for all items at [redacted] and [redacted] and for [redacted]% of the items at [redacted]. Integral or echelon-stock information will be used and the type or reorder technique will follow a reactive logic.

5.2. Inventory Control Decisions

The purpose of this section is to define the type of inventory control system. The two main characteristics is the type of inventory review (continuous or periodic) and order quantity (fixed lot size or variable lot-size)

Inventory Review: In the case of continuous review, the stock level is monitored constantly and, immediately after this level drops below a reorder point, an order can be placed to replenish the stock. In the case of periodic review, the stock level is inspected periodically, so that orders are generated at review moments only (de Kok et. al, 1996).

Currently, the LDCs orders are placed every week towards the CDC according to the status of the inventory at that point, the assumption for the regional supply chain will be the same, meaning that there is a *periodic review* and so, the period review of LDCs is equal to **one week**. However, [redacted] as LDC is situated in the same warehouse as the RDC, and so, the assumption is that inventory in LDC-[redacted] is reviewed daily; thus this LDC has a review period equal to **one day**.

At the upstream echelon, the review period varies between vendors. The Far East vendors whose orders can be consolidated for transportation benefits have a review period of 4 or 5 weeks. The review period for vendors that have established MOQs equal to FCL or FTL is usually longer, so orders are placed between longer periods of time in order to fulfill the vendor requirements and the demand requirements. The table in Appendix B presents the review periods in weeks that will be assumed in this study.

Order quantity: The type of order quantity refers to whether an order can have any value in order to raise the inventory level up to certain point or whether orders have to be placed according to a lot size. In this inventory system, each vendor has defined a fixed quantity of selling units in a master carton (the minimum distribution lot size). According to the European Guidelines of Office Depot, for quality and efficiency reasons, vendors are required to supply in the following ways: A complete pallet, a pallet layer or multiple of layers, or a complete carton. These guidelines are also applicable for items shipped from the RDC. Figure 9 provides a graphical representation.

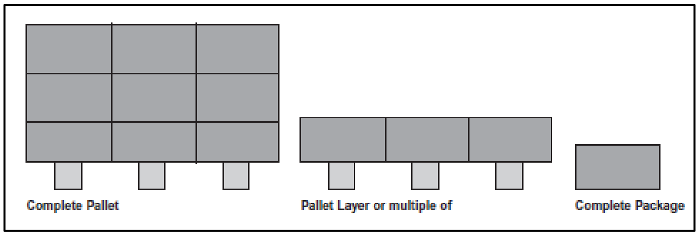


Figure 9. Representation of the three lot sizes

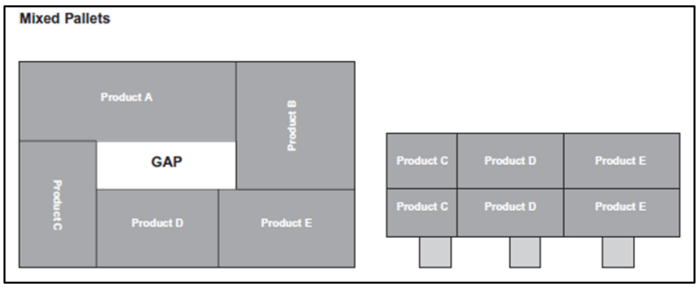


Figure 10. Representation of the mixed pallet when ordering in cartons.

In consequence, this is the logic that would guide the inventory planners at both echelons when deciding on the order quantity. Inventory planners have information of the number of selling units in per carton, per pallet layer and per complete pallet, and the order quantity would be equal to one of these lot sizes or a multiple of the lot size.

Due to transportation procedures, when ordering a certain number of cartons, that do not fit a layer or a complete pallet quantity, these are also expected to be received on a pallet. In these cases, the vendor allocates the cartons in a mixed pallet that must be sealed with plastic. The mixed pallet should be built according to figure 10.

5.3. Inventory Control Policy

Given the characteristics presented in the sections below, the inventory policy selected for this system is a *(R,s,nQ)* policy, in which every review period *R* the echelon-inventory position is reviewed, if it is equal or below to a reorder point s, an order equal or a multiple *n* of a lot size *Q* is placed.

At the LDCs the policy is represented in Figure 11. This is, every *R* periods the local Inventory position defined as the stock on hand plus outstanding orders minus

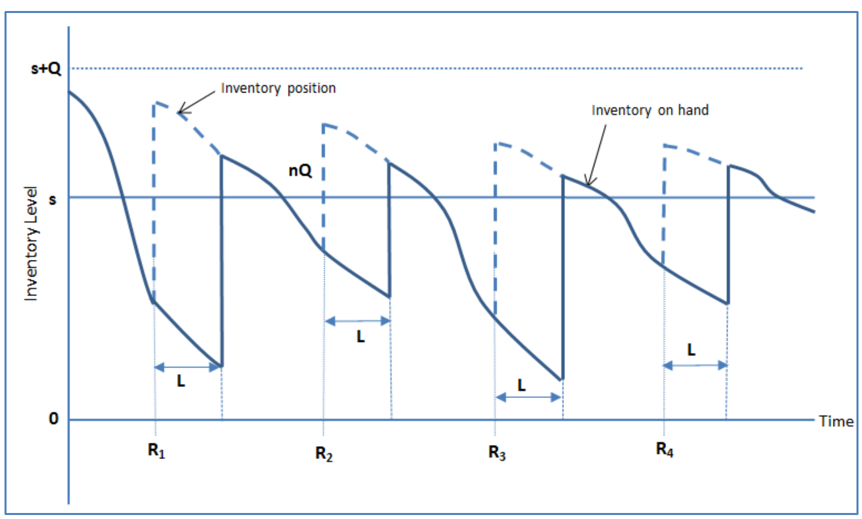


Figure 11. Inventory position and inventory on hand in the (R,s,nQ) policy at the LDCs

the backorders is compared with the reorder point S_{ij}; if it is equal or below to the reorder point, an order equal to $n_{ij}Q_{ij}$ is placed, where Q_{ij} is the lot size, and n_{ij} is an integer number such that the order $n_{ij}Q_{ij}$ raises the inventory position above the reorder point. In the graph an order is placed in every reorder period, however, if the inventory position does not reach the reorder level, no order is placed for that review period. The maximum level that the inventory can reach is equal to the reorder level plus the lot size.

The lead time to the LDC will be assumed to be one day. This study will assume deterministic lead times.

The policy for item *i* at the RDC is represented by figure 12. In this case, every review period *R*, the echelon inventory position defined as the sum of the local inventory positions at the LDCs plus outstanding orders to the external supplier, is compared with the reorder point S_i, if it is equal or below to this value, an order of n_iQ_i, where Q_i is the lot size at the RDC, and n_i is the minimum integer number such that the order n_jQ_i raises the echelon inventory position above the reorder point.

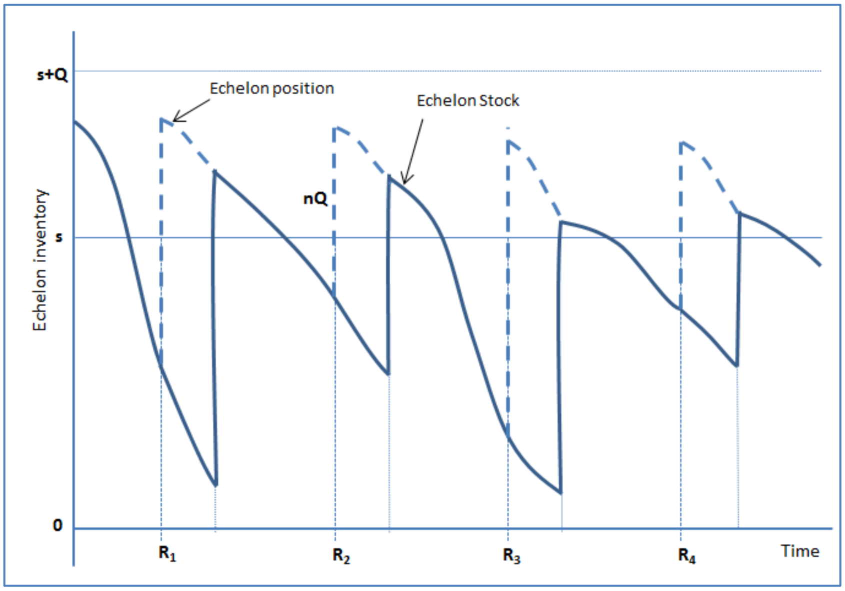


Figure 12. Echelon position and inventory on hand in the (R,s,nQ) policy at the RDC

The inventory policy selected assumes in case the inventory on hand at the RDC is not enough to fulfill an order from the LDC, partial fulfillment of orders. The allocation rule assumed will be explained in detail in chapter 8 with the description of the simulation model.

In the case of customer demand at LDCs, when customer demand cannot be fulfilled, it can be backordered or partially fulfilled with the available inventory. In reality, when the LDC is out of stock, the customer has three options: to wait until the product is available (backorders are allowed), to substitute with a similar product or to cancel the purchase. The first two outcomes are most likely to happen.

In summary, the inventory policy selected for both echelons has the following characteristics:

- Inventory is reviewed periodically
- Orders are placed when the inventory position is equal or above the reorder point
- The order placed is equal to a lot size or a multiple of a lot size necessary to bring the inventory position above the reorder point
- Customer demand can be backordered
- Partial shipments are allowed to every LDC and to customer.
- Deterministic and fixed lead times
- Echelon-stock inventory information is used to replenish the RDC

Part IV: Plan of Action

The purpose of the plan of action is to describe the procedure, assumptions and models used to obtain the optimal parameters in the (R,s,nQ) policy selected, these parameters are lot size (Q) and the reorder points (s). The outcome of the following chapters is used to provide the answer to the second research sub-question "*What are the control parameters for each SKU at each location?*"

6. POLICY PARAMETERS – Optimal Lot Size

In the current situation, at the upper echelon, the inventory planner aggregates the forecasts of all LDCs and based on the forecasted monthly demand, the order is placed towards the vendors. The orders are placed in terms of multiples of a lot size: Carton, Pallet Layer and Full Pallet, and the decisions are only based on the average demand of the last 6 months and the forecast. Inventory related costs are not involved in the selection of the lot size. On the other hand, currently the LDCs place an order to the CDC based on a given MOQ that most of the times is equal to an outer carton. This means that it is possible for an LDC to place an order equal to one carton every week.

The most common approach in determining the appropriate order quantity is the Economic Order Quantity, also known as the EOQ, based on the minimization of total relevant costs; relevant in the sense that they are affected by the choice of the order quantity. This approach takes into account the purchase costs, the ordering cost and the carrying costs. As explained in section 5.2, there are three base order quantities that are handled in the DCs: Carton, Pallet layer and Full pallet. The methodology to define the cost optimal lot size is to compute total relevant costs for the average order size in each of the LDCs for the three lot sizes, then, the lot size with the minimum cost will be selected.

6.1. Relevant Costs

The costs measured in the cost function are those that significantly change when the lot size changes. These are: Inventory handling costs and the Inventory carrying costs.

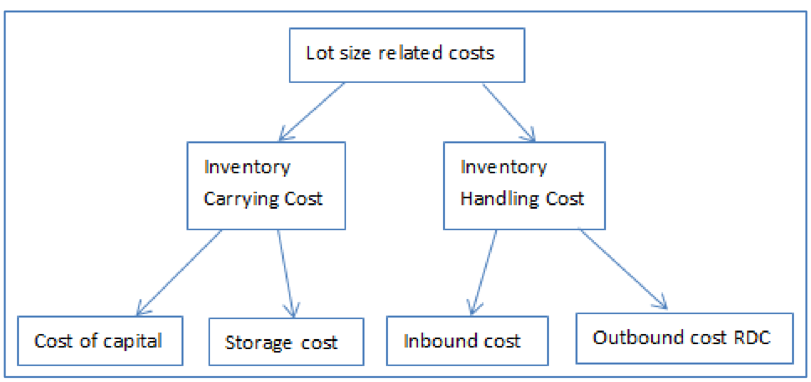


Figure 13. Relevant costs that change with the value of the lot size.

The inventory carrying costs are normally expressed as a percentage of each dollar carried on the average inventory throughout a full year. It includes costs of capital invested, insurance, taxes, obsolescence risk and storage. The two significant costs taken into account are the cost of money invested in inventory and the cost of storage space in the warehouse.

The handling costs are those involved in the activities of inbound and outbound of each order at the warehouses. Manual activities such unloading a container, palletizing and storing goods in the warehouse are included, as well as the expedition of orders from the RDC to the LDCs.

Other costs such freight from the supplier are assumed to be fixed; for Far East suppliers, freight is paid on containers that can transport multiple consolidated orders and volumes of shipment can vary from one order to another. For some European vendors, the purchase price already includes the freight cost to the warehouse, most of the times. Transportation costs between warehouses are out of the scope of this project, given the assumption that there will be enough availability and capacity in the transportation between the RDC and LDCs with a fixed cost.

In the next subsections, the calculation of each cost is explained in detail.

The total cost function for the RDC and LDCs are the following:

TCF_{RDC} = Cost of capital + Inbound cost +Warehouse storage cost

TCF_{LDC} = Cost of capital + Warehouse storage cost + Inbound cost + Outbound cost at RDC

6.2. Cost Model at RDC

The first step is to calculate the integer number *n* of lot sizes that will cover the average demand during the time between arrivals of orders; which is the length of the review period. The formula to compute *n* is the following:

$$n_{i,x} = \left\lceil \frac{\sum_j \mu_{ij} R_i}{Q_i^x} \right\rceil \tag{6.1}$$

Where:

$n_{i,x}$ = number of lot sizes x of item i, where x= carton, layer or pallet
μ_{ij}= Average weekly demand of item i at LDC j, in selling units where j: [redacted], [redacted] or [redacted], computed from March 2011 until February 2012, assuming 52 weeks in the year.
R_i=Review period of item i in weeks
Q_i^x= Number of selling units of item i in a lot size x

6.2.1. Cost of Capital at RDC

The costs of capital denotes the money tied up which has been borrowed or directly spent by the company in exchange for the inventory, this value depends on the internal interest rate at Office Depot. According to Silver et al. (1998), the most common convention of costing is to use:

$$\mathrm{C_i = \bar{I}_i * v_i * r} \tag{6.2}$$

Where:

$\boldsymbol{\bar{I}_i} = \frac{\boldsymbol{n_{i,x} * Q_i^x}}{\boldsymbol{2}}$ is the average cycle inventory in a system with lot-sizing
$\boldsymbol{v_i}$= is the landed value of the item $\boldsymbol{i}$
$\boldsymbol{r}$= annual internal interest rate at Office Depot, that is given by the company as [redacted]%

6.2.2. Inbound Cost at RDC

The inbound cost differs by vendor. In the case of Far East vendors, goods arrive to the RDC in 20" or 40" containers in form of loose cartons. The inbound activities include unloading the cartons, sorting by SKU, placing the cartons on a pallet, checking the packing list, wrapping and sending the pallets to the storage location.

In case of European vendors, goods arrive in trucks already palletized. Therefore, the inbound activities include unloading the pallets, checking, scanning the barcode and sending the pallet to the storage location. In case multiple SKUs arrive in form of a mixed pallet, additional activities are necessary. The plastic wrap is opened; the cartons are sorted and allocated by SKU on pallets for internal distribution to the picking locations of full case (or carton). Before these are stored, each carton is labeled with a barcode.

- **Inbound cost of containers: Unloading, checking, palletizing and storing**

Each month, containers arriving to Europe contain consolidated orders from multiple vendors. The time spent in inbound highly depends on the number of cartons, SKUs in each container and the size of the cartons that determines the number of pallets needed.

Currently, when a container is unloaded, the total inbound time and the number of cartons and pallets used are registered. This historical data base contains information of [redacted] containers unloaded in [redacted] during 2010 and 2011, with information on the number of cartons offloaded, number of pallets required and hours spent in unloading, palletizing, checking and wrapping. Appendix C presents the details of these observations.

Given the data available, the most accurate method to estimate the inbound time for each of the lot sizes is multiple regression analysis. This is a statistical technique that can be used to analyze the relationship between a single (criterion) dependent variable and multiple independent (predictor) variables. In this case, the predictors are: 'Number of cartons offloaded' and 'Number of pallets'. The variable predicted is the inbound time in hours. Details of the regression analysis are presented in Appendix D.

The results of the regression analysis suggest that unloading one carton from the container requires [redacted] minutes and preparing a pallet to be stored would take [redacted] minutes. A fixed time spent in lifting the pallet and placing it in the storage location must be added.

The [redacted] minutes include the following activities: unloading the cartons, placing them on the pallets, checking the packing list against the content of the pallet, wrapping the pallet with plastic folio and labeling. This time applies to lot sizes of <u>pallets and layers.</u>

It is assumed that full pallets and layers are stored in the VNA (Very Narrow Aisles) section, which is an area with a width in aisles of 1.2 meters with pallet racks that have 8 levels of height above ground level. Figure 14 shows a picture of this type of pallet racks.

