MORTEZA POURAKBAR

End-of-Life Inventory Decisions of Service Parts

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End-of-life voorraad beslissingen voor reserve onderdelen

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Morteza Pourakbar
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Chapter 1

Introduction

1.1 Service Parts Inventory Management

The last decades have been called the "golden age" of services. This is due to the fact that companies have sold so many units over the years that their after-markets have become drastically larger than the original equipment business. The Aberdeen Group's study (2005) shows that the sales of spare parts and after-sales consist 8% of the annual gross domestic product of the United States. It is approximately $1 trillion every year on assets they already own. This means that the US aftermarket is bigger than all but the world's eight largest economies. This brings a huge interest and motivation for companies to improve their service sectors. After-sale support is notoriously difficult to manage. However, aftermarket's obvious charm is generation of a low risk revenue stream over a long period of time. For instance, in aviation industries, service obligations can run as long as 25 years (Cohen et al. 2006).

One key aspect in efficient aftermarket service management is how enterprises deal with service parts inventories. Since service parts are considered slow moving, it is not cost effective for companies to hold excess inventories in order to insure rapid service deliveries. Effectively managing service inventories provides a great opportunity for companies to reduce costs while maintaining or improving customer service levels. There are certain challenges that differentiate service parts inventories from production parts inventories. First, service companies face service obligations. Efficient inventory management systems should ensure meeting of service obligations while minimizing costs. Another challenge that service parts inventory management should deal with is demand variability, which makes it difficult to forecast demand and may lead to a demand and supply mismatch.

Furthermore, with rapid technology developments and shortened service life cycles, service parts are subject to a huge risk of obsolescence. This chapter is organized as follows. In the rest of this section these challenges are studied in more detail to identify the importance of service parts inventory management. Next, different phases in service parts inventory management are characterized and since this dissertation is more focused on final-phase, the end-of-life phase is investigated in more detail. This chapter ends with an outline to this dissertation.

1.1.1 Service Obligations

Service parts may be associated with capital-intensive products that call for a prompt service in case of failure. According to Aberdeen research (2005), particularly in industries such as utilities, telecommunications, and healthcare, in which customers require near-100% asset availability, a speedy issue resolution is paramount. Nearly 70% of respondents in the Aberdeen research indicated that the typical aftermarket service response times required in service level agreements have shrunk to 48 hours or less. In order to maintain satisfaction among the installed base, companies need to employ intelligent planning of service parts to ensure the right part is in the right place at the right time. Service providers offer an array of service contracts for a single product. These service contracts impose different service requirements for service providers against different prices. Murthy and Blischke (2005) discuss the factors that form the distinction among various service contracts. In general one could argue that the distinctions are induced by varying: 1) service responses and/or repair time commitments; and 2) price and/or cost structures. The response times vary significantly from situation to situation. For example in mission critical situations, the service provider is always present on-site whereas in the same day delivery, the response time varies from 2 to 24 hours. Cohen et al. (2006) highlight that consumer products such as TVs and PCs have lower response time requirements. On the other hand, businesses like computing machines, construction equipment and aircraft have typically very short response time requirements. The failure to meet service obligations may results in penalties that are negotiated during the contract formalization. The main challenge is to manage inventory such that the system is highly responsive and at the same time avoids inventory carrying and obsolescence costs.

1.1.2 Demand Forecasting

Service parts are considered slow moving and demand forecasting for them is notoriously difficult. Demand for spare parts might be inventory-driven or maintenance driven. Maintenance-driven demands are either for proactive or reactive maintenance activities. The portion of demand which is inventory-driven, for example regular replenishment, together with parts needed for proactive maintenance are better structured whereas the demands originating from a reactive maintenance activity occur in an erratic fashion due to the random occurrences of failures or malfunctions. Above all, the development of spare parts demand goes hand in hand with the dynamics of market demand for products.

Demand forecasting in spare parts inventory management is of vital importance. The gain due to an accurate forecasting system can be bountiful. Traditional black-box forecasting approaches may be misleading. It is mainly because parts and products demand pattern vary with the stage of the life cycles they are in. The pattern is distinguished by an initial growth, steady maturity and a final decline signifying initial, maturity and final phases. Moreover, actual customers demand may depend on many local factors including the type of system, type of service contract, maintenance scheme, and state of her system. Therefore, it introduces the idea of using all available information on the so-called installed base (Dekker et al., 2010). What distinguishes installed base forecasting is the inclusion of installed base information in addition to the historic data.

1.1.3 Risk of Obsolescence

Essentially obsolescence happens when the demand for parts drops substantially. It is because either the product is no longer in use or the part reached its end of the life-cycle and is replaced by another one. Where the life cycles of parts end before life cycle of products, this phenomenon is called "life-cycle mismatch" (Solomon et al. 2000). This phenomenon has been studied and verified in various papers including (Bass 1969, Dekker et al. 2010).

Life-cycle mismatch is most severe when parts with short life cycles are used in long-lived products (Bradley, Guerrero, 2008) as is the case with capital-intensive electronic equipment. For example, the intended life cycles of public safety communication equipment, large Internet routers, and military systems are 20 years or more whereas the commercial-of-the-shelf (COTS) electronics parts that they rely on such as memory, microprocessors, and resistors, often have the life cycles that last in the order of two years (Livingston 2000, Spiegel 2004). Shorter-lived consumer products (e.g. personal computers, digital cameras, and cell phones) consume a majority of these COTS electronic components, and designers of these products readily apply newer generations of electronic parts in successive product generations. With new product design and evolution, parts manufacturers discontinue older generations of electronic parts, leaving the manufacturers of long-lived infrastructure goods without sources for parts.

However, when the demand drops substantially the excessive parts on stock are no longer needed and they are considered obsolete. Van Jaarsveld and Dekker (2010) consider an OEM providing spare parts for capital-intensive products. They discuss that main reasons for demand variability and thus parts obsolescence are changing maintenance policy on original product, changing operating conditions or operating location of original product and use of alternative part sources. Cattani and Souza (2003) report that at a typical HP computer manufacturing division obsolescence can reduce profit by up to 1% a year. Moreover, Cohen et al. (2006) report that even though original equipment manufacturers carry on average 10% of annual sales as spares, 23% of parts become obsolete every year. These examples signify the role that a spare parts inventory system can play in reducing the risk of obsolescence by lowering the level of inventories without affecting the system's responsiveness.

1.2 Different Phases in Spare Parts Inventory Management

To formulate and implement an efficient service part inventory management system, it is of primary concern to identify in which phase of the service-life cycle the part is. The phases are basically differentiated based on the demand pattern the part is following. The part life cycle is not necessarily similar to the associated product life cycle. The service part typically follows the underlying product's life-cycle, but with a time lag. In general, the service life cycle of a part illustrates the evolution of demand for service parts from the time that the associated product is introduced to the market until the last service contract or warranty expires. Figure 1 depicts the service life cycle. In the sequel of this section we explain characteristics distinguishing each phase. Since, a major part of this dissertation is pertinent to the final phase inventory management of service parts, the

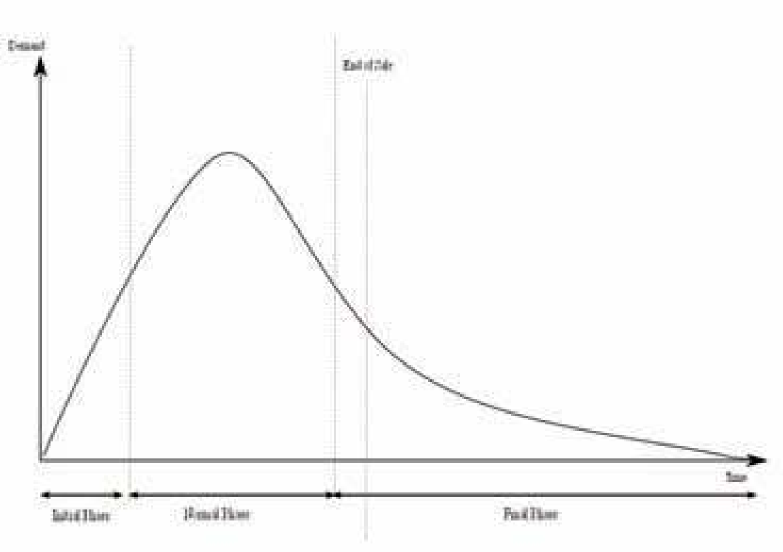

Figure 1.1: Service life cycle of a typical spare part

final phase is scrutinized in detail. An extensive literature review on studies concerning service parts inventory management in the final phase is also presented.

1.2.1 Initial Phase

The initial phase is the first phase in the service life cycle of service parts. In this phase, simultaneous to product introduction to the market, the production of spare parts starts and the first demand for service arrives. The main challenge in this phase is how to control inventories without any history of demand. However, demand for service parts is typically low and since the part is in production, there is the opportunity to adapt for demand fluctuations by changing the production rates.

There is not an ample literature on this phase. However, studies on initiation of an inventory system can be associated with service parts initial phase inventory problem. A common setting for inventory problem in the initial phase is that there is no initial stock and the production rate is finite. It is then, in general, optimal to use initial order quantities so that demand satisfaction can be sustained. Among this studies are Axsäter (1988), Ding and Grubbström (1991), Grubbström and Ding (1993) and Axsäter (2011). Axsäter (2008) considers a related situation where the forecasts are improving. It turns out that this will also affect the initial order quantities. Other reasons to use different initial order quantities can be learning and forecasting effects, which change the production rate, see for example Elmaghraby (1990), and Klastorin and Moinzadeh (1989).

1.2.2 Normal Phase

During the normal phase the production of service parts is up and running that provides management with the ability to adjust production rate to meet demand. The main characteristic of this phase differentiating it from initial phase is that there exists sufficient historic data to forecast the demand behavior. The literature on service parts inventory management in this phase abounds and most of the time it is difficult to distinguish the regular inventory management literature from service parts related literature.

1.2.3 Final Phase

A service part enters the final phase as soon as the part production is terminated and the final phase ends when the last service (or warranty) contract expires. In general, the final phase is the longest period within the life cycle of a service part. For instance, in the electronics industry this phase may last from four up to thirty years while the production of electronic appliances is normally terminated after less than two years (Teunter and Klein Haneveld, 2002). In the past decades, there has been a significant increase in innovation. As a result, a typical product (for example consumer electronics) may go through all of its life cycle stages including development, initial, normal and final production within a year, or less. Accordingly, due to this spurt in innovation, the final order is now typically placed within a year after production kick-off. As a consequence, the difficulty of accurately predicting demand over time and the lack of a sound inventory system to estimate final order quantities have resulted in many cost ineffective purchases. On the one hand, companies are mandated to satisfy customer demand for service parts due to warranty or service contract obligations, but on the other hand, they face a huge obsolescence and disposal risk at the end of the final phase. Many firms have encountered large write-offs of excess inventory after the product life ultimately ends. For example, IBM disclosed a $1 billion loss from its personal-computer business in 1998, attributed to excess PCs in dealer channels that had to be sold at a steep discount (Bulkeley, 1999).

One of the main problems in the final phase inventory management is that the acquisition of parts is no longer guaranteed and companies are forced to decide on the final order quantity when production ends. Basically, during the final phase, customers return defective products for service. Various strategic decisions can be made on how to deal with this mismatch in order to keep the product in the market. These include substituting another part for the obsolete one, obtaining the discontinued part from an after market manufacturer, redesigning the product, discontinuing the product or purchasing a sufficient volume of the obsolete part to sustain production of the product for its remaining life time; this is called a *life-time* or a *last-time* buy (Bradley and Guerrero, (2008)). In this dissertation, we focus on the last-time or end-of-life buy as a countermeasure tool to cope with the final phase inventory problem.

In general, research on the end-of-life inventory problem can be divided into three categories: service-driven, cost-driven and forecasting based approaches. In a service-driven approach, a service level is optimized regardless of the cost incurred by the system. A cost-driven approach gives a monetary value to the unserved part of the demand by means of back-order or penalty costs, and then adopts a policy to minimize the total cost. Forecasting based approaches ignore production and inventory costs and build models to mimic the demand behavior during the final phase. These models are used to predict the total demand in the final phase and this predicted value is used as the final order quantity. In the sequel to this section, we will briefly review the literature and provide examples of these three approaches to the end-of-life inventory problem.

Fortuin (1980, 1981) describes a service level approach and addresses non-repairable items or consumable spare parts. He derives a number of curves by which the optimal final order quantity for a given service level can be obtained. He assumes an exponentially decreasing demand pattern and uses a normal approximation to derive expression for several service levels. Another service-driven approach is developed by van Kooten and Tan (2009) for a system in which parts are subject to the risk of condemnation. They build a transient Markovian model to represent the problem for a repairable spare part with a certain repair probability and repair lead time. They also develop some approximate models that allow involvement of further real world characteristics.

Basically, a cost-driven approach decides on the quantity purchased by weighing the cost of ordering too many against the cost of buying too few, or in other words, a newsvendor problem approach. Among this category of works is Teunter and Fortuin (1999).

They assume that failed parts can be remanufactured and reused. They find a near optimal solution for the final order quantity and further extend their work by introducing a dispose-down-to level policy which allows unused parts to be removed from stock before the end of the horizon. This approach is applied at Philips Consumer Electronics and results are shown in Teunter and Fortuin (1998). Another cost-driven approach is developed by Teunter and Klein Haneveld (1998) in which they analyze a multi-part life time problem from an equipment supplier perspective. The equipment supplier allows the machine operator to place a final order for critical parts to keep the machine operational to the end of the horizon. Teunter and Klein Haneveld's model minimizes a firm's internal cost for maintaining an obsolete machine where the failure rate of each part is independent of the failure rates of other parts. In another paper, Teunter and Klein Haneveld (2002) consider the possibility of ordering in the final phase, but they assume that if the part is not ordered at the beginning of the final phase, its price will be higher in the later stages. They propose an ordering policy consisting of an initial order-up-to level at the beginning of the final phase followed by a subsequent series of decreasing order-up-to levels for various intervals of the planning horizon.