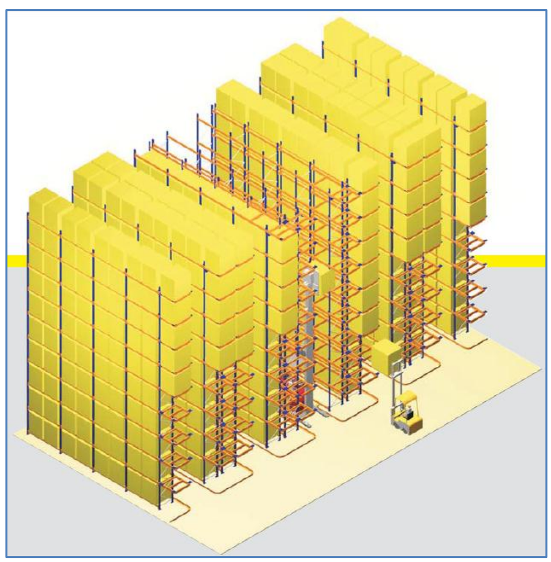


Figure 14. Pallet racks in the VNA section

At the end of the aisles there are 'Pick Up & Dispatch' stations in which a pallet moved from the inbound area is placed by a standard forklift truck and then, it is taken by a 'reach truck' or a VNA special type of machines that are able to lift the loads up to any level in the rack and that moves forward and backwards through the narrow aisles. According to estimations in the RDC, storing loads in this area takes [redacted] minutes in average.

The annual inbound cost is estimated by multiplying the average number of orders in a year, the inbound time of the batch size and the cost per minute. In the region UK &

Ireland the standard rate is £[redacted] per hour of labor force.

The notation used is as follows:

$n_{i,x}$ = number of batches with size x of item i, where x= carton, layer or pallet
TD_{ij}: Total yearly demand of item i in number in LDC j in selling units computed from March 2011 to February 2012.
Q_i^x= Number of selling units of item i in a batch size x,
IN_i^x= Annual cost of inbound of lot size x of item i

The annual inbound cost of ordering $n_{i,pallet}$ amount of pallets is estimated as follows:

$$IN_i^{pallet} = \left[[\text{redacted}] * \frac{\sum_j TD_{ij}}{Q_i^{carton}} + ([\text{redacted}]) * \frac{\sum_j TD_{ij}}{Q_i^{pallet}} \right] * \left[\frac{£[\text{redacted}]}{60} \right] \tag{6.3}$$

In case of receiving $n_{i,layer}$ layers, the time to palletize and store one pallet is multiplied by the rounded up number of pallets used.

$$IN_i^{layer} = \left[[\text{redacted}] * \frac{\sum_j TD_{ij}}{Q_i^{carton}} + ([\text{redacted}]) * \frac{\sum_j TD_{ij}}{n_{i,layer} * Q_i^{layer}} * \left\lceil \frac{n_{i,layer} * Q_i^{layer}}{Q_i^{pallet}} \right\rceil \right] * \left[\frac{£[\text{redacted}]}{60} \right] \tag{6.4}$$

In the case of receiving orders in cartons, the quantity received is checked against the packing list and each carton in labeled with a sticker. When, the quantity of cartons is less or equal to 50% of a full pallet, this is allocated in a pallet with other SKUs that will be stored in different picking locations but nearby locations, depending on the zone of the warehouse where the driver is assigned. According to inbound managers, in average, the number of different SKUs placed on a pallet for internal storage is 5 SKUs. This means that forklift will take one pallet to one zone of the warehouse where approximate 5 different SKUs will be stored in their respective picking locations.

Checking, labeling and placing the cartons on the pallet takes an average of [redacted] minutes per pallet that then is ready to be taken to the picking locations. This is assumed to be the same time needed when receiving orders in cartons from European Suppliers. These loose cartons are stored in locations for 'full case' picking in the area of Wide Aisles; consisting in pallet racks with 4 levels high above ground level, with usually more than 2.5 meters of space in the aisle and where a standard forklift truck is used.

The average time to take the pallet built in the receiving area and allocate the cartons in the ground locations is in average [redacted] minutes. Therefore, each time that $n_{i,cartons}$ cartons are received, the average time for the inbound process after the unloading, is [redacted] divided by the number of SKUs allocated at the same time, which in average is 5. If the average order size of a SKU is more than 20% of a full pallet, it is assumed this SKU is handled in the warehouse using single-SKU-pallets.

When the order size is more than 50% of a full pallet, it is most likely that cartons are stored in the high levels of the Wide Aisles, where pallets need to be wrapped. When this is the case, the time spent is longer and so it is assumed to be [redacted] minutes per pallet (the handling time resulted in the regression analysis). The time to allocate these pallets to the top levels of the wide aisles is assumed to be slightly higher and so, it is increased to [redacted] minutes.

Given this information, the annual inbound cost is calculated with the average number of orders received in a year, multiplied with the cost of the time spent in unloading each carton from the container and the time to allocate these cartons on a pallet and take them to the storage location.

$$IN_i^{carton} = \left[\text{[redacted]} * \frac{\sum_j TD_{ij}}{Q_i^{carton}} + \left(\frac{\sum_j TD_{ij}}{n_{i,carton} * Q_i^{carton}}\right) * b \right] * \left[\frac{£\text{[redacted]}}{60}\right] \quad (6.5)$$

Where:

$$b = (\text{[redacted]}) * \frac{1}{5} \qquad if \left(\frac{n_{i,carton} Q_i^{carton}}{Q_i^{pallet}}\right) \leq \frac{1}{5}$$

$$b = (\text{[redacted]}) * 1 \qquad if\ \frac{1}{5} < \left(\frac{n_{i,carton} Q_i^{carton}}{Q_i^{pallet}}\right) \leq \frac{1}{2}$$

$$b = (\text{[redacted]}) * \left\lceil \frac{n_{i,carton} * Q_i^{carton}}{Q_i^{pallet}} \right\rceil \qquad if\ \frac{n_{i,carton} * Q_i^{carton}}{Q_i^{pallet}} > 1/2$$

- **Inbound cost of European items: Unloading pallets, checking and storing**

Since European vendors deliver items already on pallets, the inbound process consists of unloading the pallets, checking the content against the purchase order and placing each pallet into the storage location. Unloading one pallet requires in average [redacted] minutes. After the pallet has been unloaded, the time to place it in the storage area should be added, this is the same [redacted] minutes taken for Far East products that are stored in the VNA area. The equation for inbound costs of pallets is:

$$IN_i^{pallet} = \frac{\sum_j TD_{ij}}{Q_i^{pallet}} * (\text{[redacted]}) * \frac{£\text{[redacted]}}{60} \quad (6.6)$$

When ordering layers, the time is multiplied by the integer number of pallets that accounts for the $n_{i,layer}$ ordered. The inbound cost per layer is computed as follows:

$$IN_i^{layer} = \left[\frac{\sum_j TD_{ij}}{n_{i,layer} * Q_i^{layer}} * (\text{[redacted]}) \left\lceil \frac{n_{i,layer} * Q_i^{layer}}{Q_i^{pallet}} \right\rceil \right] * \left[\frac{£\text{[redacted]}}{60}\right] \quad (6.7)$$

When the lot size is equal to cartons, these are usually shipped by the vendor in a mixed pallet containing other SKUs that were ordered in cartons as well. After offloading, the plastic wrap is opened and the cartons are sorted by SKU, checked against the PO, labeled with a barcode and placed on a pallet. In order to estimate the unloading time per carton, the time spent in one pallet is divided in the average number of SKUs received in a mixed pallet. The number of SKUs shipped in a mixed pallet has been computed with historical data of mixed pallets received during the first semester of year 2012 from the CDC; this number is equal to [redacted] SKUs. Following the same logic as in formulae 3.5 and 3.6, the following formula represents the inbound cost for the lot size equal to cartons:

$$IN_i^{carton} = \left[\frac{\sum_j TD_{ij}}{n_{i,carton} * Q_i^{carton}} \right] * [\text{[redacted]} a + b] * \left[\frac{£\text{[redacted]}}{60}\right] \quad (6.8)$$

Where:

$$a = \frac{1}{\text{[redacted]}}, if \left(\frac{Q_i^{pallet}}{n_{i,carton} Q_i^{carton}}\right) \geq \text{[redacted]}, else\ a = \left\lceil \frac{n_{i,carton} * Q_i^{carton}}{Q_i^{pallet}} \right\rceil$$

$$b = (\text{[redacted]}) * \frac{1}{5} \qquad if \left(\frac{n_{i,carton} Q_i^{carton}}{Q_i^{pallet}}\right) \leq \frac{1}{5}$$

$b = ($[redacted]$) * 1 \qquad if\ \frac{1}{5} < \left(\frac{n_{i,carton} Q_i^{carton}}{Q_i^{pallet}}\right) \leq \frac{1}{2}$

$b = ($[redacted]$) * \left\lceil \frac{n_{i,carton} * Q_i^{carton}}{Q_i^{pallet}} \right\rceil \qquad if\ \frac{n_{i,carton} * Q_i^{carton}}{Q_i^{pallet}} > 1/2$

6.2.3. Storage cost at RDC and LDCs

The third cost that changes with the lot size is the annual cost of storage in each DC. Costs for holding inventory include warehouse space costs and equipment maintenance. In the UK & Ireland storage takes place in rented warehouses managed by personal of Office Depot.

As a consumer DCs, the warehouses in [redacted] and [redacted] are characterized by a high degree of automatization, with a conveyor belt that allows an automatic process of picking selling units and full cases with the use of laser scanners along the conveyor. The area of interest is the one equiped with high pallet racks for storing full-pallets and layers, and the area for storing full cases. The capacities of the warehouses are given in the table 5.

CONFIDENTIAL

Table 5. Capacities of each warehouse in pallet spaces per warehouse location

In order to obtain a fair allocation of costs within the warehouse, the approach used is to allocate the total annual costs related to the operation of the warehouse, to the area used for storage, in [redacted] and [redacted] these are the areas for VNA and Wide Aisle and in [redacted] storage only takes place in Wide Aisles.

The annual costs includes: Building rent, property maintenance, real estate taxes, utilities (excluding telephone) and property insurance. The data obtained from financial managers does not include the use of equipment, in particular of the VNA machines which are more expensive than the standard forklifts trucks. Thus, an extra [redacted]% of the cost is allocated to the locations in VNA to account for the use of different equipment. In addition, the VNA section in [redacted] and [redacted] has a height of 15 mts to the ceiling, while the height of the rest of the warehouse is 10.5 mts; assuming linearity in costs, the pallet place in the VNA is increased with the correspondant difference in space.

CONFIDENTIAL

Table 6. Area of storage locations and cost per pallet in VNA area and Wide Aisles area

[1] The local costs were given in Pounds (£). Throughout the report the figures are presented in Euros (€). The following exchange rate was used for this matter: 1 £= 0.830095959 €

Table 6 presents the resulting annual storage cost per pallet place at each of the storage locations.

After establishing the storage cost and assuming the average inventory equals half of the order size, the annual storage cost of the average inventory is computed as follows:

$$S_i^{pallet} = \left\lceil \frac{n_{i,pallet}}{2} \right\rceil * s_{j,pallet} \quad (6.9)$$

Where:

$s_{j,pallet}$= annual cost of a pallet place in LDC j in VNA for j=[redacted] and [redacted] and in Wide Aisle for j=[redacted]

In the case of layers, it will be assumed that when the size of the pallet is less or equal than half pallet load, the cost assigned is half of the rate of a pallet space, given that the space usage is less. The cost is computed as follows:

$$S_i^{layer} = \left\lceil \frac{n_{i,layer} Q_{layer}}{2 * Q_{pallet}} \right\rceil * s_{j,layer} \quad (6.10)$$

Where:

$$s_{j.layer} = \frac{s_{j,pallet}}{2} \quad if \quad n_{i,layer} \leq 0.5 * \left(\frac{Q_{i,pallet}}{Q_{i,layer}}\right) \quad else, \; s_{j,layer} = s_{j,pallet}$$

In the case of cartons, the storage cost can be approximated by multiplying the cost of a pallet space by one fifth to include enough tolerance space for handling activities. For high volume products with less than 5 cartons fitting on a pallet, this rate is divided by the number of cartons per pallet. The cost is computed with equation 6.11 and $s_{j,pallet,WA}$ should be the storage rate in the Wide Aisles area:

$$S_i^{carton} = s_{j,pallet,WA} * a \quad (6.11)$$

Where: $a = \frac{1}{5} \quad if \; \left(\frac{Q_{pallet}}{n_{i,carton} * Q_{carton}}\right) \geq 5 \quad else \quad a = \left\lceil \frac{n_{i,carton} * Q_i^{carton}}{2 * Q_i^{pallet}} \right\rceil$

6.3. Cost model of lot size at LDCs

The integer multiple of the batch size is again defined for each LDC, where the

$$n_{i,j,x} = \left\lceil \frac{\mu_{ij} R_{ij}}{Q_{ij}^x} \right\rceil \quad (6.12)$$

Where
$n_{i,j,x}$ = number of item i with lot size x at LDC j, where x= carton, layer or pallet
μ_{ij}= Average weekly demand of item i at LDC j, in selling units
R_{ij}=Review period of item i in weeks at LDC j
Q_{ij}^x= Number of selling pieces of item i in a batch size x, where x= carton, layer or pallet in LDC j

Recalling the cost function at the LDC

TCF_{LDC}= Cost of capital + Warehouse storage cost + Inbound cost + Outbound cost at RDC

6.3.1. Cost of Capital at LDC

The cost of capital at each LDC is computed with the same procedure as for the RDC, using formula 6.2

6.3.2. Inbound cost at LDC

When an order from the RDC is received, the activities include unloading the pallets from the truck, taking the full pallets or layers to the storage area in the VNA and allocating loose cartons that arrive in a mixed pallet, to the picking locations for full case.

Since both echelons need continuous communication and effective practice, if the ordering process is controlled and well organized, there is no need to check the content of every shipment against the packing list. Therefore, the inbound process could be faster if the expedition of orders at the RDC already includes manual activities as labeling. In addition, it is also possible that the mixed pallets at the RDC are built in such a way that upon arrival to the LDCs, SKUs in the same pallet are stored in nearby picking locations, avoiding the re-allocation of cartons on different pallets. Subject to these conditions, the handling time of cartons at LDCs can be reduced. The assumption for this study is a reduction of 50% of the time spent in inbound at the RDC. Consequently, when ordering a quantity of cartons that corresponds to more than 50% of a pallet load, the pallet would be wrapped but without extra activities as labeling and checking it is also assumed that the time incurred is 50% less.

Following this logic, the equations are presented below:

$$IN_i^{pallet} = \frac{TD_{ij}}{Q_{ij}^{pallet}} * (\text{[redacted]}) * \left[\frac{\pounds\text{[redacted]}}{60}\right] \tag{6.13}$$

$$IN_i^{layer} = \left[\frac{TD_{ij}}{n_{i,j,layer}*Q_{ij}^{layer}} * (\text{[redacted]}) * \left\lceil\frac{n_{i,j,layer}*Q_{ij}^{layer}}{Q_{ij}^{pallet}}\right\rceil\right] * \left[\frac{\pounds\text{[redacted]}}{60}\right] \tag{6.14}$$

$$IN_i^{carton} = \left[\frac{TD_{ij}}{n_{i,j,carton}*Q_{ij}^{carton}}\right] * [\text{[redacted]}a + b] * \left[\frac{\pounds\text{[redacted]}}{60}\right] \tag{6.15}$$

Where

$$a = \frac{1}{\text{[redacted]}}, if \left(\frac{Q_i^{pallet}}{n_{i,carton}Q_i^{carton}}\right) \geq \text{[redacted]}, else\ a = \left\lceil\frac{n_{i,carton} * Q_i^{carton}}{Q_i^{pallet}}\right\rceil$$

$$b = (\text{[redacted]}) * \frac{1}{5} \qquad if \left(\frac{n_{i,carton}Q_i^{carton}}{Q_i^{pallet}}\right) \leq \frac{1}{5}$$

$$b = (\text{[redacted]}) * 1 \qquad if\ \frac{1}{5} < \left(\frac{n_{i,carton}Q_i^{carton}}{Q_i^{pallet}}\right) \leq \frac{1}{2}$$

$$b = (\text{[redacted]}) * \left\lceil\frac{n_{i,carton} * Q_i^{carton}}{Q_i^{pallet}}\right\rceil \qquad if\ \frac{n_{i,carton} * Q_i^{carton}}{Q_i^{pallet}} > 1/2$$

For [redacted] as LDC, this cost is assumed to be zero. These formulae hold for [redacted]; however in [redacted] any lot size is stored in the Wide Aisles, so, the inbound process is faster as it does not require the use of a 'reach truck'. Instead of [redacted] minutes in formulae 6.13 and 6.14, the time to store pallets in the Wide Aisles of [redacted] minutes is used instead.

6.3.3. Outbound cost RDC-LDC ([redacted] and [redacted])

The outbound of pallets and layers consists of collecting the pallet from the storage location and loading it into the truck. In the case of cartons, a mixed pallet needs to be built for the transportation in trucks. Cartons are picked and placed in the outbound area where they are stacked on a pallet and wrapped in plastic. The picking process is rather quick due to the use of an automated conveyor belt that transports the full case to the outbound area. The rates for expediting cartons and full pallets have been previously determined by the warehouse managers[2]. The rates are summarized in table 7.

When, expediting layers, the cost depends on whether the complete number of layers is available in the storage area or whether cartons need to be picked. For purpose of this approximation, the option that will be less expensive is multiplied by the number of outbound instances in a year.

Cost factor	Cost driver	Outbound costs (€/outbound)
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Table 7. Outbound rates at the RDC

The outbound costs are computed with the following equations:

$$OU_i^{pallet} = \frac{TD_{ij}}{Q_{ij}^{pallet}} * € \text{[redacted]} \tag{6.17}$$

$$OU_i^{layer} = \frac{TD_{ij}}{n_{i,j,layer} * Q_{ij}^{layer}} * MIN\left[€ \text{[redacted]} * \left\lceil \frac{n_{i,j,layer} * Q_i^{layer}}{Q_i^{pallet}} \right\rceil, * (€ \text{[redacted]}) * \left\lceil \frac{n_{i,j,layer} * Q_i^{layer}}{Q_i^{carton}} \right\rceil \right]$$

(6.18)

$$OU_i^{carton} = \frac{TD_{ij}}{Q_{ij}^{carton}} * (€ \text{[redacted]} + € \text{[redacted]}) \tag{6.19}$$

Outbound cost RDC-LDC [redacted]

Since the warehouse in [redacted] is taken as a third LDC, it is assumed that the outbound consists of picking the lot size from the storage locations and allocating the order to the different picking locations in the active areas of the warehouse. The outbound time depends on the distance to be travelled within the warehouse that varies from item to item. So, due to lack of information, the time to move a load from the receiving area to the storage area is used to approximate the time to move a load from the storage areas to the active areas. In case of cartons, the same logic is followed; assuming that if the load is 20% or less than a pallet size, the driver would most likely pick 5 SKUs in the same pallet. While for loads between 20% and 50% a single-SKU pallet is used and cartons are picked from ground levels and finally, for loads higher than a half pallet size, cartons are mostly picked from high levels. The following formulae are used to compute the inbound cost for [redacted] as LDC.

$$IN_i^{pallet} = \frac{TD_{ij}}{Q_{ij}^{pallet}} * \text{[redacted]} * \frac{£\text{[redacted]}}{60} \quad (6.20)$$

$$IN_i^{layer} = \frac{TD_{ij}}{n_{i,j,layer} * Q_{ij}^{layer}} * \text{[redacted]} * \left\lceil \frac{n_{i,j,layer} * Q_{ij}^{layer}}{Q_{ij}^{pallet}} \right\rceil * \left\lceil \frac{£\text{[redacted]}}{60} \right\rceil \quad (6.21)$$

$$IN_i^{carton} = \frac{TD_{ij}}{n_{i,j,carton} * Q_{ij}^{carton}} * b * \left\lceil \frac{£\text{[redacted]}}{60} \right\rceil \quad (6.22)$$

$$b = \text{[redacted]} * \frac{1}{5} \qquad if \left(\frac{n_{i,carton} Q_i^{carton}}{Q_i^{pallet}} \right) \leq \frac{1}{5}$$

$$b = \text{[redacted]} * 1 \qquad if\ \frac{1}{5} < \left(\frac{n_{i,carton} Q_i^{carton}}{Q_i^{pallet}} \right) \leq \frac{1}{2}$$

$$b = 5 * \left\lceil \frac{n_{i,carton} * Q_i^{carton}}{Q_i^{pallet}} \right\rceil \qquad if\ \frac{n_{i,carton} * Q_i^{carton}}{Q_i^{pallet}} > 1/2$$

6.3.4. Storage Cost

For the LDCs [redacted] and [redacted] the storage costs are computed using the rates and formulae presented in section 6.2.3, that mentions the storage cost at the RDC. In the case of [redacted]-LDC, the storage rate is determined by the cost of a pallet space in the active area of the warehouse. The capacity and annual cost allocated to this area have been used to compute an annual cost of pallet place, details are found in table 8.

Site	Area of Warehouse	Area of active loop, and Full-case	Pallet spaces available	Cost of pallet place in active loop and full case
[redacted]	[redacted]	Approx. [redacted]	[redacted]	€ [redacted]

Table 8. Storage cost in the active loop and full case area at the RDC

The storage cost in [redacted] as LDC is computed using formulae 6.9, 6.10 and 6.11 with the rate shown in table 8 being equal to $s_{j,pallet}$ and $s_{j,pallet,WA}$

6.4. Expectations

- It is expected that when the monthly demand is large the total cost function is minimum when ordering in large lot-sizes as pallets, because the handling cost will significantly decreased when less replenishments are needed over one year.
- It is expected that a large part of the assortment would have a lot size equal to a pallet size at the RDC, while in the LDCs lot sizes would be smaller. In the case of [redacted]-LDC it is expected that most of the items are replenished in lot sizes equal to a carton due to the review period equal to one day.
- It is expected that the majority of the items has short order cycles at the LDCs (of 1-2 weeks). While in the RDC it is expected that the majority of the Asian assortment has order cycles of around 4 weeks and shorter order cycles for the European assortment.

7. POLICY PARAMETERS - Reorder Point

Based on the analysis of Silver et al. (1998) of decision rules for periodic-review, order-up-to level (R,S) control systems; an analogy of the order-up-to level (*S*) with the reorder point (*s*) is used to determine the logic of the reorder point in our system (*R, s, nQ*), with the difference that demand transactions are unit-sized based on the lot size *Q*. According to these authors, in the periodic review systems, the key time period over which protection is required is the duration of *R+L* (review period plus lead time). Assuming that an order *X* is placed at t_0 and an order *Y* is placed at $t_0 + R$, order *X* is received at $t_0 + L$ and order *Y* is received at $t_0 + R + L$. It is recognized that once order *X* has been placed, no other later orders can be received until time $t_0 + R + L$. Therefore, the reorder point at t_0 should be sufficient to cover the demand through a period of duration $R + L$. A stock out can occur at the end of the period (after $t_0 + L$) if the total demand in an interval of length $R + L$ exceeds the reorder point *s*.

In this setting the value of *R* is assumed to be predetermined. Silver et al. (1998) clarifies that in most situations, the effects of the two decisions variables *R* and *s,* are not independent, that is, the best value of *R* depends on the *s* value, and vice versa.

In addition, the reorder point includes a value of the safety stock which is defined by Silver et al. (1998) as the amount of inventory kept on hand, to allow for the uncertainty of demand and the uncertainty of supply in the short run. When demand is probabilistic, there is definite chance of not being able to satisfy some of the demand on a routine basis directly out of stock. If demand is unusually large, a stock out may occur and if demand is lower than anticipated, the company would incur in inventory carrying costs.

In Silver et al. (1998), several methods to establish the safety stock are described. The approach used in this study to establish the reorder points is based on the customer service level. The service level becomes the constraint when setting the safety stock. As the service level required becomes higher, also the safety stock investment increases. The measure of service used in this study and in Office Depot is the P2 measure or the measure known as the *Fill rate* which is defined as the fraction of customer demand that is met routinely; that is without backorders or lost sales (Silver, 1998). In the current situation, the 'Line Performance' of customer demand in Office Depot is 99.5%.

Procedures to find the optimal reorder point in inventory systems with echelon-stock information and periodic review have been extensively studied. However, as mentioned in the literature review, studies of echelon-stock policies that include the lot sizing are very limited. The optimal policies for multi-echelon inventory with lot sizing have been studied by Chao & Xhou (1999) but only for serial systems (equivalent to a divergent system with only one retailer) without any extension to divergent systems. Moreover, studies of integral policies in a divergent supply chain with lot sizing usually assume a negligible impact of the imbalance on the service level. In this project, the effect of lot-sizing in the probability of imbalance and the possible impact on the service level should be taken into account.

Donselaar (1990) provides a set of integral or echelon-stock norms in divergent systems with lot-sizes. The author provides a set of formulae for several periodic review-inventory systems which are used to study the 2-echelon divergent system with lot-sizing, taking into account the impact of the imbalance in the service level. The system involves one 'common part' which goes into several 'final products'. In this system, the common part is the stock in the RDC and the final products correspond to the stock in the LDCs.

Imbalance occurs when the inventory at one or more of the downstream locations deviates from the average inventory of the echelon, causing an overestimation of the service level. The paper tackles this problem by providing an approximation of the average imbalance and increasing the system stock norm in order to decrease the negative impact of the imbalance. The following characteristics are assumed in this model:

- All order policies are periodic review, echelon re-order point policies (R,s,nQ) with lot-sizing.
- The lot-size of the common part is a multiple of the lot-size of the final products.
- Demand is assumed to be stationary in time, meaning that the average demand and standard deviation are constant over time.
- Demand for consecutive periods and for different products is assumed to be independent
- Demand that is cannot be satisfied due to shortage of stock will be backordered at all locations.
- The indicator for the performance of the system is the service level, instead of costs.
- The final products are assumed to be identical with respect to their lead time, lot-size and demand characteristics.

Given that most of the assumptions in the paper are in line with the inventory system in this project, the analysis and methods published in Donselaar (1990) will serve as a base to calculate the reorder points at all locations, with additional modifications and approximations that fit better the characteristics of our inventory system.

The approximations in Donselaar (1990) have been tested in terms of target service level (denoted by α), this service level is used for setting the safety stocks at all stockpoints of the system. Office Depot has a target service level of 99.5%, meaning that 99.5% of the customer orders must be fulfilled on time and complete.

7.1 Reorder point at the LDC

Donselaar (1990) derives the formula of the reorder point from the analysis of a single stage linear system with lot sizing, assuming that the inventory just after demand took place (IAD) is normally distributed. The formula takes into account the coverage of the demand of the lead time plus review period $(l_j + 1)\mu_j$ and the safety stock that includes a variance term due to lot sizing and a remaining inventory expected due to the lot size. It is important to clarify that $Q_{i,j}$ is not the average order size, but it is the minimum quantity (or a multiple of this) that is ordered in the LDC.

In this paper it is assumed that the review period of the common part (RDC) and the final products (LDCs) are equal to 1 period of time. Donselaar (2012) presents a modification in the integral stock formulae for the assumption of different review periods at both echelons. The first term is the average demand during the lead time plus review period and the subsequent terms represent the safety stock. The notation used is as follows:

s_{ij}=Reorder point of item i at LDC j
l_j= Lead time to LDC j
R_{ij}= Review period of item i at LDC j in weeks
μ_{ij} = Average weekly demand of item i at LDC j
Q_{ij}= Lot size in selling units of item i at LDC j
σ_{ij}= Standard deviation of demand of item i at LDC j
α= Real Service Level, defined as the percentage of periods, that demand can be met instantaneously from the inventory on hand, α= 0.995
α'= Fictitious service level used to determine the safety factor in a two-echelon system with depot.

The formula of the integral stock norm of the final products (LDCs) is:

$$s_{ij} = (l_j + R_{ij})\mu_{ij} \underbrace{- \frac{1}{2}Q_{ij} + k \cdot \sqrt{\frac{1}{12}Q_{i,j}^2 + (l_j + R_{i,j})\sigma_{ij}^2}}_{\textit{Safety Stock}} \tag{7.1}$$

Donselaar (1990) provides two approximations for the reorder point. The first approximation assumes that IAD is normally distributed, if this is the case, given a target service level α=99.5%, the safety factor k is calculated as follows:

$$\Phi(k) = \alpha' \tag{7.2}$$

The second approximation, assumes that the IAD follows a uniform distribution and it is preferred when the lot size of the final products is relatively large. When this approximation is used, the safety factor k is calculated as follows:

$$k = (\alpha' - 0.5)\sqrt{12} \tag{7.2'}$$

Both in (7.2) and (7.2'), α' is used, which is derived according to Donselaar (2012) from α in the following way:

$$\alpha' = \frac{2R_{i,com}\alpha + R_{ij}}{2R_{i,com} + R_{ij}} \tag{7.3}$$

The paper indicates a rule to select one of the two approximations based on the comparison of the variance of imbalance and the variance of demand, indicating that when $\frac{1}{12}Q_{i,j} \geq 4(l_j + R_{i,j})\sigma_{i,j}^2$ the uniform distribution (k derived with (7.2')) is preferred over the normal distribution (k derived with (7.2)). Hereafter, the reorder point calculated with the Normal approximation is denoted as $s_{ij,NORM}$ and the reorder point calculated with the Uniform approximation is denotes as $s_{ij,UNIF}$.

7.2 Reorder point at the RDC

The formula of the reorder point for the common part described in Donselaar (1990) was developed from the analysis of the two stage linear system with lot sizing with the addition of the imbalance factor for the divergent system. The formula is provided with a term for the variance of imbalance, σ_{imb}^2. In a system with depot and 2 or more final products, the variance of imbalance for each of the final products is approximated as: $\sigma_{ij,imb}^2 = \frac{1}{12}{Q_{ij}}^2$. Moreover, the RDC orders, if necessary, a minimum quantity or multiples of a minimum quantity represented by $Q_{i,com}$.

Donselaar (2012) provides a modification of the formula for the integral reorder point in case of different review periods at both echelons, it is presented as follows:

$$s_{i,com} = \sum_j (L_i + l_j + R_{i,com})\mu_{i,j}$$
$$\underbrace{-\frac{1}{2}Q_{i,com} + k\left[\frac{1}{12}Q_{i,com}^2 + \sum_j (L_i + R_{i,com} - R_{i,j})\sigma_{ij}^2 + \left\{\sum_j \sqrt{(l_j + R_{ij})\sigma_{ij}^2 + \sigma_{ij,imb}^2}\right\}^2\right]^{1/2}}_{\textit{Safety Stock}}$$

(7.4)

The same logic as for the LDC is followed and given a target service level of α=99.5%. The safety factor k is calculated as follows when the IAD is approximated with a Normal distribution:

$$\Phi(k) = \alpha' \tag{7.5}$$

When assuming a Uniform distribution for the IAD the safety factor is derived as follows:

$$k = (\alpha' - 0.5)\sqrt{12} \tag{7.5'}$$

Both in (7.5) and (7.5'), α' is used, which is derived from α in the following way:

$$\alpha' = \frac{2R_{i,com}\alpha + R_{ij}}{2R_{i,com} + R_{ij}} \tag{7.6}$$

The paper suggests using the Uniform approximation when $\frac{1}{12}Q_{i,com}^2 \geq 4 \cdot VAR$, with:

$$VAR = \left[\frac{1}{12}Q_{i,com}^2 + \sum_j (L_i + R_{i,com} - R_{ij})\sigma_{ij}^2 + \left\{\sum_j \sqrt{(l_j + R_{ij})\sigma_{ij}^2 + \sigma_{ij,imb}^2}\right\}^2\right]$$

Otherwise, the normal approximation is preferred. Hereafter, the reorder point calculated with the Normal approximation is denoted as $s_{i,com,NORM}$ and the reorder point calculated with the Uniform approximation is denoted as $s_{i,com,UNIF}$

Where:

$s_{i,com}$=Reorder point of item i at the depot
l_j= Lead time to LDC j
L_i= Lead time of item i to depot
R_{ij}= Review period in weeks of item i at LDC j
$R_{i,com}$=Review period in weeks if item i at the depot
μ_{ij} = Average weekly demand of item i at LDC j
$Q_{i,com}$= Lot size in selling units of item i at the depot
σ_{ij}= Standard deviation of demand of item i at LDC j
$\sigma_{ij,imb}^2$=Variance of imbalance of item i at LDC j
α= Service Level
α'= Fictitious service level used to determine the safety factor in a two-echelon system with depot.

Since the safety stock at the depot should cover the demand during the lead time and review period of *all* locations, the $R_{i,j}$ used in equation 7.6 is the review period at [redacted] and [redacted], equivalent to one week.

The integral stock norms developed in this paper for both RDC and LDCs were proven to work well in systems with a desired service level of 95% for which the assumptions of Normal and Uniform distributions for the IAD are appropriate when using the Gamma distribution for the demand. Simulations carried during the course of the project showed that when using these approximations with a target service level of 99.5%, the service level is below the target in LDC-[redacted]. In consequence, it was found that a third approximation is needed, assuming that IAD is Gamma distributed. Details of the third approximation and the procedure to derive the reorder points of the LDCs and RDC is shown in the confidential Appendix H developed by the author of the integral stock norms described in this section.

7.3 Derivation of the service level α

After finding the reorder point at each LDC (s_{ij}) using the procedure in this chapter and in Appendix H, it is possible to analytically derive the service level provided by the policy parameters.

The reorder points are calculated such that the service level is equal to the probability that demand during the lead time plus review period $(l_j + R_{ij})$ is less than or equal to the reorder point plus a variable u that varies in a range from 0 to the lot size Q_{ij}. This is summarized as follows:

$$\alpha = P(D_{l+R} \leq s_{ij} + u)$$

$$\text{With } D_{l+R} \sim \Gamma(\mu_{l+R}, \sigma_{l+R}) \quad \text{and} \quad u \sim unif[0, Q_{ij}]$$

The value of α can be derived from:

$$\alpha = \int_0^{Q_{ij}} P\left(D_{l+R} \leq s_{ij} + u\right) * P(U = u)du$$

Knowing that the probability of a variable uniformly distributed is the same for any value of u and that the demand during $l_j + R_{ij}$ is Gamma distributed, the value of α can be calculated by implementing a sum of the cumulative function of the Gamma distribution, over a range of *n* values of u from 0 to Q_{ij}. Then the sum is multiplied with the probability of u which is $1/n$. This derivation was implemented in Microsoft Excel.

7.4 Measuring the performance

The performance of the reorder levels are measured in terms of the service level achieved. The service levels are computed analytically and through simulation. The results are explained in chapter 9 and 10 respectively.

The KPI used to evaluate the service level in Office Depot is called OTAC (On Time Accurate and Complete) this measure evaluates the percentage of orders that could be fulfilled entirely with inventory on hand and delivered on time. [redacted]s. In this study, only the percentage of orders unfulfilled due to inventory backorders is taken as the performance measure of the current inventory system.