Cattani and Souza (2003) have developed another cost-driven approach that studies the effect of delaying a last-time buy. They perform a newsvendor analysis which considers overage and underage costs to evaluate the effect of delaying final order placement. Bradley and Guerrero (2009) consider different parts of a product becoming obsolete sequentially over product life time in which a final order for each one has to be placed. In their model, they assume that once a life-time buy inventory for any part is depleted, manufacturing of the product ceases forever. An exact and two heuristic approaches are developed to solve this problem.

Forecasting based approaches focus on forecasting demand for a discontinued product instead of dealing with the production or inventory problem. This approach was first developed by Moore (1971) whose model forecasts the *all-time requirements* of consumable service parts in the motor-car industry. By plotting the sales data on a logarithmic scale, Moore obtains three families of curves to be common for 85% of the spare parts considered. Later on, Ritchie and Wilcox (1977) develop a method, using renewal theory, to forecast all-time future demand for spare parts to the moment of the final production run. A more recent work by Hong et. al. (2008) develops a stochastic forecasting model using the number of product sales, the product discard rate, the failure rate of the service part and the replacement probability of the failed part. The model decides on the final order quantity based on the forecasting results.

1.3 Outline of the Dissertation

1.3.1 Final Phase Inventory with Alternative Service Policy

The literature relevant to the management of the final phase inventory focuses only on the repair of defective products by replacing the defective part of the product with a functioning spare part. This part may either be a new part or a repaired returned item. To the best of our knowledge, the literature considers this as the only way to service customers. This approach is feasible to service the demands for capital-intensive goods and their associated spare parts. However, for consumer electronic goods, other approaches should be considered because of the continuous price erosion of these products over time which may even exceed an annual rate of 30%, while the repair associated costs may stay steady over time. Consequently, this introduces the idea that there may be a break-even point in time within the final phase after which the regular repair policy is no longer the best cost-effective policy. After this point, a firm can satisfy customer demands through an alternative service policy such as offering a discount on a new model of the product, giving credit or monetary compensation to customers, or swapping the defective product with the same or a similar one.

The main question is whether it is feasible to incorporate an alternative service policy such as swapping the old product with a new one or offering customers a discount on the new generation of the product rather than repairing the defective products. Next, we seek to answer how considering an alternative policy affects the end-of-life inventory decision making.

Having a real-world case study from consumer electronics industry, our work develops a new cost-driven approach. Several issues distinguish our work in this field. First, we develop a model incorporating an alternative service policy and show how this results in cost efficiency. Secondly, we exploit a more sophisticated and detailed model for the cost function that captures the characteristics of a real world problem more precisely. Furthermore, according to the case study demand analysis, a non-stationary Poisson demand process is shown to represent the demand behavior more accurately and is used as a basis for our analysis. We also investigate the effect of ignoring the non-stationarity in the demand pattern. Even though these assumptions complicate the problem, we show that it is possible to give elementary expressions for the considered expected total cost function by applying the standard techniques of martingale theory. We study an array of policies that can be adopted in practice. These policies consider the possibility of having a disposal option or dynamically updating the inventory levels after demand realization. An extensive numerical analysis is carried out in order to gain insights into the importance of various cost terms.

1.3.2 Final phase Inventory with Phase-out Returns

Besides the final order, a secondary source of spare part acquisition is the repair of the defective returned items. These parts may be recovered and used to service customers during the final phase. Triggered by a real-life business case we consider an additional spare part acquisition option, namely phase-out returns. These are returns retrieved from customers that phase out one system platform to exchange it for a new platform. Phase-out systems, however, may still be exploited to meet the demand of customers who continue to use the old platform. Due to today's replacement rates, supply of phase-outs can abound and an OEM often faces multiple phase-out occurrences in the final phase. These returns are still often in good (repairable) condition and can be used to avoid cost and to improve system performance. Examples of phase-out returns are found in various industries including aviation technologies, medical devices and military equipments.

In summary, this chapter addresses the inventory planning challenges of a service part in its final phase, when serviceable parts can also be acquired from the repair of failed parts and the cannibalization of system phase-outs. We take a fully analytical approach in investigating the following research questions.

- What are the characteristics of an optimal repair control policy in the final phase and how are these influenced by phase-out returns?
- What is the impact of uncertainty in the timing and quantity of phase-outs on the performance of the system? In other words, how valuable is phase-out information?
- How do heuristic repair policies perform compared to the optimal policy?

We contribute to the literature in several ways. First, we characterize the structure of the optimal policy in the final phase of the service life cycle considering phase-out occurrence. Secondly, we show that repair operations should be controlled according to a time-varying threshold level by which the system decides to trigger a repair operation based on the time remaining to the end of the horizon and the level of serviceable and repairable inventory. Thirdly, we investigate the value of phase-out information by considering cases in which phase-out schedule and quantities are subject to randomness and show that phase-out uncertainty should be taken into account when negotiating service agreements. Fourthly, we show that there is a considerable gap between the optimal policy and the heuristic repair control policies that have been previously suggested in the literature.

1.3.3 Final Phase Inventory with Customer Differentiation

With the technology developments and shortening of products life cycles, service parts enter the end-of-life phase sooner. Consequently, companies face a huge service responsibility while the parts are in the final phase and parts provisioning is not guaranteed any longer. Therefore, companies are mandated to take into account various types of service obligations they have while making the final order quantity decisions.

The service agreements oblige the company to provide its customers with a certain service level. It has been common in practice that companies offer different service levels versus different prices. As a result, customers are segmented according to the service level they choose. This introduces the idea of rationing available inventories for some customer classes. The practice of rationing inventory (or capacity) among different customer classes is an increasingly important tool for balancing supply with demand in environments where requirements for service vary widely. Basically a rationing policy issues stock to some customers while it refuses or delays demand fulfillment for others. It is analogous to the highly successful yield management policies adopted by airlines and hotels. In capital-intensive goods industry there are several examples of implementing a customer differentiation scheme. For example defense systems (Deshpande et. al. 2003a and 2003b), semiconductor manufacturing equipment (Kranenberg and Van Houtum 2008), and mobile phone operating systems (Möllering and Thonemann 2008). Essentially, there are various situations that illustrate the importance of customer differentiation for inventory control, namely demand criticality based differentiation or service contract based differentiation. The criticality of the demand for the spare parts can be due to various reasons. First, a spare part can be critical in one place and non-critical in another. For example, breaking down of a mainframe computer at a stock exchange has more severe financial impact than when a mainframe computer in a library goes down. Another situation wherein demand criticality arises is identified where demands happen for both regular replenishment and emergency orders. Obviously, a demand for an emergency order is given a higher priority than a regular replenishment order.