The second measures derived with the policy parameters are value of safety stock required to achieve the computed service level and the value of the average inventory. In section 9.5 these measures are shown as well as a comparison with the current value of the average inventory.

8 SIMULATION MODEL

The decision to use a simulation model has been motivated by the fact that the reorder points were computed with findings that are not available in the literature yet. Thus, the approximation has not been empirically tested. Van Donselaar (1990) presents the simulation results of the system described in this paper with different values of lot sizes, variability, demand rate and number of retailers. However, due to the modifications in the formulae for different review period at the LDCs and RDC, the existence of customer demand at the RDC and the additional approximation derived by the author to accommodate very high service levels; the use of a simulation model is preferred in order to check the performance of the policy parameters in terms of service level.

A simulation model can be either discrete or continuous. This simulation model studies a discrete system because the state variables change instantaneously at separate points in time. These points in time are the ones at which an *event* occurs, where an *event* is defined as an instantaneous occurrence that may change the state of the system, (Law, 1991). In this inventory system, the points in time are defined as a single day of operations in the DCs. Law (1991) identifies the following events in the simulation of an inventory system with policy (s,S): the order-arrival event, the demand event and the inventory-evaluation event.

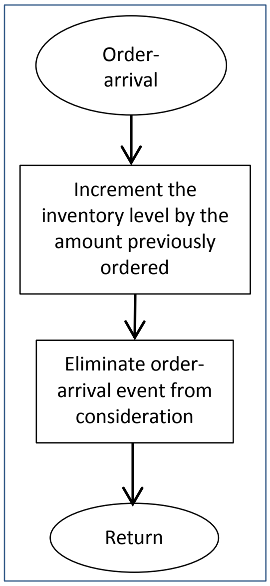


Figure 15. Order arrival event

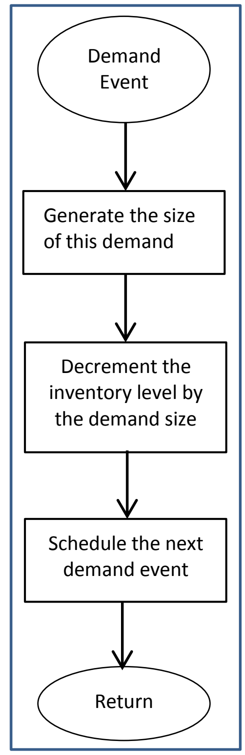


Figure 16. Demand event

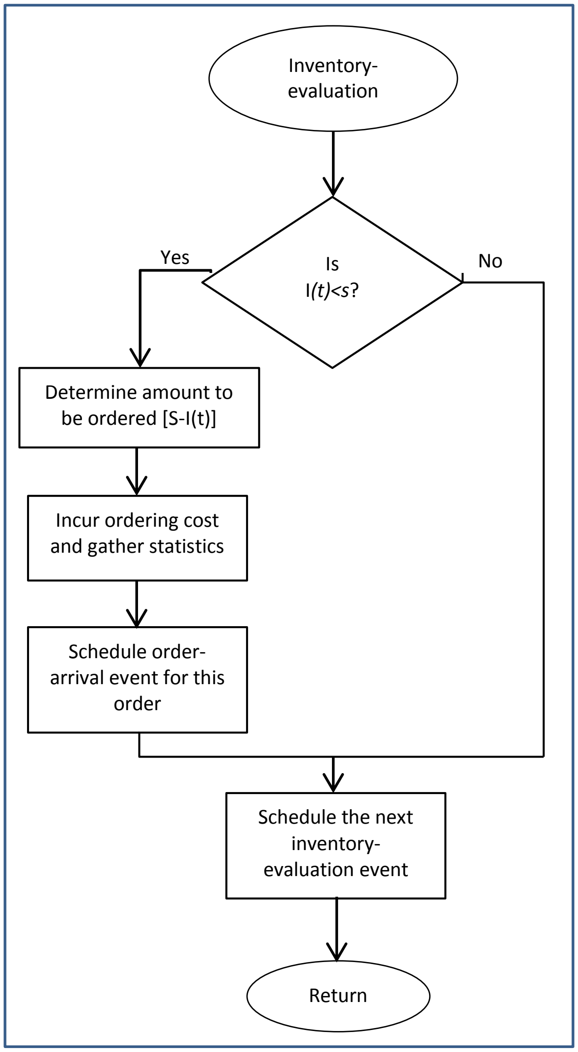
In the first event presented in figure 15 (Law, 1991), the order-arrival event, the state of the system changes when an order that was previously placed, arrives from the supplier, this occurs when the due date for delivery is equal to the current date. The inventory level is increased by the amount of the order, which then has to be delisted from the inventory in-transit.

In the second event presented in figure 16 (Law, 1991), demand is generated from the Gamma Distribution given the parameters of shape and scale proper of each product. After demand is generated the inventory level is decreased by the demand size, if demand is greater than the inventory available, the inventory is set as zero and the remaining amount is backordered and fulfilled with the next order-arrival event. A demand event occurs every period of time over the simulation period.

The inventory-evaluation event, presented in figure 17 (Law, 1991), will take place only at the beginning of the week, in case of LDCs, the *inventory position* IP_j of LDC_j is evaluated against the reorder point s_j, if it is equal or below the reorder point, the minimum number n of lot sizes Q_j necessary to bring the inventory position above the reorder point is ordered. In case of RDC, the inventory-evaluation event will take place only at the review periods pre-defined for each vendor. The *echelon inventory position* is evaluated against the reorder point s, if the echelon inventory position is at or below the reorder point an order nQ is placed to raise the echelon inventory position above the reorder point. Ordering costs are not measured in this simulation model. When an order is placed, the order-arrival event is scheduled, in form of a delivery due date.

The simulation model involves 4 inventory systems: 1 RDC and 3 LDCs. All models operate in a synchronic way. The inventory-evaluation event at each of the LDCs is used as input for the demand-event in the RDC. Likewise, the order-arrival event at the LDCs depends on the quantity available at the RDC, evaluated in the demand event at RDC.

Figure 17. Inventory-evaluation event



The simulation model is built in Microsoft Excel 2010; the complete description of the formulae, as well as a screenshot of the simulation is shown in Appendix E. The time base of the simulation is *working days* assuming that demand-event only takes place during the 5 working days of the week, a year is considered to have 5*52=260 days.

8.1 Simulation Model Parameters

For each system, decisions have to be made on issues such the initial conditions of the system, the length of the warm-up period (if any), the length of the simulation run(s) and the number of independent simulation runs (replications) (Law, 1991). Moreover, in a divergent supply chain an allocation rule must be determined; in the next subsections the allocation rule is explained.

8.1.1 Initial conditions, warm up period and simulation length

The initial conditions in the inventory system relate to the starting inventory in each DC. All locations should start with an initial quantity of inventory. If the RDC initiates with zero stock, the LDCs would have a propagation of backorders over a long period of time that would not be satisfied until the RDC receives enough inventory to fulfill all these backorders. In order to avoid this, it will be assumed that the initial inventory at all locations is equal to the reorder point plus half of the lot size ($s+Q/2$). Moreover, it is also assumed an initial backorder quantity of zero.

According to Law (1991) the warm-up period is necessary for a simulation model to reach a steady state where the initial conditions do not have an effect on the outcome anymore. According to the initial conditions, no order is placed at the first review period (day 1 in the simulation). Then, the inventory level would decrease and probably a first order is placed at the next review moment. The physical inventory will reach a steady state after the lead time has passed. The warm-up period required is therefore, the review period plus the lead time. A warm-up period of 100 days will be used for the inventory system at the RDC. The plot shown in Appendix F confirms this choice.

Since the system at the RDC needs the input orders from the LDCs in order to reach the steady state, consequently, the outcome at the LDCs is measured after the warm-up period of the RDC.

The next parameter to be defined is the simulation length. The length of the simulation should be significantly longer than the warm-up period. Given that the warm-up period is 4 months, a length of 5 years of operations will be used in this simulation model.

Finally, the number of simulation runs required for each different input has to be chosen such that the steady state of the output is achieved. As the outcome of interest is the service level, the number of runs should be the minimum such that the service level reaches a steady state. The approach used to decide on the number of runs is to test the model for two situations: with high/low coefficient of variation and with small/large lot size. The graphs in Appendix F suggest that with 200 replicates, the system can provide steady results.

8.1.2 Demand distribution

An important input parameter is the customer demand at the LDCs. The Gamma distribution is selected for this simulation model over the normal and negative exponential distribution. According Snyder (1984), these two latter distributions are incapable of adequately describing the demand characteristics of all items found in the typical inventory. The limitations of the normal distribution include the existence of negative values. In this paper it is argued that the Gamma distribution fits better to the demand characteristics and is particularly preferred for controlling slow moving items. A more detailed overview of the Gamma distribution is shown in Appendix I.

The average demand (μ) and standard deviation (σ) of the daily demand are used to compute the parameters of the gamma distribution. Given that the average demand and standard deviation are available per week, the daily demand is calculated with $\mu_{day} = \mu_{week}/5$ and the daily standard deviation is $\sigma_{day} = \sigma_{week}/\sqrt{5}$

The shape (α) and scale (β) parameters that Microsoft Excel uses are obtained as follows:

$$\alpha = \left(\frac{\mu_{day}}{\sigma_{day}}\right)^2 \quad \beta = \frac{\sigma_{day}^2}{\mu_{day}}$$

8.1.3 Allocation Rule

An allocation rule is needed in order to indicate the proportion of the available stock at the RDC that should be delivered to each of the LDCs in case of stock out. As long as the RDC has enough inventory, all orders from LDCs are completely satisfied; however, when available inventory is partial shipments to the LDCs will be allowed. The allocation rule assumed in this project has been developed by Donselaar (2012), the exact procedure and detailed formulae are given in a confidential section in Appendix E.

8.2 Output Parameters

The performance of the policy parameters is measured in terms of customer service level. The approximations of the stock policies in Donselaar (1990) were measured in terms of a pre-defined service level, defined as the percentage of periods that demand can be met instantaneously from the inventory on hand. Since this paper was the base to compute the optimal parameters, the same performance measure is used. The required service level is 99.5% for the LDCs and 98% for the RDC which is known as the 'Line Item Performance' at Office Depot.

In the model, the service level of each location including LDCs and RDC were measured with the ratio of all periods with zero backorders and the total number of periods, meaning the percentage of periods in which the demand was totally fulfilled with inventory on hand.

Other outcomes are also generated in the results. These are the percentage of periods in which a lot size smaller than the optimal lot-size was delivered to each LDC and the average fraction of the lot-size delivered to each LDC. All results are measured after the warm-up period.

8.3 Validation of the Simulation Model

The validation is concerned with determining whether the conceptual simulation model (as opposed to the computer program) is an accurate representation of the system under study (Law, 1991). The simulation in this study is used as a tool to test the given input parameters mainly in terms of customer service level; meaning that there is not existing output data to which the model can be compared.

Moreover, the inventory model studied is different from the actual system and the parameters are also different. Thus, some other tests can be performed to test the validity of each inventory system and the combination of LDCs and RDC.

In order to test each inventory system individually, the following validity tests were performed:

- With zero demand, the service level is always 100% because the backorder events are also zero.
- Assuming an unlimited availability from the RDC, so that every order placed is completely received after the lead time the service level should be very close to the target or even above 99.5%. This test was performed for a random sample of 10 products and the service level is as expected. In this case, also the sum of orders placed is the same as the sum of orders received.
- In the RDC, it is assumed unlimited availability of the supplier, so the sum of all orders placed is equal to the sum of all orders received and in transit at the termination period.
- It was checked that in case the stock on hand is zero, backorders start to accumulate and these are fulfilled after the lead time elapsed from the next review moment.

In order to test the integration of all the inventory systems the following aspects were revised:

- The echelon inventory position over all the simulation is indeed the sum of the local inventory positions of LDC plus RDC.
- The sum of outbound quantities at the RDC is equal to the sum of the inbound quantities at LDCs.
- It was checked that in case of a shortage in the RDC, the inventory on hand was allocated according to the allocation rule established, allowing for smaller lot-sizes when necessary.

8.4 Design of Experiments

Due to the amount of items and the number of replications needed, only a subset of all SKUs will be tested. The sample should be chosen such that reflects all different characteristics that could influence the performance of the system. The characteristics that will be used to select the sample are: Lead time, the order cycle and the variability. Moreover, a distinction between the SKUs delivered to LDC-[redacted] through the RDC and the SKUs delivered has been made

The sample is taken from the items that belong to each of the blocks of table 9. The first cutoff point is the SKUs with lead times greater than 10 weeks (Asian suppliers and one European supplier). The second characteristic is the demand variability, the cutoff point is the weekly CV (measured with LDC-[redacted]) greater than 1, meaning a high variability and a weekly CV less or equal to 1 indicating low variability in demand. Finally, the sample is divided with regard to the order cycle of a lot size in weeks computed with the ratio of the lot size and the weekly demand. The first cutoff point is an order cycle less than 4 weeks in all LDCs and the second cutoff point is an order cycle equal or greater to 4 weeks. The purpose of this last classification is to check whether the differences in lot-sizing combined with the demand impact the performance of the policy. The sample is divided into groups as indicated in the table below:

SKUs with RDC shipment

	Vendor lead time ≥ 10 weeks		Vendor lead time < 10 weeks	
	CV≤1	**CV>1**	**CV≤1**	**CV>1**
Lot size order cycle < 4 weeks in all LDCs	[redacted] SKUs {Group 1}	[redacted] SKUs {Group 2}	[redacted] SKUs {Group 7}	[redacted] SKUs {Group 8}
Order cycle of the lot-size ≥ 4weeks in all LDCs	[redacted] SKUs {Group 3}	[redacted] SKUs {Group 4}	[redacted] SKUs {Group 9}	[redacted] SKUs {Group 10}
Remaining	[redacted] SKUs {Group 5}	[redacted] SKUs {Group 6}	[redacted] SKUs {Group 11}	[redacted] SKUs {Group 12}

Table 9. Distribution of SKUs within the sample groups for SKUs with RDC shipment

SKUs with LDC shipment (to LDC-[redacted])

Direct to [redacted], Indirect to [redacted] and [redacted]	140 SKUs {Group 13}

Table 10. Number of SKUs with LDC shipment

From each group, a random sample of 8 SKUs is selected for testing the reorder levels in the simulation model. The selection of the sample is constraint to items with a positive average demand in all LDCs. In chapter 10 the simulation results are provided.

Part IV: Intervention

The purpose of this section is to show the results of the policy strategy, specifically, in terms of order cycles, safety stock and average inventory. Chapter 9 described the detailed results of the analytical model used to compute the lot sizes and the reorder points. Chapter 10 presents the results found using the simulation model.

9 RESULTS ANALYTICAL MODEL

9.1 Order Cycles

Using the cost formulae derived in section 6.1, a yearly cost of the average order in each of the three lot sizes was calculated, and the lot size with the minimum cost is selected for each item per location. Alongside this, with the average order size and the weekly demand, the order cycles were computed. This translates into the average number of weeks between placements of two orders.

Figure 18 presents the distribution of the items over the order cycles ranges at RDC. It can be seen that the vast majority of Far East products have an order cycle from 4 to 6 weeks; this is expected given a review period of 4 weeks, except for chairs, these are ordered every 2 weeks. In the case of European items, fast-moving SKUs with cycles lasting less than 4 weeks belong to [redacted]. This is the vendor of toners that accounts for [redacted]% of the whole assortment.

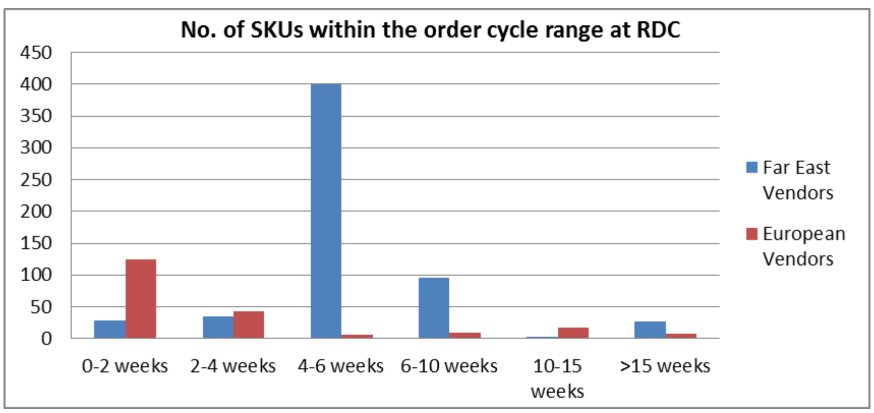


Figure 18. Distribution of order cycles at RDC

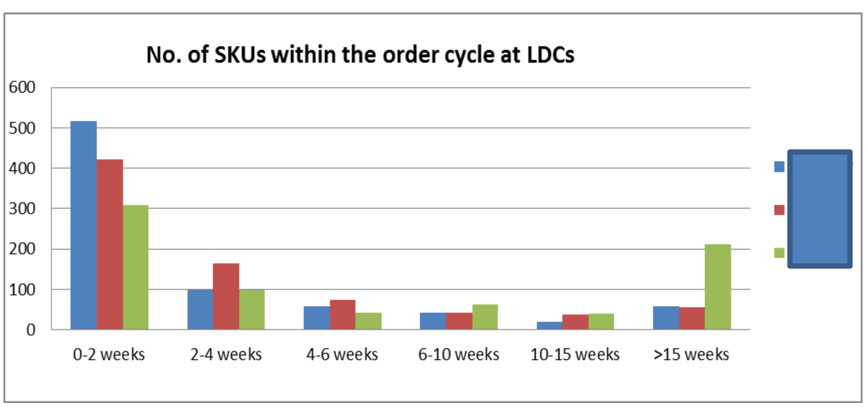


Figure 19. Distribution of order cycles at LDCs

With regard to cycles at the LDCs, it is seen in Figure 19 that more than 50% of the assortment has short cycles in [redacted] and [redacted]; while in [redacted], long cycles characterize the major part of the assortment. Long cycles in [redacted] and [redacted] are mainly caused by low run rates or demand, compared to the size of the smallest lot size (a carton). However, the results showed that for [redacted]% of the items with cycles greater than 4 weeks, the cost- optimal lot size is a Layer or a Pallet. The reason is the trade-off between the cost of capital and storage versus the handling costs. Depending on the annual usage, in some situations, it becomes more economical to order large lot sizes fewer times per year, than ordering small lot sizes and therefore, incurring more handling activities.