In environments in which manufacturers of complex goods sell directly to customers, service parts are distributed primarily through service contracts. For OEMs and service providers that handle performance-based service contracts for customers, service payments are based on up-time performance or equipment availability, rather than actual support cost. This includes companies in the aerospace and defense, industrial chemical, semi-conductor equipment, and networking and telecom industries (Aberdeen Group, 2005). Service providers offer an array of service contracts for a single product. These service contracts impose different service requirements for service providers against different prices. Murthy and Blischke (2005) discuss the factors that form the distinction among various service contracts. In general one could argue that the distinctions are induced by varying: 1) Service responses and/or repair time commitments; and 2) Price and/or cost structures. The response times vary significantly from situation to situation.

Considering this aspect, we study the inventory control problem of a capital-intensive product service part when the part production is discontinued. We proceed by characterizing the structure of an optimal inventory control policy in the final phase where customers are differentiated. We consider both demand criticality based differentiation and contract based differentiation schemes. We show that in these settings inventories should be controlled according to time dependent threshold levels that consider the level of available inventory. Moreover, we study the advantages of incorporating the critical level policies in this problem.

1.3.4 Floating Stock Policy

This chapter of the dissertation is not directly related to service parts inventory management. It aims at dynamically managing inventories in an integrated inventory-transportation system. We introduce and formulate a rather new distribution concept called "floating stock". The idea is that by advanced deployment and carefully tuning demand with transport modes, we can reduce non-moving inventories, shorten lead times and improve the order fill rate. This strategy benefits from floating of stocks and the existence of the intermodal terminals to postpone the selection of the destination so that a pooling effect can be obtained in comparison to the direct road transport. Although the term floating stock is relatively new, the concept has been used for a long time. It is used when shippers send their containers in advance of demand from Asia to Europe or to the US and the final destination is determined only in the final port. An example is North American lumber, where producers would ship loads to north central and eastern customers before demand had finalized. The flatcars or boxcars were held at transit yards in the Mid-West until a customer order was received. This practice enabled western US producers to compete in the eastern markets against their southern competitors in terms of lead times. Yet, there is almost no literature available on floating stocks, as the terminology is not yet standardized.

In this chapter, we consider a Fast Moving Consumer Goods (FMCG) supply chain consisting of two echelons (the manufacturer‘s warehouse and intermodal terminals) and present a mathematical formulation for floating stock policy. These models address the question of how to schedule shipment of containers through intermodal channels. We present two approaches to deal with floating stocks. The first is a time-based policy that tries to find the optimal shipping time, and the second is a quantity-based policy that triggers shipping of a container when the total number of containers available in the pipeline and regional terminals hits a certain threshold level. By conducting a numerical study we show that the floating study offers the best opportunity to benefit from low storage costs without affecting fill rate. Moreover, the floating stock policy can reduce costs and lead times in spite of possibly higher transportation costs of an intermodal connection.

Chapter 2

End-of-Life Inventory Decisions for Consumer Electronics Service Parts*

2.1 Introduction

This chapter considers the inventory control of service parts of a consumer electronics (CE) manufacturer in the final phase of their service life cycle. In the literature, this is known as the end-of-life (EOL) inventory problem, the final buy problem (FBP), or the end of production problem (EOP). The final phase starts when service part production is terminated and ends when the last service (or warranty) contract expires. In general, the final phase is the longest period within the life cycle of a service part. For instance, in the electronics industry this phase may last from four up to thirty years while the production of electronic appliances is normally terminated after less than two years (Teunter and Klein Haneveld, 2002). In the past decade, there has been a significant increase in innovation throughout the consumer electronics industry. As a result, a typical product may go through all of its life cycle stages including development, initial, normal and final production within a year, or less. Accordingly, due to this spurt in innovation, the final order is now typically placed within a year after production kick-off. As a consequence, the difficulty of accurately predicting demand over time and the lack of a sound inventory system to estimate final order quantities have resulted in many cost ineffective purchases. On the one hand, companies are mandated to satisfy customer demand for service parts due to warranty obligations, but on the other hand, they face a huge obsolescence and disposal risk at the end of the final phase. Many firms have encountered large write-offs

*This chapter is based on Pourakbar, Frenk and Dekker (2009).

of excess inventory after the product life ultimately ends. For example, IBM disclosed a \$1 billion loss from its personal-computer business in 1998, attributed to excess PCs in dealer channels that had to be sold at a steep discount (Bulkeley, 1999).

One of the main problems in the final phase inventory management is that the acquisition of parts is no longer guaranteed and companies are forced to decide on the final order quantity when production ends. Basically, during the final phase, customers return defective products for service. The literature relevant to the management of the final phase inventory focuses only on the repair of defective products by replacing the defective part of the product with a functioning spare part. This part may either be a new part or a repaired returned item. To the best of our knowledge, the literature considers this as the only way to service customers. This approach is feasible to service the demands for capital-intensive goods and their associated spare parts. However, for consumer electronic goods, other approaches should be considered because of the continuous price erosion of these products over time which may even exceed an annual rate of 30%, while the repair associated costs may stay steady over time. Consequently, this introduces the idea that there may be a breakeven point in time within the final phase after which the regular repair policy is no longer the best cost-effective policy. After this point, a firm can satisfy customer demands through an alternative service such as offering a discount on a new model of the product, giving credit or monetary compensation to customers, or swapping the defective product with the same or a similar one.

We contribute to the literature of the end-of-life inventory problem by developing a new methodology which introduces the possibility of switching to an alternative policy. In this paper, "repair policy" means the whole process of replacement of the defective part of a product with a functioning spare part while "alternative policy" refers to satisfying customer demands through other means as illustrated above.

The modeling approach is based on a real world case study. This problem was brought to us by a major European consumer electronic goods manufacturer. The company is a prominent global player in this industry and is one of the companies involved in the European Information and Communication Industry Association (EICTA) in which members have agreed on the length of the service period for different products. In general, the consumer electronic service parts or non-professional service parts comprise the majority of parts stocked in service departments and it is reported that two-thirds of the total stock of spare parts belongs to this category. Although our methods are generic, we consider a cathode ray tube (CRT) as the service part to illustrate our approach. CRTs were a relatively expensive and crucial element in TV screens and monitors in the 1990s. Due to the introduction of liquid crystal display (LCD), plasma and organic light emitting diode (OLED) screens, CRTs have become obsolete and their production has been terminated. For the company, obsolescence of CRTs kept in stock in anticipation of demand for service is an enormous challenge. The demand originates from the large installed base of households that own CRT-based products such as TVs and monitors.

The company's current approach is somewhat complex due to differences between the various regions and agreements with the logistic service providers. It basically stems from the ideas mentioned in Teunter and Fortuin (1999) for a nearly cost-optimal final order, where a fixed annual drop in demand is assumed and a newsvendor type of problem is solved using a predicted repair rate. Scrapping before the end of the horizon or an alternative policy are not considered. This yields a rather simple problem to be solved. However, the company has observed that CE products may have an annual price erosion of up to 30%. Consequently, the company has an incentive to investigate an alternative policy to service customers, in addition to simply purchasing a quantity of stocks to sustain repair activities over a long period of time. In other words, it is keen to examine whether it is feasible to implement an alternative policy and whether this will lead to any cost efficiency. The company's preferred alternative service policy is swapping the defective product with a similar one since products used in this policy can be obtained from third parties at an eroding price and therefore the company need not stock products. From a practical standpoint, there are many cases, particularly for consumer electronic appliances, where swapping is actually more cost-effective than using expensive spare parts to repair defective products.

The remainder of this chapter is structured as follows: Section 2 reviews the relevant literature. Section 3 develops building blocks for a cost-driven model and ends by proposing a closed-form expression for the expected total discounted cost in terms of elementary functions. By applying the results of section 3, section 4 proposes a variety of end-of-life policies. A numerical analysis is presented in section 5 and finally section 6 contains discussion and conclusions.

2.2 Introduction of the Problem and Model

This section briefly describes the problem whereas the next section provides more details about the cost structure. Throughout this paper, we define the end-of-life inventory problem as the problem of finding the final order quantity, n, of service parts that covers the demand for a finite service period $[0, T]$. We define time 0 to be the time that provisioning decision needs to be made and deterministic time T as the time that all service obligations expire. The model aims at minimizing the expected total discounted cost function given the possibility of switching to an alternative service policy at time τ before the end of the horizon. In other words, before time τ the system operates in accordance with the repair policy and services customers by replacing the defective part with a spare one. At time τ the repair policy is terminated and the system switches to an alternative service policy that runs to the end of the horizon. If swapping is the preferred alternative service policy, then from time τ to T all demands are satisfied by exchanging the defective product with an alternative one rather than repairing it. Since this approach to the final phase of service can be characterized by two decision variables, n and τ, we call it an (n, τ) policy. According to an (n, τ) policy, a final production batch of size n of spare parts is delivered to the inventory system at the beginning of the final phase. The total provisioning cost is $c_p n$ with c_p denoting either the purchasing or production cost per part. These spare parts have inventory holding costs $h > 0$ per unit per time. For any demand occurring before time τ, with probability $0 < q < 1$ (independent of the arrival process), the returned defective part can be repaired at repair cost c_r. After the repair, this part is placed back into the defective product at a service cost c_s. If the defective part is non-repairable, a new part is taken from the serviceable inventory and is placed into the defective product at service cost c_s.

For all non-repairable parts arriving before time τ for which there are no spare parts available in stock, demand is satisfied through an alternative policy. In this case, the cost to meet demand is $c_a + p$ with p a penalty cost that is incurred due to the occurrence of stock-out before the switching time τ. This is called *forced exchange policy* and c_a is the associated alternative policy cost incurred per item. From time τ to the end of the final phase all demands are serviced through an alternative policy at cost c_a. Furthermore, if there is stock available at the switching time τ, all the remaining inventory has to be scrapped at a cost of c_{scr} per unit. All cost terms and notation are summarized in Table

Table 2.1: Notation summary

Notation	Definition
c_p	Provisioning cost of each part
h	Holding cost per item per time
c_s	Service cost per item
c_r	Repair cost per repairable item
p	Penalty cost per item
c_a	Alternative policy cost per item
c_{scr}	Scrapping cost per item
q	Repair yield factor
γ	Price erosion factor per time
δ	Discounting factor per time
n	Final order quantity
τ	Time to switch to the alternative policy

2.1. In summary, the fundamental assumptions of this model are as follows:
A1: The demand process is assumed to be a non-stationary Poisson process with a decreasing intensity function. In practice it is observed that demand arrival for service parts in the final phase declines over time due to the decreasing number of installed bases in the market. This behavior cannot be characterized by a stationary Poisson process.
A2: The repair lead time is assumed to be negligible. This assumption is common in the remanufacturing literature and makes the analysis tractable (see for example Souza et al., 2002 and Atasu, Cetinkaya, 2006). Moreover, in the context of this case, the negligibility can be justified because the repair lead times are much shorter than the planning period.
A3: All costs are discounted back to the beginning of the horizon. The exponential unit price erosion factor which applies to the devaluation of alternative policy cost is denoted by γ and all other costs are exponentially discounted to the beginning of the horizon with a discount factor $\delta > 0$.

2.2.1 Demand Behavior

Demand behavior is an important aspect when deciding upon the final order quantity and the time to switch to the alternative policy. In this paper, we assume that the demand for spare parts is a non-stationary Poisson process. Intuitively, this makes sense, since the number of products available in the market is sufficiently large and diminishes over time and consequently the demand for service parts decreases. Sigar (2007) analyzes demand for CE spare parts including CRTs over an eight-year period. In this study, the assumption of a Poisson demand stream was validated and several models regarding the intensity function were introduced and tested. Among these models, the poly-exponential model given by $\lambda(t) = t^2 exp(a - bt)$ with constant parameters a and b showed the best performance regarding demand prediction. In this paper, we consider the same intensity function. It should be noted that our proposed approach is generic and can be adapted for any type of positive intensity function. With intensity function $\lambda(t)$ the so-called mean value function is given by $\Lambda(t) = \int_0^t \lambda(s)ds$. To make the problem analytically tractable, we apply a piecewise linear approximation to the mean value function $\Lambda(t)$ in the analysis. We will elaborate on this issue in section 5 which deals with the numerical analysis.

2.2.2 Inventory Process

This section introduces notation and definitions to build up the equations expressing the inventory process. The demand process for spare parts is given by a non-stationary Poisson process defined by $\mathbf{N}_\Lambda := \{\mathbf{N}(\Lambda(t)) : t \geq 0\}$ with Λ a strictly increasing continuous function and $\mathbf{N}$ a Poisson process. Since $1 - q$ is the probability of an arriving defective part being non-repairable, the net stock inventory process of spare parts decreases before the policy switching time, τ, according to a non-stationary Poisson process with a strictly increasing mean value function $\Lambda_1(t) = (1 - q)\Lambda(t)$, $t \geq 0$. This is due to the well-known thinning property of a non-stationary Poisson process (Ross (1970)). Hence, it follows that the net inventory process $\mathbf{IN} = \{\mathbf{IN}(t) : t \leq \tau\}$ has the form

$$\mathbf{IN}(t) = n - \mathbf{N}_{\Lambda_1}(t). \tag{2.1}$$

Moreover, by (2.1) the hitting time σ_n at which the net stock process equals zero is given by

$$\sigma_n := \min\{t \geq 0 : \mathbf{N}_{\Lambda_1}(t) \geq n\}. \tag{2.2}$$

Since the function Λ is strictly increasing and continuous, we obtain that its inverse function $\Lambda^{-1} : [0, \infty) \to [0, \infty)$ given by

$$\Lambda^{-1}(s) = \inf\{t \geq 0 : \Lambda(t) > s\} \tag{2.3}$$

is strictly increasing, continuous and satisfies $\Lambda^{-1}(\Lambda(t)) = t$ for every $t \geq 0$. Also, since $\Lambda_1(t) = (1-q)\Lambda(t)$ we obtain $\Lambda_1^{-1}(s) = \Lambda^{-1}((1-q)^{-1}s)$. This implies by (2.2) that