Figure 20 shows an example of the total cost function for the three lot sizes of an item with weekly demand of [redacted] units in LDC-[redacted]. It has an optimal lot size equal to a pallet of [redacted] units. It is shown that the handling cost decreases significantly when ordering in pallets. This is mainly due to the outbound rate for pallets at the RDC, making more economical to send pallets from the RDC rather than cartons.

On the other hand, in [redacted], the long cycles for most of the items are explained by the low demand rates rather than by large lot sizes.

The separate plots distinguishing Far East and European items are available in Appendix G along with the three plots with each cost factor and the total cost for all items ordered in cartons, layers and pallets. It is shown that the European assortment is characterized by short order cycles compared to Far East products.

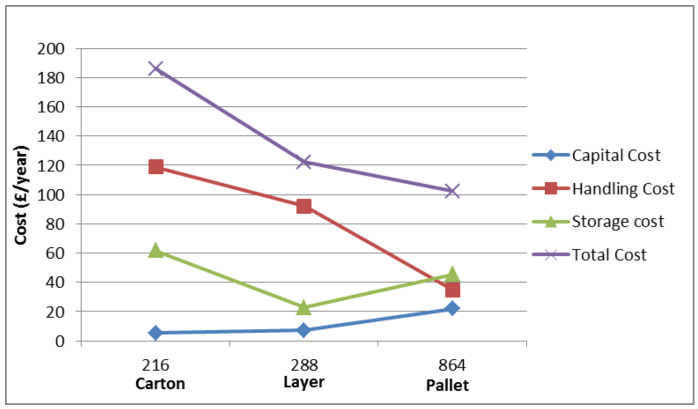


Figure 20. Example of the cost function of an item with optimal lot size equal to a pallet.

9.2 Validation of lot sizes

The outcome of the lot sizing is a key result which drives the performance of the two-echelon inventory system with echelon-stock information. Recalling the literature review, the system has a high risk of imbalance when lot sizes at the LDCs are large compared to the lot size of the RDC. The table 11 summarizes the assortment in each location that is ordered with the respective lot sizes

As seen in table 11, a large part of the assortment at the LDCs has an optimal lot size equal to a carton, while in the RDC the majority of items should be ordered in pallets and layers. With regard to the risk of imbalance due to large lot sizes, attention should be paid to the LDC-[redacted] for those SKUs with a relatively large lot size with respect to the other LDCs.

To validate the lot sizes, a comparison with the actual system is performed. Currently, the only results that can be compared are the lot sizes of the items that have *indirect shipping* (strictly through the CDC). This would then resemble the ordering method to the RDC. At the moment, most of the assortment is being ordered with *direct shipping to LDCs/RDC,* so lot sizes are defined accordingly. However, order history from the LDCs for both logistic channels showed that although the flow for one SKU is direct shipping, the LDCs ordered indirectly to the CDC during the transition from the indirect shipping mode

Table 11. Percentage of the lot sizes in each location

CONFIDENTIAL

to the direct shipping mode.

In order to compare lot-sizes only based on the shipment through RDC, the lot sizes of [redacted] SKUs at LDC-[redacted] with CDC flow were compared with the findings of this study. It was observed that the proposed lot size and the current lot size are the same for 70% of this sample.

From the items that are ordered with different lot sizes, it is seen that currently some chairs are ordered per unit (Q=1) while the optimal lot size suggests ordering in pallet quantities. In such cases, the handling cost of single cartons becomes higher as well as the storage cost. It was also observed that European products with low demand rates are being ordered in multiples of layers rather than in cartons as suggested by the cost-optimal lot sizes. Although, in these cases the handling cost when ordering cartons is higher than when ordering layers, the difference in cost relies on the capital cost.

According to the cost functions described in chapter 6, the system with the current lot sizes performs with around 8% more annual operating costs than with the cost-optimal lot sizes presented in the proposed solution. This result is based on the comparison of SKUs with indirect shipping flow in LDC-[redacted].

9.3 Annual operational costs

With regard to the annual operation expenses of the cost-optimal lot sizes, it is seen in figure 21 that the dominant cost driver is the handling cost. This finding is in line with empirical studies in the retail industry. Van Der Vlist (2007) indicates that the order size not only determines the amount of cycle stock, it also may have a strong impact on one of the most dominant supply chain components: the cost of handling. In general, the handling costs per item are lower when units that are being handled are larger. From the cost breakdown it is seen that in LDC-[redacted] the handling cost has the highest impact since more than [redacted]% of items are ordered in cartons.

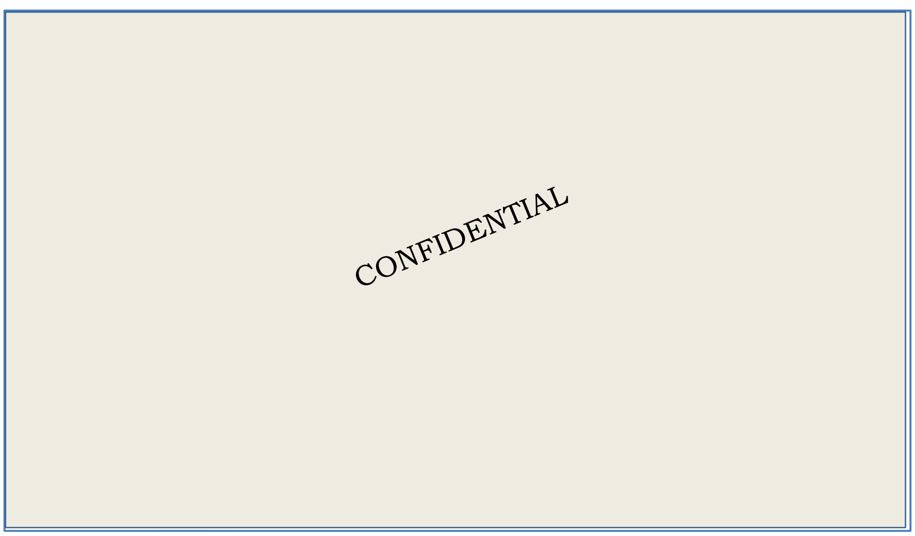


Figure 21. Proportion of each cost factor with the cost-optimal lot sizes.

The sum of all cost drivers over all locations is equal to an annual cost of € [redacted]. This is an estimation of the capital, storage and handling costs that Office Depot would incur on an annual basis when ordering and handling the [redacted] SKUs in the scope of the project with the lot-sizes proposed for the regional supply chain. In the actual situation, Office Depot does not perform any type of allocation of costs to activities; and so the logistic costs presented in this study could not be compared with the current logistic costs.

9.4 Obsolescence risk

Obsolescence risk is measured differently in each of the regions of Office Depot Europe. In the region of UK & Ireland, for regular stock, the obsolescence risk is measured based on a maximum order cycle of [redacted]. [redacted]. The results of the lot sizes showed that all SKUs with cycles greater than 24 weeks ([redacted] SKU in LDC-[redacted] and [redacted] SKUs in LDC-[redacted]) have a lot size equal to a Layer. In order to avoid any obsolescence risk due to large lot sizes, in these situations a smaller lot size is preferred. This has an additional annual cost of € [redacted] per year.

9.5 Cycle stock and Safety Stock

According to Silver et al. (1998) in a system with lot-sizing the average cycle stock would be half of the total order size; this is the portion of the inventory that varies directly with the amount purchased. Therefore, the total average inventory in the distribution center would be half of the lot size plus the safety stock, presented graphically in figure 22.

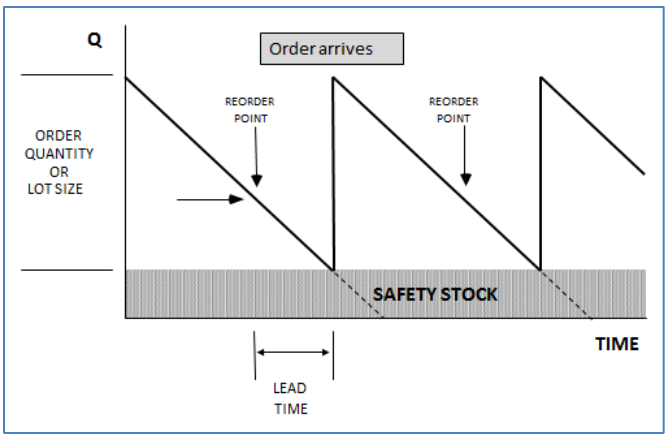


Figure 22. Cycle stock and safety stock in a system with lot sizing

In this graph the slope represents the demand rate. The reorder point is triggered by the review period in combination with the inventory level. Given this, the average inventory can be computed with $^{Q}/_{2} + SS$, where the Q is the order size and SS is equal to the safety stock. In our system the average inventory can be calculated with $^{nQ}/_{2} + SS$ where nQ is the average order size and the safety stock is derived from the reorder points calculated with the procedure in chapter 7. Formula 9.1 is used to calculate the average inventory in each LDC and formula 9.2 is used to calculate the average inventory of the entire system, following the notation of the report:

$$^{n_{ij}Q_{ij}}/_{2} + s_{ij} - (l_j + R_{ij})\mu_{ij} \qquad (9.1)$$

$$^{n_{i,com}Q_{i,com}}/_{2} + s_{i,com} - \sum_j (L_i + l_j + R_{i,com})\mu_{i,j} \qquad (9.2)$$

With:

$$n_{ij} = \left\lceil \frac{\mu_{ij} R_{ij}}{Q_{ij}} \right\rceil \quad \text{and} \quad n_{i,com} = \left\lceil \frac{\sum_j \mu_{ij} R_i}{Q_{ij}} \right\rceil$$

Recalling that the target service level of 99.5% has been defined for the entire assortment, the investment in safety stock per SKU directly depends on this target with the safety factor K. According to the reorder level formulae, the value of the safety stock also depends on the variability of the demand and the variance of imbalance.

With regard to the variability of demand, when the standard deviation of demand is high, then the level of safety stock increases. High demand variability is a proper characteristic of items with lumpy demand and slow moving items with few demand events during the replenishment cycle. Therefore, for items with low and irregular sales, given the target service level, the safety stock investment results in a high quantity of stock. With regard to the variance of imbalance and the approximation of this parameter, given as $\sigma^2_{ij,imb} = \frac{1}{12} Q_{ij}{}^2$; items with a relatively large lot size, would also require more safety stock than items with small lot sizes at the LDCs.

9.5.1 Overall performance

Table 12 presents the value of the average cycle stock, the safety stock and the sum of these two inventories that provides the total average inventory at each stockpoint. This was calculated with the average order size of each item. These figures were computed for a subset of [redacted] SKUs, all with demand occurrence at all LDCs and with information of inventory value in the current situation.

It is important to mention that calculations are based on the average demand and standard deviation of the weekly demand from March, 2011 to February, 2012. The data used in this report does not include any replacements of vendors and discontinuation of items that could have occurred during the course of the project.

Location	Average cycle stock with RDC approach	Safety stock value with RDC approach	Total average inventory in RDC approach	Average days of inventory
LDC-[redacted]	€ [redacted]	€ [redacted]	€ [redacted]	[redacted]
LDC-[redacted]	€ [redacted]	€ [redacted]	€ [redacted]	[redacted]
LDC-[redacted]	€ [redacted]	€ [redacted]	€ [redacted]	[redacted]
RDC	€ [redacted]	€ [redacted]	€ [redacted]	
TOTAL	**€** [redacted]	**€** [redacted]	**€** [redacted]	

Table 12. Value of average cycle stock and safety stock and days of inventory with the calculated reorder levels

The table indicates that the two-echelon replenishment policy would operate with an average inventory value equal to **€** [redacted] for the [redacted] SKUs included in this analysis. The analytical calculation of the service level indicates that weighted average of the customer service level (assigning a weight according the weekly demand) in LDC-[redacted] is **99.53%**, in LDC-[redacted] is **99.66%** and in LDC-[redacted] is **99.65%**.

In order to evaluate the proposed solution with the current performance of the system, the average inventory value during the year 2011 has been investigated for the same subset of items. Table 13 presents the average inventory value per stockpoint, calculated with the average of the ending inventory week by week.

The inventory value in the CDC belongs only to those SKUs that are ordered exclusively via CDC. Since the inventory in CDC is planned and purchased according to aggregated requirements of all regions, the value that corresponds to this region has been approximated by multiplying the portion of the total sales out to UK & Ireland at SKU level with the actual inventory value at CDC. This number provides an approximated value of the inventory at CDC allocated to the region.

Location	Current value of average inventory	Current average of days of inventory
LDC-[redacted]	€ [redacted]	[redacted]
LDC-[redacted]	€ [redacted]	[redacted]
LDC-[redacted]	€ [redacted]	[redacted]
CDC	€ [redacted]	
TOTAL	**€** [redacted]	

Table 13. Value of average inventory and days of inventory in the current supply chain

According to the results, the regional configuration proposed could provide around [redacted]% of savings in inventory cost compared to the current situation. It is seen that in the current supply chain, the days of inventory in [redacted] and [redacted] are significantly high since most of the orders are placed with a direct flow. Consequently, higher safety stock is needed to cover the demand during lead time plus review period.

Comparing the inventory value at [redacted] as LDC and RDC, this warehouse can operate with [redacted]% less than the current inventory value. Comparing LDC-[redacted], it is seen that this policy leads to a reduction of [redacted]% in inventory costs with a faster turnover than with the current system. On the other hand, the solution leads to a higher inventory cost in [redacted]. This could probably be explained by the high amount of slow movers in this DC that need a significant amount of safety stock due to the high requirements of service level.

With regard to the current service level, the overall measure of the OTAC (percentage of order on time, accurate and complete) for the entire assortment (PB and OEM) during the first half of year 2012 has been [redacted]% in UK (LDC-[redacted] and LDC-[redacted]) and [redacted]% in LDC-[redacted]. Although this information is not available at SKU level, these measures already provide an indication that not all SKUs have the same performance. Therefore, besides the inventory value reduction, these integral norms can also improve the customer service level.

9.5.2 Direct shipping to LDCs/RDC approach vs. RDC approach

In order to compare the current *direct shipping flow* to LDCs against the RDC concept proposed, the actual value of inventory of SKUs ordered directly is compared with the inventory value of the solution proposed for the same subset of products. Table 14 shows the current inventory value and average days of inventory in each of the LDCs in the two columns on the right side. The value of inventory and number of days of inventory with the solution proposed are presented in the two columns on the left side of Table 14. According to the results, with the RDC approach, the inventory value can be reduced by [redacted]%. Moreover, [redacted] can operate as the RDC with [redacted]% less of inventory and LDC-[redacted] can reduce the inventory value by around [redacted]%.

Location	Current value of inventory	Current average of days of inventory	Value of inventory with RDC approach	Number days of inventory with RDC approach
LDC-[redacted]	€ [redacted]	[redacted]	€ [redacted]	[redacted]
LDC-[redacted]	€ [redacted]	[redacted]	€ [redacted]	[redacted]
LDC-[redacted]	€ [redacted]	[redacted]	€ [redacted]	[redacted]
CDC/RDC	-	-	€ [redacted]	
TOTAL	**€** [redacted]		**€** [redacted]	

Table 14. Value of average inventory and days of inventory in the current supply chain

With respect to the value of the safety stocks, a comparison with the current safety stocks might not lead to accurate or reliable results due to the following reasons:

- Currently, only [redacted] SKUs have *Indirect shipping flow* predefined; therefore, the majority of products are ordered at [redacted] and [redacted] taking a *direct shipping flow* and so, the safety stocks are not comparable. Moreover, during the year 2011 the transition from *Indirect shipping* to *Direct shipping* was initiated in the region of UK & Ireland. Consequently, order history showed that in order to use the inventory remaining in the CDC, the LDCs placed orders with a CDC flow and with a direct flow for the same item during the course of 2011 and 2012.
- The calculation of the current safety stock is a black box, in the sense that there is no certainty about the time zone used in the calculation of the safety quantities. In other words, the average demand and standard deviation used by the replenishment system could have been different from the values used in this project.
- There is no certainty of whether the current safety stocks and reorder levels are achieving the target service level of 99.5% at SKU level.