$$\begin{aligned} \sigma_n &= \Lambda_1^{-1}(\inf\{\Lambda_1(s) \geq 0 : \mathbf{N}(\Lambda_1(s)) \geq n\}) = \Lambda_1^{-1}(\inf\{t \geq 0 : \mathbf{N}(t) \geq n\}) \\ &= \Lambda_1^{-1}(\mathbf{T}_n) = \Lambda^{-1}((1-q)^{-1}\mathbf{T}_n) \end{aligned} \tag{2.4}$$

with $\mathbf{T}_n := \sum_{k=1}^{n} \mathbf{X}_k$ and $\mathbf{X}_k$ a sequence of independent and exponentially distributed random variables. Using (2.4) we can calculate the hitting time of the process $\mathbf{N}_{\Lambda_1}$ in n. Clearly it expresses the intuition that arrival time of the nth non-repairable part depends on the inverse of the mean value function of the corresponding Poisson arrival process.

2.2.3 Exact Calculation of Expected Discounted Cost Using a Martingale Approach

In this section, we give an exact calculation of the total expected discounted cost function, $C_\delta(n,\tau)$, of a (n,τ)-policy, by showing that a related cost process is a martingale with filtration $(\mathcal{F}_t)_{0\leq t\leq\infty}$ (see Protter (1992)) and $\tau \wedge \sigma_n := \min\{\tau, \sigma_n\}$ is a stopping time of this process. The optional sampling theorem for martingales enables us to simplify our calculations.

To start with the different cost components, let $C_{1,\delta}(n,\tau)$ with discount factor $\delta > 0$ be the expected total discounted inventory holding cost of an (n,τ) policy. The holding cost is discounted back to the beginning of the final phase so that capital costs do not have to be included in the holding cost rates. This is especially important in an inventory system with both repair and disposal options. These two options have different associated capital costs and as a result, it is not clear what the correct capital holding cost rates should be (see (Teunter et al.., 2000) for a detailed discussion of this issue). In our setting, holding cost incorporates storage, warehouse material handling, insurance, and loss and damage (shrinkage) costs but not capital cost. The system incurs inventory costs either up to time τ or to the time σ_n of hitting inventory level 0 (whichever occurs first). Therefore, the discounted inventory holding cost is given by

$$C_{1,\delta}(n,\tau) = h\mathbb{E}\left(\int_0^{\tau\wedge\sigma_n} \exp(-\delta t)\mathbf{IN}(t)dt\right). \tag{2.5}$$

Hence by (2.1) and (2.5) we obtain

$$C_{1,\delta}(n,\tau) = hn\delta^{-1}(1-\mathbb{E}(\exp(-\delta(\tau\wedge\sigma_n)))) - h\mathbb{E}\left(\int_0^{\tau\wedge\sigma_n}\exp(-\delta t)\mathbf{N}_{\Lambda_1}(t)dt\right). \quad (2.6)$$

Whenever the system provides service to an end customer by replacing the failed part with a properly functioning one, a service cost c_s is incurred. This is probably the most difficult cost to estimate among all the costs identified in the process. In the literature, it is usually ignored or it is claimed to be negligible. However, due to high labor costs especially in Europe and North America, it is, in fact, considerable. Service cost mainly includes labor cost incurred during the diagnosis and replacement of failed parts. To calculate the expected total discounted service cost, $C_{2,\delta}(n,\tau)$, of an (n,τ) policy over the planning horizon, we first observe that up to time $\tau\wedge\sigma_n$ all arriving defective parts incur a service cost c_s, while from time $\tau\wedge\sigma_n$ up to time τ this only applies to repairable parts. Using the thinning property, the arrival process of repairable parts is a non-stationary Poisson process with mean value function $\Lambda_2(t) = q\Lambda(t)$ for every $t \geq 0$. This yields

$$C_{2,\delta}(n,\tau) = c_s\mathbb{E}\left(\int_0^{\tau\wedge\sigma_n}\exp(-\delta t)d\mathbf{N}_{\Lambda}(t)\right) + c_s\mathbb{E}\left(\int_{\tau\wedge\sigma_n}^{\tau}\exp(-\delta t)d\mathbf{N}_{\Lambda_2}(t)\right). \quad (2.7)$$

Perceivably in (2.7), the first term represents the service cost for all demands before the inventory depletion time. The second term applies for all repairable parts arriving after depletion time and before policy switching time. It is worth noting that the above integral is a Riemann-Stieltjes integral (see chapter 1 of Widder (1946)). Using well-known properties of a non-stationary Poisson process and the definition of a Riemann-Stieltjes integral the expression in (2.7) for the expected total discounted service costs can be rewritten as follows

$$\begin{aligned} C_{2,\delta}(n,\tau) &= qc_s\int_0^{\tau}\exp(-\delta t)d\Lambda(t) + c_s\mathbb{E}\left(\int_0^{\tau\wedge\sigma_n}\exp(-\delta t)d(\mathbf{N}_{\Lambda}-\mathbf{N}_{\Lambda_2})(t)\right) \\ &= qc_s\int_0^{\tau}\exp(-\delta t)d\Lambda(t) + c_s\mathbb{E}\left(\int_0^{\tau\wedge\sigma_n}\exp(-\delta t)d\mathbf{N}_{\Lambda_1}(t)\right). \end{aligned} \quad (2.8)$$

Parts repair cost is incurred whenever a repairable defective part is repaired. In most service related research, this cost is assumed to be small compared to other costs and therefore neglected. However, using the same argument as mentioned above with reference to the service cost, it may be worth including in the model. In our setting, repair cost includes labor and freight cost. The latter is the cost of transporting the part to the repair shop and then to the service department once repaired. In order to calculate this cost, we use the definition of τ and observe that the repair policy terminates at time τ. Since with probability q a defective part can be repaired, the arrival process of repairable parts is a non-stationary Poisson process with mean value function $\Lambda_2(t) = q\Lambda(t)$ for every $t \geq 0$. Hence the expected total discounted repair cost $C_3(n, \tau)$ of an (n, τ) policy is given by

$$C_{3,\delta}(n,\tau) = c_r \mathbb{E}\left(\int_0^\tau \exp(-\delta t) d\mathbf{N}_{\Lambda_2}(t)\right) = qc_r \int_0^\tau \exp(-\delta t) d\Lambda(t). \tag{2.9}$$

From time τ, $\tau \leq T$, to the end of the final phase period, the EOL process is in the alternative policy state and demands for service are met by an alternative policy instead of the repair policy. However, if the inventory level hits zero before τ, the system is forced to switch earlier to the alternative policy for non-repairable parts. This alternative service can include swapping a product with a new one, leniency, monetary compensation or offering an alternative product. This cost is referred to as the alternative policy costs, c_a. Alternative service is provided in two circumstances. The first is when there is a stock-out before the policy switching time. In this case, repair policy is still less expensive than the alternative policy, implying an (potentially extremely) unpleasant situation. This case of policy switching is referred to as a *forced policy exchange*. Additional costs called *penalty costs* denoted by p are applicable for these exchanges and can be due to customer dissatisfaction or the possibility of a cheaper alternative service only being available at some later time. Moreover, acquiring products before the planned time τ may impose extra ordering costs to the system. For these reasons, the penalty cost, p, is added to the computation and the alternative policy cost per non-repairable parts arriving before τ equals $c_a + p$. The second circumstance happens when there is demand for service after policy switching time, τ. In this event called *regular policy exchange*, an alternative policy is the preferred service policy. For regular policy exchanges, the costs incurred, c_a, are mostly the cost of running the alternative policy. It should be noted that the costs due to forced exchanges are calculated over the shortages (non-repairable items arrival) before τ, whereas the costs due to policy exchanges are calculated simply over the demand after policy switching time. Therefore, the total expected discounted penalty and alternative policy costs up to the end of the service period is given by

$$C_{4,\gamma}(n,\tau) = c_a \mathbb{E}\left(\int_\tau^T \exp(-\gamma t) d\mathbf{N}_\Lambda(t)\right) + (c_a + p)\mathbb{E}\left(\int_{\tau\wedge\sigma_n}^\tau \exp(-\gamma t) d\mathbf{N}_{\Lambda_1}(t)\right). \tag{2.10}$$

By applying the well-known properties of a non-stationary Poisson process we obtain by (2.10) that

$$C_{4,\gamma}(n,\tau) = \begin{cases} c_a \int_\tau^T \exp(-\gamma t) d\Lambda(t) + (1-q)(c_a+p) \int_0^\tau \exp(-\gamma t) d\Lambda(t) \\ -(c_a+p)\mathbb{E}\left(\int_0^{\tau\wedge\sigma_n} \exp(-\gamma t) d\mathbf{N}_{\Lambda_1}(t)\right). \end{cases} \tag{2.11}$$

When all service obligations have ended or when the switching time has arrived, the stock on hand turns into excess stock and has to be removed from the warehouse. Scrapping costs include disposal, transportation and environmental cost since most countries heavily tax stock disposal. It is worth noting that in some cases, excess stock can be sold to a third party at a salvage value. In such a situation, the corresponding scrapping cost is negative since it generates revenue. The system only incurs scrapping cost in case $\tau \leq \sigma_n$, which means there are serviceable items available in inventory at policy switching time. Using (2.1) together with the fact that $\mathbf{IN}(\tau\wedge\sigma_n) = 0$ for $\tau \geq \sigma_n$, we have

$$\begin{aligned} C_{5,\delta}(n,\tau) &= c_{scr}\mathbb{E}(\exp(-\delta(\tau\wedge\sigma_n))\mathbf{IN}(\tau\wedge\sigma_n)) \\ &= nc_{scr}\mathbb{E}(\exp(-\delta(\tau\wedge\sigma_n))) - c_{scr}\mathbb{E}(\exp(-\delta(\tau\wedge\sigma_n))\mathbf{N}_{\Lambda_1}(\tau\wedge\sigma_n)). \end{aligned} \tag{2.12}$$

The last cost term that needs to be calculated for an (n,τ) policy is the final order provisioning cost. This is either purchasing or production cost incurred for n parts and is calculated by:

$$C_{6,\delta}(n,\tau) = c_p n. \tag{2.13}$$

Adding the individual cost components listed in (2.6), (2.8), (2.9), (2.11), (2.12) and (2.13) we finally obtain the average discounted cost $C_{\delta,\gamma}(n,\tau)$ of an (n,τ) policy given by

$$C_{\delta,\gamma}(n,\tau) = \sum_{i=1,i\neq 4}^{6} C_{i,\delta}(n,\tau) + C_{4,\gamma}(n,\tau). \tag{2.14}$$

Using the following lemmas, we can simplify different expectations appeared in the calculation of the expected total cost. The following lemma is useful in simplifying the term $\mathbb{E}\left(\int_0^{\tau\wedge\sigma_n} \exp(-\delta t)\mathbf{N}_{\Lambda_1}(t)dt\right)$ appears in calculation of total expected holding cost (equation 2.6).

Lemma 1. *If σ_n is the hitting time of the process $\mathbf{N}_{\Lambda_1}$ in n, then for $\delta > 0$ it follows*

$$\begin{aligned} &\delta\mathbb{E}\left(\int_0^{\tau\wedge\sigma_n}\exp(-\delta t)\mathbf{N}_{\Lambda_1}(t)dt\right) \\ = \;& \mathbb{E}\left(\int_0^{\tau\wedge\sigma_n}\exp(-\delta v)d\mathbf{N}_{\Lambda_1}(v)\right) - \mathbb{E}(\exp(-\delta(\tau\wedge\sigma_n)\mathbf{N}_{\Lambda_1}(\tau\wedge\sigma_n)). \end{aligned} \tag{2.15}$$

Proof. Since $\mathbf{N}(\Lambda_1(0)) = 0$ and each sample path of the increasing process $t \to \mathbf{N}_{\Lambda_1}(t)$ is of bounded variation we obtain by Theorem 15a of Widder (1946) that for every $s > 0$

$$\begin{aligned} \delta\int_0^s \exp(-\delta t)\mathbf{N}_{\Lambda_1}(t)dt &= \delta\int_0^s \exp(-\delta t)\int_0^t d\mathbf{N}_{\Lambda_1}(v)dt \\ &= \delta\int_0^s\int_v^s \exp(-\delta t)dtd\mathbf{N}_{\Lambda_1}(v) \\ &= \int_0^s(\exp(-\delta v) - \exp(-\delta s))d\mathbf{N}_{\Lambda_1}(v) \\ &= \int_0^s \exp(-\delta v)d\mathbf{N}_{\Lambda_1}(v) - \exp(-\delta s)\mathbf{N}_{\Lambda_1}(s). \end{aligned} \tag{2.16}$$

This implies

$$\delta\int_0^{\tau\wedge\sigma_n}\exp(-\delta t)\mathbf{N}_{\Lambda_1}(t)dt = \int_0^{\tau\wedge\sigma_n}\exp(-\delta v)d\mathbf{N}_{\Lambda_1}(v) - \exp(-\delta(\tau\wedge\sigma_n))\mathbf{N}_{\Lambda_1}(\tau\wedge\sigma_n)$$

and by taking expectations the desired result follows. □

To simplify the notational burden, for $\alpha \geq 0$ we introduce the expectations

$$J_1(\alpha, n, \tau) := \mathbb{E}(\exp(-\alpha(\tau\wedge\sigma_n))), \tag{2.17}$$

$$J_2(\alpha, n, \tau) := \mathbb{E}\left(\int_0^{\tau\wedge\sigma_n}\exp(-\alpha t)d\mathbf{N}_{\Lambda_1}(t)\right) \tag{2.18}$$

and

$$J_3(\alpha, n, \tau) := \mathbb{E}(\exp(-\alpha(\tau\wedge\sigma_n))\mathbf{N}_{\Lambda_1}(\tau\wedge\sigma_n)). \tag{2.19}$$