9.5.3 Indirect shipping approach vs. RDC approach

Since only the safety stocks that have an indirect shipping flow (51 SKUs) can be compared with the proposed RDC approach, an analysis was performed in LDC-[redacted]. It showed that the value of the safety stock in the solution proposed is [redacted]% higher than the current safety stock, with an overall performance of 99.65% against 99.69% in the actual system. However, by looking to the service level at SKU level with the current safety stocks, it was found that [redacted]% of these items perform with a service level below 99%. The lowest service level (below 95%) belongs to the most expensive items (chairs and step tools) while the low-value items perform with a service level higher than target. On the other hand, the safety stock of the solution provides a service level above 99% for every item in this group, with a difference of € [redacted] in inventory value.

10 RESULTS OF SIMULATION

10.1 Results of customer service level

The sample selected according to the design of experiments is composed of 43 SKUs with a supplier lead time greater than 10 weeks, 25 SKUs with supplier lead time of less than 10 weeks and 8 SKUs with a direct shipping flow to LDC-[redacted]. Appendix J summarizes the simulation results in a table that shows the service level obtained with simulation and below each result, in italics, the service level calculated analytically.

In order to conclude whether the replenishment policy performs well, a service level equal or greater than 99% is assumed to be within an acceptable range. According to tables J1, J2 and J2 in appendix J, every item in all groups performed with a service level greater than 99% at all LDCs. This indicates that in general the policy will provide acceptable results regardless the lead time, demand variability or lot size.

The average service level of the entire sample is **99.89%** at LDC-[redacted], **99.46%** at LDC-[redacted] and **99.89%** at LDC-[redacted]. In LDC-[redacted], It was found that 53% of the SKUs in Groups 1 to 6 (SKUs with supplier lead time ≥10 weeks) have a service level below the target. The other LDCs experience service levels greater than 99.8%. In groups 7 to 12 (SKUs with supplier lead time<10 weeks), 24% of the sample also presents lower service levels at LDC-[redacted] with respect to the other two locations. Finally, the same findings hold for group 12 (SKUs with direct flow to [redacted]). This discrepancy among LDCs seems to be more frequent in items with a long supply lead time. Moreover, as seen in the Appendix J, in all scenarios this difference in service levels is also found with the analytical derivation.

10.2 Results of the allocation rule

Recalling the simulation description, an allocation rule is needed to decide the amount of stock to send to each LDC in case of a stock-out situation at the RDC. The allocation rule designed by the author of the integral stock norms allows the RDC to send less than the quantity ordered by the LDC in case the inventory on hand at the RDC is not enough to satisfy all locations. Therefore, in such cases the RDC sends only the amount necessary to cover the demand until the next delivery from the vendor.

With respect to these output parameters, two results of the simulation model are the probability of sending a partial shipment to each LDC and the percentage of the incoming order that is actually sent. For purpose of analysis, tables J4 and J5 in Appendix J, show the percentage of the order size shipped for SKUs-LDC with a probability of receiving a partial order equal or greater than 5%.

The results generated with the simulation runs showed that in average the RDC allocated partial orders with a probability of **0.52%** to LDC-[redacted], **1.17%** to LDC-[redacted] and **0.35%** to LDC-[redacted]. Detailed results showed that in both samples (with short and long lead time) the probability of a partial allocation is greater than 5% in LDC-[redacted] for SKUs with different order cycles among the LDCs. This means that when the lot-size at LDC-[redacted] is relatively large and the RDC is unable to send the entire request, this LDC is most likely to receive less than the optimal lot size. Simulation results showed that when this occurs, the quantity allocated is more than 60% of the incoming order from LDC-[redacted].

10.3 Simulation with equal review period at all LDCs

The findings in section 10.1 showed that the service level in LDC-[redacted] tends to be lower than the service level in the other two LDCs. A possible explanation is the difference in the review period. By allowing a review period of one day at LDC-[redacted] with zero lead time, the stock allocated needs to cover only for one day of demand, while in the case of the other two LDCs, larger orders are placed for coverage of one week of demand. Due to randomness in demand, it is possible that LDC-[redacted] encounters more stock-out situations with a one-day review period than the other two LDCs with a one-week review period. The hypothesis generated from this finding is that the service level is lower in [redacted] due to the shorter review period in this location with respect to the other two LDCs.

In order to validate this hypothesis, the policy parameters were calculated again with the assumption of a one-week review period at all LDCs and these are tested with the simulation model. The SKUs analyzed were only those that presented significant differences in service level. The results in Appendix K show that under the assumption of equal review periods, every SKU performed above the target service level at all LDCs. Therefore, it is concluded that the difference in review periods at the LDCs affects the customer service level of the proposed replenishment parameters, resulting in a lower performance at the LDC with a shorter review period. A modification of the allocation rule is tested in order to check if this discrepancy could be corrected. Details are presented in the confidential section of appendix E.

Finally, as seen in all simulation results, the simulated service levels always outperform the service levels computed analytically in every scenario, with no indication of effects due to lead time, demand variability or lot size. Further academic research is suggested in order to find out the reason of this discrepancy between the analytical results and the simulation results.

Part V: Evaluation

The main objective of this phase is to evaluate the solution to the problem. Chapter 11 describes the extent to which the findings can be applied to the regional supply chain in Office Depot and the limitations of the solution. Chapter 12 presents the general conclusions, the recommendations for improvements and for further research. At the end of this chapter, the impact on literature is described.

11. APPLICATION OF FINDINGS

The research objective is to define a methodology to plan and control inventory in the two-echelon supply chain of UK & Ireland. Firstly, the recollection of theory presented in Appendix L can be used by the company to guide the selection of the type of coordination, the suitability of central stock function, the status of information and the type of reorder logic for a product. Although this master thesis has focused on only one replenishment strategy described in Chapter 5, in case Office Depot decides to re-evaluate this strategy, these guidelines can provide assistance in designing a new replenishment approach.

Secondly, at the present, the company does not perform any type of logistics activity-based costing, in which relevant costs are assigned to specific activities incurred in ordering, distributing and handling one SKU. This study provides research about the regional logistic costs, based on information provided by local warehouse managers. The formulae to assign the relevant logistic costs to each product at every stockpoint are explicitly described. Therefore, with the definition of the total cost functions presented in chapter 6, it is possible to select the cost-optimal lot size in the regional supply chain for any product with the following input information: the number of selling units in one outer carton, one pallet-layer and one full pallet, the estimated weekly demand and the product value.

Moreover, the application of such allocation of costs to logistic activities can also be used in other regions with a validation of the handling times, the labor force rates, the capacities of the warehouse, the annual operational costs of the warehouse and the outbound rates to other LDCs.

In third place, the lot sizes and the reorder points provided in this master thesis can be used at each stockpoint in case Office Depot decides to select the RDC approach with integral information in the UK & Ireland for the SKUs under the scope of this project, taking into account that demand parameters were derived from historical information of 2011. The evaluation of the policy showed that it performs with a service level above 99% at all LDCs.

11.1 Limitations

The first limitation is regarding the validation of the logistic costs generated. Since the cost model proposed in this study is new to the company and no allocation of costs to activities has been generated so far, there are not cost figures that could be used to validate the costs. In addition, the resulting lot sizes could only be validated with a limited number of SKUs due to the difference of the RDC approach with the direct shipping method used nowadays.

The second limitation is that the performance of the solution could not be compared in terms of safety stock with the current situation, due to the many differences in both structures and the lack of information behind the calculation of the current safety stocks. Consequently, a comparison of both systems in terms of customer service levels at SKU level was not possible.

Finally, one limitation for the general public is that the literature contribution of this research project is not yet published. Specifically the approximation for the reorder points for very high service levels and the full description of the allocation rule that were developed by the author of the original formulae in Donselaar (1990).

12 CONCLUSIONS

12.1 General Conclusions

The main objective of this master thesis project was to build a replenishment strategy to plan and control the inventory in the two-echelon supply chain in UK & Ireland, composed of one RDC ([redacted]) and three LDCs ([redacted], [redacted] and [redacted]). The project is focused on those Private Brand products that are sourced and purchased at the European headquarters.

The selection of the replenishment strategy based on the ownership of responsibilities within the company, the market and product characteristics and the IT capacities, resulted in a strategy with:

- Decentralized coordination (pull system)
- Central stock function for all products in [redacted] and [redacted], and for [redacted]% of the assortment in [redacted].
- Integral or echelon-stock information
- Reactive (R,s,nQ) policy, with periodic review at both echelons (R), a reorder point (s) and orders in multiples of a lot size (Q)

The selection of the policy triggered the development of two procedures. First, a total cost function to select the cost-optimal lot size at every stockpoint. Second, the application of an approximation to calculate the reorder levels at every stockpoint based on a target service level equal to 99.5%.

The outcome of the cost-optimal lot sizes is based on the minimization of annual capital cost, handling cost and storage cost. It indicated that more than [redacted]% of the assortment at the LDCs should be ordered to the RDC in multiples of an outer carton. In the upper echelon (RDC), orders towards the vendor should be placed in multiples of full pallet and pallet-layer quantities for [redacted]% of the assortment. The findings also indicate that the order cycles at the RDC would be mostly between 4 and 6 weeks and shorter than 4 weeks at the LDCs. Long order cycles are mainly caused by low demand rates compared to the size of the minimum lot size.

The total cost function indicates that the dominant logistic cost is the handling cost. This is incurred when containers and trucks are unloaded, items are stored in the warehouse and orders are expedited to other LDCs. The estimated annual cost when using the lot sizes proposed for the SKUs within the scope of the project is € [redacted]

The outcome of the reorder points at SKU level given the cost-optimal lot size found in the first part provides a customer service level (computed analytically) above the target at all LDCs. Furthermore, in terms of inventory value, in average the RDC approach would operate with approximately [redacted]% less inventory in the whole supply chain compared to the actual approach. The warehouse in [redacted] can operate as RDC with [redacted]% less inventory than in the current situation. The policy allocates [redacted]% more inventory in LDC-[redacted].

Finally, the simulation results showed that the RDC approach performs with a service level at SKU level above 99% at all LDCs. Moreover, the results suggest that neither the supplier lead time, nor the demand variability and nor the differences in lot sizes have a significant impact in the service level. However it is seen that the LDC with a shorter review period experiences a low service level compared to the other two stockpoints.

With regard to the allocation rule assumed in this project, shipments of less than the optimal quantity to the LDCs are allowed only when necessary. The findings suggest that in average the probability of shipping partial orders to the LDCs is less than 1% for [redacted] and [redacted] and 1.17% for [redacted]. The partial allocation was mostly observed in SKUs with a large lot size at [redacted]; therefore, with significant differences in order cycles among LDCs. The conclusion is that the RDC will typically have enough stock on hand to meet the entire requirements of the LDCs. Further simulations suggest that the allocation rule has no impact on the difference in service levels.

12.2 Recommendations to Office Depot

The development of this project has led to some possibilities for improvement. Each recommendation is discussed in detail.

Clasification of products and target service level

It is important to note that every product contributes in different proportions to the company's profits. Therefore, high profitable products that are key to the business, should not receive the same efforts as products with medium and low demand rates. [redacted]

[redacted]

According to Teunter et al., (2009) the most important reason for applying an ABC classification is that, in most practical cases, the number of SKUs is too large to implement SKU-specific inventory control methods and many companies use this classification to set different service levels to SKUs within each class. Recalling the reorder point calculation, the safety stock needed for each item is directly dependent on the target service level. Thus, setting the same service level for the entire assortment causes the need of high amount of safety stock for products that provide very low profits to the company.

For instance, in diverse literature it is suggested that products with high volume of sales should get the highest service level, while slow-moving items should get the lowest service level. Other authors have proposed other approaches, as Teunter et al., (2009) who suggest a classification based on the minimization of inventory costs, and then SKUs with high backorder cost and high demand rate should get the highest service level, as opposed to SKUs with high holding cost that should get a lower target service.

Allocation of logistic costs

The second recommendation is with regard to the allocation of costs to logistic activities. In order to improve the measurements of inventory savings, the company can use this type of cost allocation to better estimate the costs involved in fulfilling a customer order. In this way, managers can get insights to evaluate whether a product, an order or customer is still profitable.

With regard to the costs measured in this master thesis, it is seen that the handling cost plays a dominant role. Thus, it is recommended to review the current handling activities at the LDCs and RDC in order to look for better methods that can improve the handling efficiency.

Vendors and lot sizes

The third recommendation is regarding the lot sizes set by some of the vendors and the decision to source slow moving products from the Far East. This study concludes that not only the large lot sizes are causing long replenishment cycles but also the low responsiveness of the market towards some of the products sourced from Far East. It would be valuable to negotiate more flexibility in the size of the MOQ as well as to analyze whether the logistic costs involved in sourcing from the Far East have a strong impact in the profit that the company is making, especially from the slow-moving products. Moreover, it should be valuable to review the product portfolio at LDC-[redacted] and evaluate if actions can be taken in order to improve the demand response of the large part of the products with very few demand events.

Central stock function

The fourth recommendation is about the selection of central stock function for certain products. In this master thesis it was defined to avoid the central stock function at LDC-[redacted] for chairs sourced in the Far East and for fast-movers toners sourced from Europe. According to the theoretical findings in Appendix L, a central stock function can also be avoided when the supply lead time is short and when the demand is rather stable than lumpy. In order to avoid freight costs between DCs, it would be recommendable to evaluate the direct shipping method to LDC of other European products, subject to having enough volumes to fill the FTL required.

Parameter Setting

The fifth recommendation is that the policy parameters should be reviewed with a high frequency especially for products with a high turnover, with the purpose of identifying any change in demand patterns or seasonality. For instance, Bowersox & Closs (1996) suggest to review the parameters in a monthly basis for the products within the A class.

12.3 Recommendations for future research

The first recommendation for future research is with regard to the classification and the setting of different service levels mentioned in the previous section. Further research can be done by classifying the SKUs by group, setting different service objectives and finding the optimal policy parameters. The purpose would be to check the differences in the safety stock needed when setting different service targets and the comparison with the performance of the actual system.

The second recommendation is with regard the logistics costs taken into account in the total cost functions. Although transportation costs were not included in the total cost function due to the assumption of a daily 'shuttle' from RDC to LDCs, it could be interesting to add the freight costs from the supplier and between LDCs, in order to estimate the dominance of this cost factor with respect to the other three logistic costs included in this study.

Finally, the evaluation of the RDC approach with respect to the actual approach has been performed in terms of inventory value and days of inventory in each LDC. The conclusion is that the RDC approach performs with less inventory than with the current system. This analysis could be extended to the relevant logistics costs, by measuring the annual operating cost of the current system and comparing the result with the annual operating costs presented in this master thesis.

12.4 Contribution to literature

As mentioned in the section of literature review, published research about inventory policies in multi-echelon divergent supply chain with lot sizing and echelon-stock information is very limited. The policy parameters provided in this master thesis have been modified to accommodate the characteristics of this two-echelon supply chain by the author of the original integral stock norms available in Donselaar (1990).

Therefore, the main contribution to literature is the development of an approximation for the integral stock norms when the service level desired is very high and when the review periods at both echelons are different. This new approximation was tested with simulation, indicating that the difference in the review period among LDCs has an impact in the service level. The result is a lower service level at the LDC with a shorter review period. Different review periods have been set due to the fact that the RDC experiences customer demand. Thus, this stockpoint is regarded as another LDC with a shorter review period. Given that no earlier research has been found about divergent supply chains with customer demand at the depot, this master thesis opens a gap for further academic research.

Finally, this master thesis has developed its own cost model for the selection of the optimal lot size at all stock points in the supply chain. This cost model takes into account specific assumptions about the warehouse operations in the definitions of the handling costs. The cost functions provided in this study can be useful for other companies that have similar characteristics in their handling activities. It also provides insight on the definition of other relevant inventory costs.

13 REFERENCES

Annual Report Office Depot, 2011

Axsater, S. "Approximate optimization of a two-level distribution inventory system". *International Journal of Production Economics* 2003; 81-82; p. 545-553.

Bowersox, D. J, Closs, D. Logistical Management, the integrated Supply Chain Process. New York; 1996.

Cachon G. "Exact evaluation of batch-ordering policies in two-echelon supply chains with periodic review". Operations Research 2001; 49; p. 79-98.

Chen F. "Optimal policies for multi-echelon inventory problems with batch ordering". *Operations Research* 2000*;* 48(3); p. 376-389.

de Kok A. G, Fransoo, J. C. "Supply Chain Management: Design, Coordination and Operation". *Handbooks in Operations Research and Management Science* 2003; Chapter 12.

de Kok A. G, Diks E.B, Logadimos A.G. "Multi-Echelon systems: A service measure perspective". Research report TUE/TM/LBS*.* 1996.

de Leeuw S, van Goor A, van Amstel R. "The selection of Distribution Control Techniques". *International Journal of Logistics Management* 1999; 10 No.1; p. 97-112.

Ganeshan R. "Managing supply chain inventories: A multiple retailer, one warehouse, multiple supplier model". *International Journal of Production Economics* 1999; 59; p. 341-354.

Law A M. Simulation Modeling and Analysis, Fourth Edition. International Edition*;* 2007

Rosenbaum B. "Inventory placement in a two-echelon inventory system" In: Schwarz LB. (Ed.)*, Multi-Level Production inventory Systems: Theory and Practice*. North-Holland, New York 1981; p. 195-207.

Seifbarghy M, Jokar M R. "Cost evaluation of a two-echelon inventory system with lost sales and approximately Poisson Demand". *International Journal of Production Economics* 2006; *102*; p. 244-254.

Silver E A, Pyke D F, Peterson R. Inventory Management and Production Planning and Scheduling. Third Edition. John Wiley & Sons; USA; 1998.

Snyder R D. "Inventory control with the gamma probability distribution", *European Journal of Operational Research* 1984; 17(3); p. 373-381

Teunter R H, Babai M Z, Syntetos A A. "ABC Classification: Service Levels and Inventory Costs". *Production and Operations Management* 2010*;* 19; p. 343-352.

van Aken J, Berends H, van der Bij H. Problem Solving in Organizations: A Methodological Handbook for Business Students. Cambridge University Press. 2007

van der Heijden, M. "Near cost-optimal inventory control policies for divergent networks under fill rate constraints". *International Journal of Production Economics* 2000; 63; p. 161-179.

van Donselaar K H. “Integral stock norms in divergent systems with lot-sizing”. *European Journal of Operational Research* 1990; 45; p. 70-87

van Donselaar K H. 2012. Personal communication

van der Vlist P. Synchronizing the Retail Supply Chain. Erasmus Research Institute of Management. 2007

14 ABREVIATIONS

CDC	Central Distribution Center
CV	Coefficient of Variation
DC	Distribution Center
FCL	Full Container Load
FTL	Full truck load
LDC	Local Distribution Center
LDL	Less than Container Load
MOQ	Minimum Order Quantity
OEM	Original Equipment Manufacturer
OTAC	On Time, Accurate & Complete
PO	Purchase Order
PB	Private Brand
RDC	Regional Distribution Center
SKU	Stock-Keeping Unit

15 APPENDICES

Appendix A. Overview of vendors

CONFIDENTIAL

Appendix B. Review Period and Lead times

CONFIDENTIAL

Appendix C. Unloading times of container at the RDC

CONFIDENTIAL

Appendix D. Regression Analysis of Inbound times at RDC

CONFIDENTIAL

Appendix E. Simulation Model

LDCs - INVENTORY SYSTEM

Assumptions:

- Orders to the RDC are placed at the end of day *t* after the demand has been fulfilled. The inbound of the order from the RDC occurs at the beginning of day *t+2*.
- In [redacted] LDC, the order is placed at the end of day *t* and received at the beginning of day *t+1*
- Backorders and partial deliveries are allowed at all LDCs

Input Parameters:

- L_j, Leadtime to location *j* in days

  L[redacted]: 1 day, L[redacted]: 2 days, L[redacted]: 2 days
- R_j, Review period at location *j* in days:

  R[redacted]: 1 day, R[redacted]: 5 days, R[redacted]: 5 days
- α_j alpha, shape parameter of the Gamma distribution at location *j*
- β_j beta, scale parameter of the Gamma distribution at location *j*
- s_j, reorder point at location *j*
- Q_j, lot size at location *j*

Stock Position:

Day (t): Current day

Start Inventory (SI_t): Starting inventory before a replenishment for day *t* equal to the ending inventory of the day before

$$SI_t=EI_{t-1}$$

Inbound order (IN_t): Replenishment quantity for day *t*. The inbound order is equal to the outbound quantity from RDC to location *j*, t-L_j periods before.

$$IN_t = OU_{RDC-j,\ t-L}$$

Start Inv.+Inbound (SII_t): Start inventory after replenishment at day *t*

$$SII_t= SI_t + IN_t$$

Demand (D_t): Incoming demand for day *t*. Generated using a random number generator (RAND()) and the inverse gamma function with the parameters calculated for each product given a daily average demand and daily standard deviation. The result is rounded to the nearest integer.

$$ROUND(GAMMAINV(RAND(), \alpha, \beta), 0)$$

Outbound (OU_t): The outbound quantity for day t is restricted to the available stock on hand and the cumulative backorders for day *t-1*. The outbound is thus, the incoming demand and the remaining backorders.

$$OU_t = MIN\ (SII_t, D_t + CB_{t-1})$$

Backorders (B_t): Amount of backorder of selling units for day *t*. If demand is greater than the available stock, the backorder is the difference between what it is available and the demand, allowing partial shipments.

$$B_t = MAX(0, D_t - SII_t)$$

Cumulative Backorders (CB_t): Cumulative backorders in selling units for day t. The starting condition is CB_0=0

$$CB_t = MAX(0, D_t - SII_t + CB_{t-1})$$

Ending inventory (EI_t): The ending inventory is equal to the starting inventory plus inbound (SII_t) quantity less the outbound quantity.

$$EI_t = SII_t - OU_t$$

Order Quantity Calculation:

Review?(R_t): With a VLOOKUP function in Excel, the outcome of this cell is a 1 when an inventory review occurs, else is equal to 0. For all LDCs the first inventory review occurs at day 1. At [redacted] and [redacted], the second review occurs at day 6, the third at day 11, and so on. At [redacted] there is a review every day.

Outstanding orders (OO_t): The outstanding orders are equivalent to the inventory in transit. It is checked by summing all previously ordered quantities with a due day later than the current day..

$$OO_t = \text{SUMIF}(DD_0{:}DD_{t-L}, >t, nQ_0{:}nQ_{t-L})$$

Inventory Position (IP_{tJ}): The inventory position for day *t* is equal to the ending inventory plus any outstanding order minus the cumulative backorders.

$$IP_{tJ} = EI_t - CB_t + OO_t$$

Order quantity (nQ_t): The order quantity for day *t* is equal to the integer number of lot sizes *n* required to bring the actual inventory position *above* the reorder point (s_{ij}) multiplied by the lot size (Q_{ij}), only when the review day is equal to 1 and the inventory position is equal or below to the reorder point, else zero. By taking the integer number of the lot sizes required to reach the reorder point plus one, it is assured that the inventory position will be raised above the reorder point. The size of the overshoot will depend on the size of Q.

$$nQ_t = \text{IF}(\text{AND}(R_t=1, IP_t<= s_{ij}), (\text{INT}((s_{ij}- IP_t)/ Q_{ij})+1)* Q_{ij},0)$$

Due date (DD_t): Due date for the arrival of the order placed at day *t* is equal to the current day plus the lead time.

$$DD_t = t+L_j$$

Output Parameters:

Pre-determined Service Level: Defined as the percentage of periods that demand can be met instantaneously from the inventory on hand (Donselaar, 1990). This is measured by counting the number of days in which the value of the backorder is equal than zero and dividing over the total simulation period. This is measured after the warm-up period.

$$\text{Service Level: COUNTIF}(B_0{:}\ B_{T,} =0)/\text{COUNT}(B_0{:}\ B_T)$$

RDC - INVENTORY SYSTEM

Assumptions:

- Orders to the supplier are placed at the end day *t* after the demand has been fulfilled. The inbound of the order occurs at the beginning of day *t+L*.
- If an order from the LDC cannot be completely satisfied with stock on hand, there is allowance for shipments of quantities less than the order placed by the LDC but always in multiples of the smallest lot size (a carton size). The RDC will satisfy orders of LDCs according to the allocation rule and in the following order: [redacted], [redacted] and [redacted].

Input Parameters:

- L, Lead time to RDC in days
- R, Review period in days
- s, reorder point at RDC
- Q, lot size at RDC
- Q_j, lot size at location *j*
- $Q_{i,carton}$, selling units in one carton of item *i*
- nQ_{tj}, Order quantity from location *j* at day *t*
- IP_{tj}, Inventory position of location *j*

- μ_j, average daily demand location *j*
- s_j, reorder point at location *j*

Allocation Rule:

CONFIDENTIAL

Stock Position:

Day (t): Current day

Start Inventory (SI_t): Starting inventory before a replenishment for day *t* equal to the ending inventory of the day before

$$SI_t = EI_{t-1}$$

Inbound order (IN_t): Replenishment quantity for day *t.* The inbound order is equal to order quantity with a due date equal to the current day.

$$IN_t = SUMIF\ (DD_0{:}DD_{t-L},{=}t,nQ_1{:}nQ_{t-L})$$

Start Inv.+Inbound (SII_t): Start inventory after replenishment at day *t*

$$SII_t = SI_t + IN_t$$

Incoming Order (IO_{tj}): Incoming order for day *t* from location *j* is equal to the order placed by the LDC *j* at day *t*.

$$IO_{tj} = nQ_{tj}$$

Allocation of inventory:

FORMULAE RELATED TO THE ALLOCATION RULE ARE CONFIDENTIAL

Backorders (B_{tj}): Amount of backorder of selling units for day *t* of location *j*. If the incoming order is greater than the available stock, the backorder is the difference between what it is available and the incoming order.

$$B_{tj} = MAX(0,\ IO_{tj} - OU_{tj})$$

Cumulative Backorders (CB_t): Cumulative backorders of selling units for day *t.* The starting condition is $CB_{0j}=0$

$$CB_{tj} = MAX(0,\ ,\ IO_{tj} - OU_{tj} + CB_{t-1,j})$$

Ending inventory (EI_t): The ending inventory is equal to the starting inventory plus inbound quantity less all the outbound quantities.

$$EI_t = SII_t - OU_{t,Ash} - OU_{t,Lei} - OU_{t,Dub}$$

Order Quantity Calculation:

Review?(R_t): The outcome of this cell is a 1 when an inventory review occurs, else is equal to 0.

Outstanding orders (OO_t): The outstanding orders are equivalent to the inventory in transit. It is checked by summing all previously ordered quantities with a due day later than the current day. It is assumed that the supplier delivers all complete orders.

$$OO_t = SUMIF\ (DD_0{:}DD_{t-L},\ >t, nQ_0{:}nQ_{t-L})$$

Inventory Position ($IP_{t,RDC}$): The inventory position for day *t* is equal to the ending inventory plus any outstanding order minus the cumulative backorders.

$$IP_t = EI_t + OO_t - CB_{t,Ash} - CB_{,Lei} - CB_{t,Dub}$$

Echelon Inventory Position (EIP_t): The echelon inventory position is defined as *All stock in transit to this stockpoint + physical stock + stock in transit and/or in hand to its downstream stockpoints – all backorders at the end-stockpoints.* This is equivalent to the sum of all Inventory positions at LDCs and RDC.

$$EIP_t = IP_{t,Lei} + IP_{t,Ash} + IPt_{t,Dub} + IP_{t,RDC}$$

Order quantity (nQ_t): The order quantity for day *t* is equal to the integer number of lot sizes *n* required to bring the actual echelon inventory position *above* the reorder point multiplied by the lot size, only when the review day is equal to 1 and the inventory position is equal or below to the reorder point, else zero.

$$nQ_t = IF(AND(R_t{=}1,\ EIP_t <= s),(INT((s - EIP_t)/\ Q)+1)*\ Q_i,0)$$

Due date (DD_t): Due date for the arrival of the order placed at day *t* is equal to the current day plus the lead time.

$$DD_t = t+L_j$$

Output Parameters:

Pre-determined Service Level: The same measure as for the LDCs is performed. This is measured by counting the number of days in which the value of the backorder at all LDCs is equal to zero and dividing over the total number of periods. The outcome is the percentage of periods in which the demand was totally fulfilled with stock on hand. This is measured after the warm-up period.

$$\text{Service Level: } COUNTIF\ (B_{0j}{:}\ B_{Tj,}\ {=}0)/COUNT(B_{0j}{:}\ B_{Tj})$$

Less than Qj?: This formula checks only the days in which a delivery to each LDC occurred and it counts the percentage of the days for which the outbound quantity was less than the optimal lot size.

Average size of Q delivered: This formula only checks the deliveries of less than the optimal lot sizes and computes the average percentage of the optimal lot-size that was delivered to all LDCs.

SIMULATION WITH A MODIFIED ALLOCATION RULE

CONFIDENTIAL

Appendix F. Tests for determining simulation parameters

Figure F1 shows the ending inventory of a random item with 5 replications, in which it is seen that the ending stock arrives to a steady state approximately 50 (lead time in working days) + 20 (review period in working days) = 70 days. As the maximum lead time for Far East products is 11 weeks and in order to assure that a steady state is achieved, a warm-up period of 100 days will be used for the inventory system at the RDC.

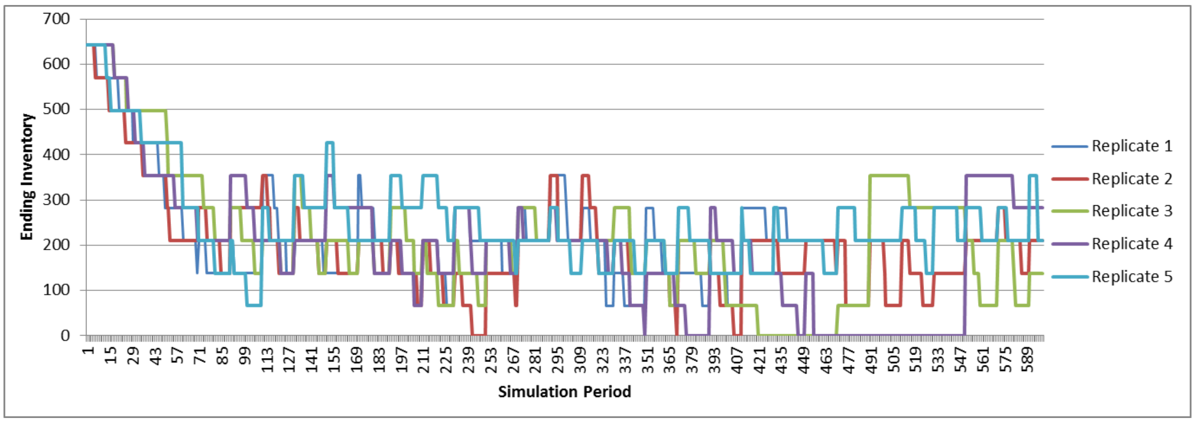


Figure F1. Ending inventory of a random item at RDC over a simulation length of 600 days

As mentioned in chapter 8, the number of runs necessary is determined by testing the service level for different values of two characteristics: the lot-size and the coefficient of variation.

Figures F2 and F3 show the service levels at LDC-[redacted] and RDC respectively, tested for three items with low, medium and high CV of the weekly demand at [redacted]. From the pictures, it can be concluded that 200 replicates would be enough to have a reliable outcome.

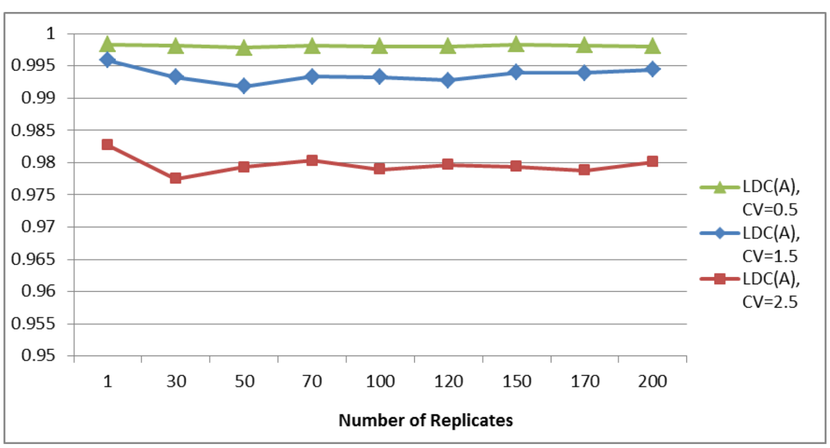


Figure F2. Service level at LDC-[redacted] with three values of weekly CV

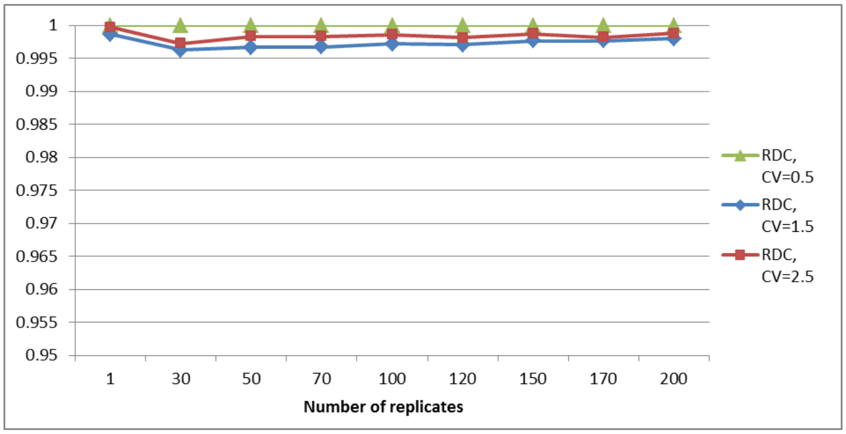


Figure F3. Service level at RDC with three values of weekly CV (at LDC-[redacted])

Figures F4 and F5 show the service levels at LDC-[redacted] and RDC respectively for two situations, when the lot size at LDCs is small (Q=1 selling unit) and when the lot size is large (a Q such that the order cycle is longer than 8 weeks). According to the results of situations, variability and lot-size, 200 runs would provide a reliable result with respect to the service level at LDCs and RDC.

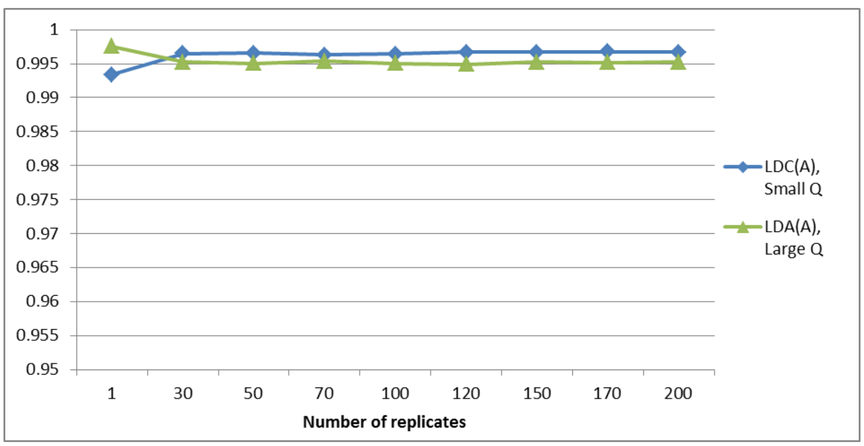


Figure F4. Service level at LDC-[redacted] when varying the lot size

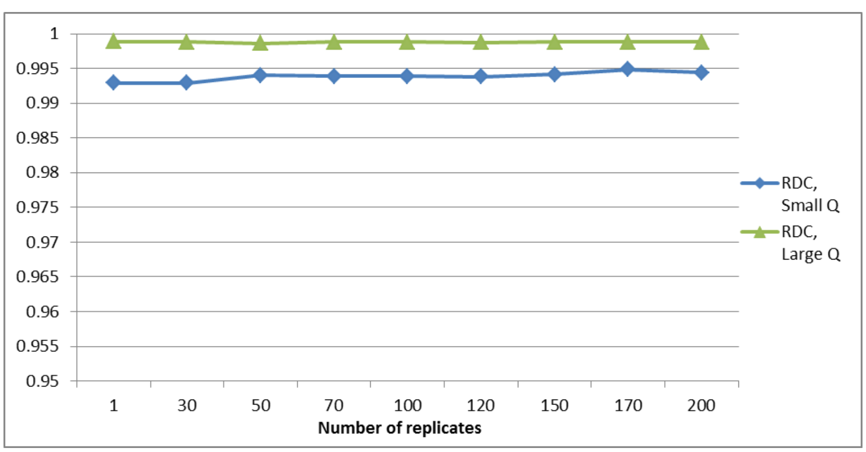


Figure F5. Service level at RDC when varying the lot size of LDC-[redacted]

Appendix G. Order cycles and cost functions.

Figure G1 presents the order cycle at the LDCs only of SKUs sourced from the Far East. As it is seen, approximately [redacted]% of the assortment in [redacted] and [redacted] are ordered with a frequency longer than two months. In [redacted] this proportion is higher. The causes of long cycles have been found to be the combination of low demand of those Far East products and the size of the minimum lot size.

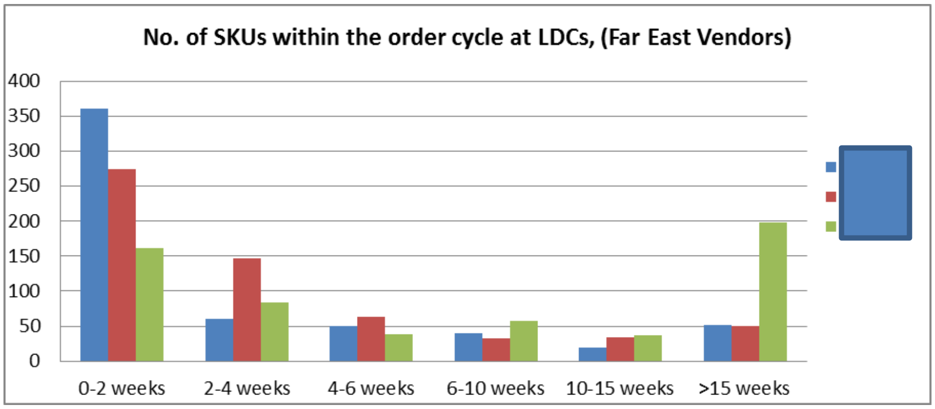


Figure G1. Order cycles at LDCs for Far East vendors

Figure G2 shows the order cycles of the European assortment, characterized by an order frequency no longer than one month in most of the cases.

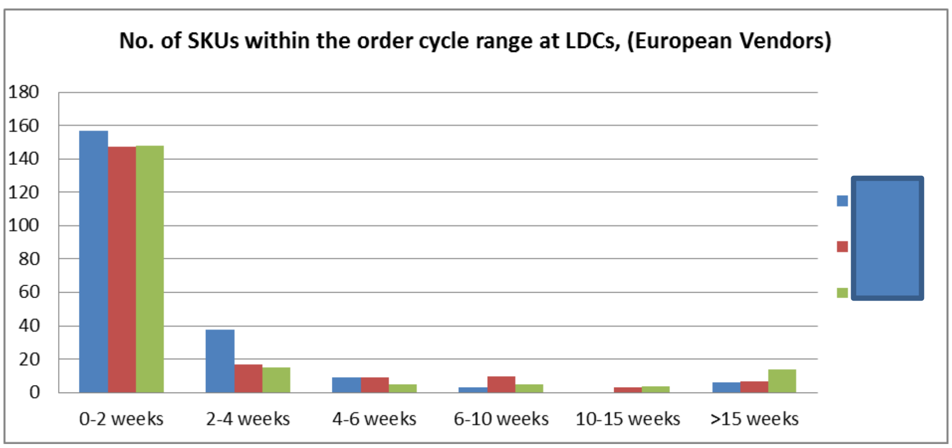


Figure G2. Order cycles at LDCs for Far East vendors

Figure G3 shows the aggregated cost curves of each cost factor en the total cost of all SKUs with an optimal lot size equal to a carton in LDC-[redacted]. These products are characterized mainly by low demand volumes, meaning few handling activities over a year. Therefore, the dominant cost factor in determining the cost-optimal lot size is the capital cost

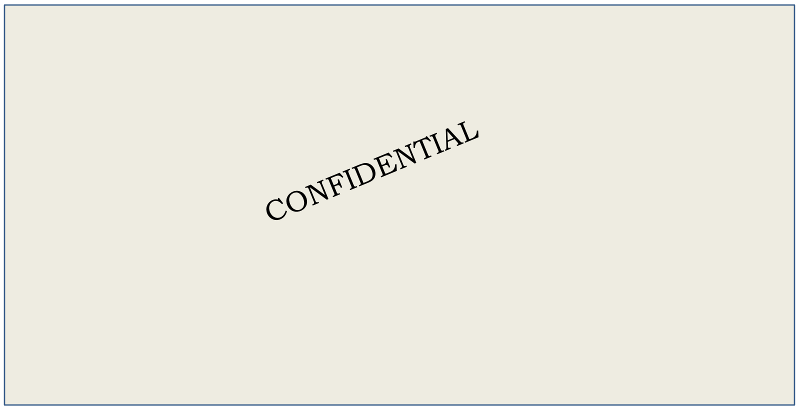


Figure G3. Total cost curve of all SKUs with a lot size equal to a carton at LDC-[redacted]

Figure G4 presents the aggreted cost curves of all SKUs with an optimal lot size of a pallet-layer in LDC-[redacted]. As it is seen, the handling cost of a layer is still higher than the handling cost of a pallet, but the total cost function is minimum for layers due to the difference of the capital and storage costs with respect to the full-pallet.

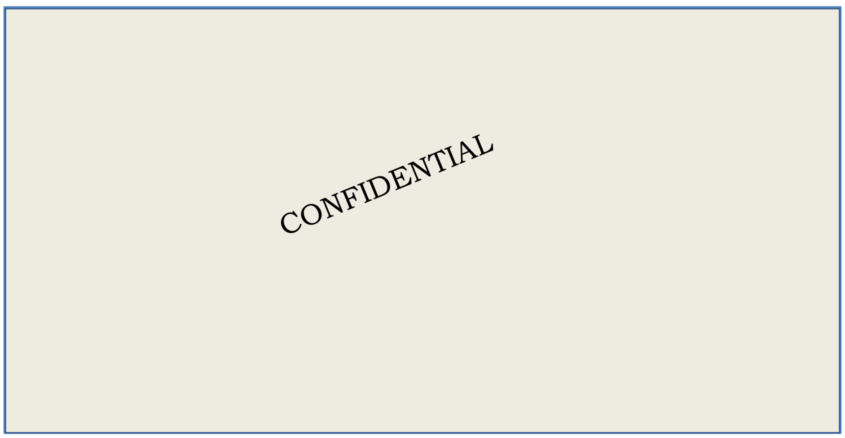


Figure G4. Total cost curve of all SKUs with a lot size equal to a layer at LDC-[redacted]

Finally, products with lot size equal to a pallet are characterized by a fast turnover, meaning that with a lot of handling activities over a year, the dominant cost becomes the handling cost. According to the cost functions, handling full-pallets is faster and therefore the less expensive than layers and cartons. Figure G5 shows the aggregated cost curves of all SKUs with a lot size equal to a full pallet in LDC-[redacted].

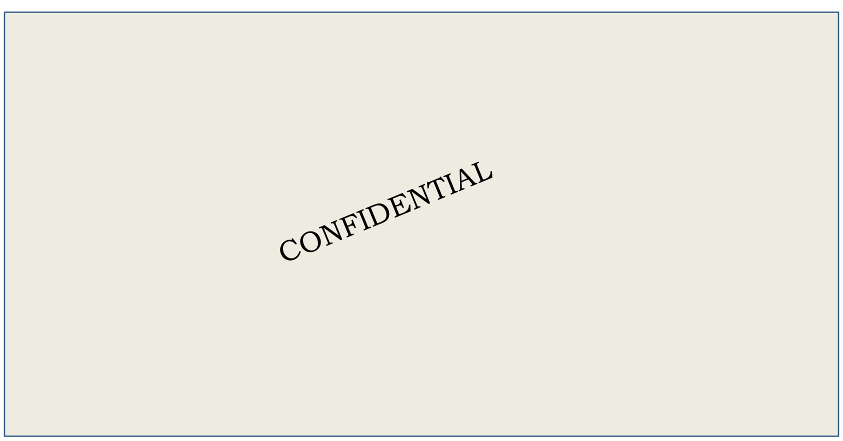


Figure G5. Total cost curve of all SKUs with a lot size equal to a pallet at LDC-[redacted]

Appendix H. Gamma approximation to compute the reorder point

CONFIDENTIAL

Appendix I. Gamma Distribution Properties

The gamma distribution is a two-parameter continuous probability distribution. The most common parameterization is with a shape parameter *k* and a scale parameter θ, both with positive values.

The probability density function of the gamma distribution can be expressed in terms of the shape and scale parameters as follows:

$$f(x) = \frac{\lambda^r x^{r-1} e^{-\lambda x}}{\Gamma(r)}, \text{ with } \Gamma(r) = \int_0^\infty x^{r-1} e^{-\lambda x} dx$$

The mean and variance are:

$$\mu = k\theta \ , \sigma^2 = k\theta^2$$

In Microsoft Excel, the parameters requested for the inverse of the gamma distribution are the shape parameter *k* and the scale parameter θ. The following is a graphical representation of the density function of the gamma distribution with different shape and scale parameters

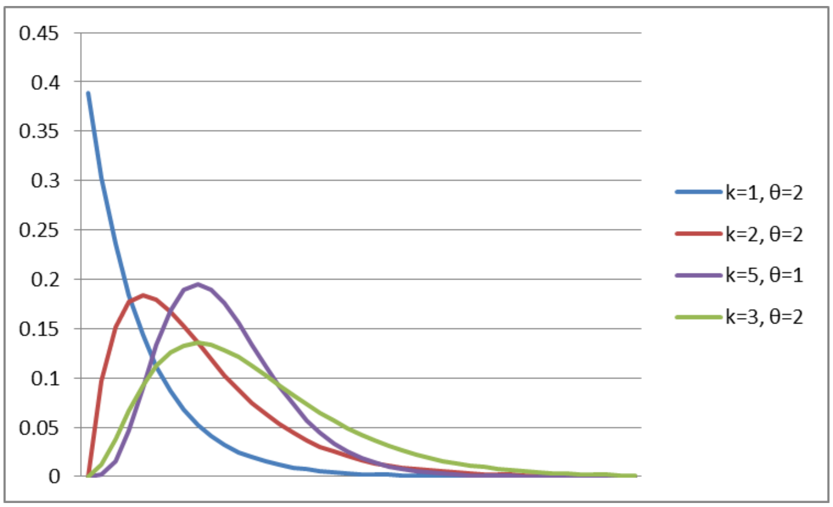


Figure I1. Probability density function of a Gamma distribution

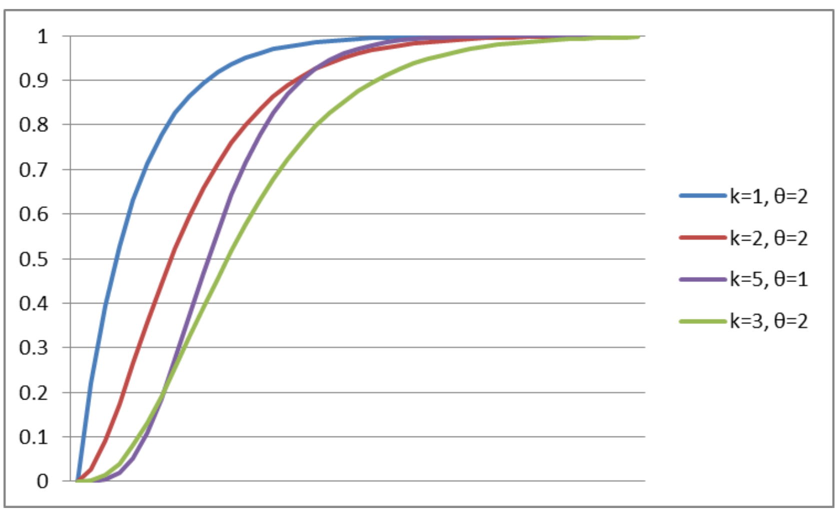


Figure I2. Cumulative distribution function of a Gamma distribution

Appendix J. Simulation Results

CONFIDENTIAL

Appendix K. Simulation results with equal review period at all LDCs

CONFIDENTIAL

Appendix L. Replenishment decision based on product and channel characteristics

This purpose of this appendix is to provide the reader with theoretical findings with regard to the selection of distribution control decisions and inventory control decisions for a product or a subset of products based on some characteristics proper of the product itself, the market and the distribution channel.

These findings are presented in form of a summary table with a recollection of theoretical and practical findings available in De Leew et al., (1999) and Bowersox & Closs (1996). Each column presents one product or channel characteristic and each row presents one type of distribution or inventory control decision. In each cell if infotmation was found, a suggestion is provided.

The main characteristics of interest at Office Depot are the demand variability, the sales volume, the product value, the physical volume of the product and the supply lead time. The distribution control decisions are: the type of allocation coordination, the central stock function and the status of information. The inventory control decision is the type of reorder logic.

In the characteristic 'Sales volume' the common ABC classification based in sales, is used to make reference to items "A" that are high-volume and fast-moving products. The moderate-volume products are called "B" and the low-volume or slow movers are known as the items "C".

Table L1. Distribution control decisions and Inventory control decisions for several product and channel characteristics

		Demand Variability	**Sales Volume**	**Product Value**	**Product Volume and batch size**	**Supply Lead Time**
		Distribution Control Decisions				
Allocation coordination	*Centralized coordination (Push control system)*		For products with high sales that are reviewed continuously, the centralized policy outperforms, also when the service level required is high		If the lot size of items C is relatively high, the imbalance risk increase, and so central coordination is preferred	When the supply lead time is long, central coordination is beneficial
	Decentralized coordination (Pull control system)	When demand variation is considerable, decentralized	Items B can be allocated by means of local coordination			Local coordination is preferred with short supply lead times, because with

		coordination is preferable. Also if stock is reviewed periodically when placing orders to the RDC.				additional demand information it is easier to put outlet orders
		Demand Variability	**Sales Volume**	**Product Value**	**Product Volume and batch size**	**Supply Lead Time**
Central stock function	*Central stock function at RDC*	If demand presents seasonality, this stock should be kept centrally. Central stock is beneficial also for products with highly fluctuations in demand	Items B and C are faced with less stable demand and less replenishment orders. As a result central stock is needed.	Valuable products should be kept centrally	If the production/ distribution lot size is large, keep a central stock function	
	Cross-docking or direct delivery		Consider the allocation directly for items A due to stable demand and high order frequency. As well as for items that require high service level	In the direct delivery, the reduction in handling activities and storage costs is significant for products with low value and high product volume.		Central stock can be abolished if the supply lead time is relatively short, to ensure a quick reaction to the market. As long as local stock levels do not rise significantly
		Demand Variability	**Sales Volume**	**Product Value**	**Product Volume and batch size**	**Supply Lead Time**
Status of information	*Installation or local information*	Use local information if there is high uncertainty in demand			When the product lot size is large, local information is preferred in order to avoid imbalance risk	
	Echelon or global information			If the product value density is high, global information is preferred	The stock reduction can be relevant for high volume products when using global information	
	Inventory control decisions					
		Demand Variability	**Sales Volume**	**Product Value**	**Product Volume and batch size**	**Supply Lead Time**
Type of reorder logic at RDC	*Time-Phased logic (DRP)*	If dependent demand, from the LDCs to the RDC has strong and stable patterns, use time phased demand.	Preferred for products with high value and high sales volume. The computational efforts and scheduling becomes difficult as the number of SKUs increases.			Use when there is certainty in the supply lead time
	Reactive Logic (Reorder point)	If dependent demand is not consistent and	Use reactive logic for products with low volume in			Use reactive logic with certainty in lead times and

		predictable use reactive logic	sales			when the production has no capacity limitations

Appendix M. Policy parameters

CONFIDENTIAL