The term $J_1(\alpha, n, \tau)$ appeared in calculation of expected total holding and scrapping costs. We observe $J_2(\alpha, n, \tau)$ in the calculation of expected total holding, scrapping and service costs. $J_3(\alpha, n, \tau)$ is used in calculation of expected scrapping cost and also in (15). By applying lemma 1 and relation (2.14) and after rearranging the expressions for different cost components in (2.6), (2.8), (2.9), (2.11), (2.12) and (2.13) we obtain

$$C_{\delta,\gamma}(n, \tau) = K(n, \tau) + \sum_{i=1}^{3}\kappa_i J_i(\delta, n, \tau) + \kappa_4 J_2(\gamma, n, \delta) \tag{2.20}$$

with

$$K(n,\tau)=\begin{cases} q(c_s+c_r)\int_0^\tau \exp(-\delta t)d\Lambda(t)+(1-q)(c_a+p)\int_0^\tau \exp(-\gamma t)d\Lambda(t) \\ +c_a\int_\tau^T \exp(-\gamma t)d\Lambda(t)+n(h\delta^{-1}+c_p)\end{cases} \tag{2.21}$$

and $\kappa_1 := n(c_{scr}-h\delta^{-1}), \kappa_2 := c_s - h\delta^{-1}, \kappa_3 := h\delta^{-1}-c_{scr}$ and $\kappa_4 := -(c_a+p)$.

Considering (2.20), we still need to evaluate the three different expectations listed in (2.17)-(2.19). To start with the first expectation we observe that

$$J_1(\alpha,n,\tau)=\exp(-\alpha\tau)\mathbb{P}\{\sigma_n>\tau\}+\mathbb{E}(\exp(-\alpha\sigma_n)\mathbf{1}_{\{\sigma_n\le\tau\}}) \tag{2.22}$$

with $\mathbf{1}_A$ denoting the Bernoulli indicator random variable of the event A. By (2.4), this shows that

$$J_1(\alpha,n,\tau)=\exp(-\alpha\tau)\mathbb{P}\{\mathbf{T}_n>\Lambda_1(\tau)\}+\mathbb{E}(\exp(-\alpha\Lambda_1^{-1}(\mathbf{T}_n))\mathbf{1}_{\{\mathbf{T}_n\le\Lambda_1(\tau)\}}) \tag{2.23}$$

To simplify the expectation $J_2(\alpha,n,\tau)$, we next show that a related process is a martingale.

Lemma 2. *If $\mathbf{N}_\Phi$ is a (non-stationary) Poisson process with continuous mean value function Φ, then for every $\alpha\ge 0$ the stochastic process $\mathbf{M}=\{\mathbf{M}_t : t\ge 0\}$ given by*

$$\mathbf{M}_t=\int_0^t \exp(-\alpha v)d\mathbf{N}_\Phi(v)-\int_0^t \exp(-\alpha v)d\Phi(v), \tag{2.24}$$

is a martingale with respect to filtration $(\mathcal{F}_t)_{0\le t\le\infty}$.

Proof. By the definition of a martingale we need to verify that $\mathbb{E}(\mathbf{M}_t|\mathcal{F}_s)\overset{a.s}{=}\mathbf{M}_s$ for every $t\ge s$. Observe for every $t\ge s$ that

$$\begin{aligned}\mathbb{E}(\textstyle\int_0^t \exp(-\alpha v)d\mathbf{N}_\Phi(v)|\mathcal{F}_s) &= \mathbb{E}(\textstyle\int_0^s \exp(-\alpha v)d\mathbf{N}_\Phi(v)|\mathcal{F}_s)+\mathbb{E}(\textstyle\int_s^t \exp(-\alpha v)d\mathbf{N}_\Phi(v)|\mathcal{F}_s) \\ &= \textstyle\int_0^s \exp(-\alpha v)d\mathbf{N}_\Phi(v)+\mathbb{E}(\textstyle\int_s^t \exp(-\alpha v)d\mathbf{N}_\Phi(v)|\mathcal{F}_s).\end{aligned}$$

Since the process $\mathbf{N}_\Phi$ has independent increments it follows

$$\mathbb{E}(\int_s^t \exp(-\alpha v)d\mathbf{N}_\Phi(v)|\mathcal{F}_s)=\mathbb{E}(\int_s^t \exp(-\alpha v)d\mathbf{N}_\Phi(v))=\int_s^t \exp(-\alpha v)d\Phi(v)$$

and this shows the desired result. □

By applying lemma 2 and using Doob's optional sampling theorem for martingales (See Theorem 18 of Protter, (1992)) the next lemma yields a simpler expression for the expectation $J_2(\alpha, n, \tau)$.

Lemma 3. *For σ_n, the hitting time of the process $\mathbf{N}_{\Lambda_1}$ in n and $\tau \wedge \sigma_n$, the stopping time, it follows by using lemma 1 that*

$$J_2(\alpha, n, \tau) = (1-q)\mathbb{E}\left(\int_0^{\tau\wedge\sigma_n} \exp(-\alpha t) d\mathbf{N}_\Lambda(t)\right)$$

and

$$\mathbb{E}\left(\int_0^{\tau\wedge\sigma_n} \exp(-\alpha t) d\mathbf{N}_\Lambda(t)\right) = \mathbb{E}\left(\int_0^{\Lambda(\tau)\wedge(1-q)^{-1}\mathbf{T}_n} \exp(-\alpha\Lambda^{-1}(t))dt\right).$$

Proof. Since the random variable $\tau \wedge \sigma_n$ is a $\mathcal{F}_t$-stopping time we obtain by Lemma 2 applied to the non-stationary Poisson arrival process of non-repairable parts with mean value function $\Lambda_1 = (1-q)\Lambda$ and the optional sampling theorem (Lipster and Shiryayev (1978)) that $\mathbb{E}\mathbf{M}_{\tau\wedge\sigma_n} = \mathbb{E}\mathbf{M}_0 = 0$. This shows in combination with relation (2.4) that

$$\begin{aligned}
\mathbb{E}\left(\int_0^{\tau\wedge\sigma_n} \exp(-\alpha t) d\mathbf{N}_{\Lambda_1}(t)\right) &= \mathbb{E}\left(\int_0^{\tau\wedge\sigma_n} \exp(-\alpha t) d\Lambda_1(t)\right) \\
&= (1-q)\mathbb{E}\left(\int_0^{\tau\wedge\sigma_n} \exp(-\alpha t) d\Lambda(t)\right) \\
&= (1-q)\mathbb{E}\left(\int_0^{\Lambda^{-1}(\Lambda(\tau)\wedge(1-q)^{-1}\mathbf{T}_n)} \exp(-\alpha t) d\Lambda(t)\right)
\end{aligned}$$

Applying now the same argument as above to the martingale driven by the non-stationary Poisson process with mean value function Λ yields the first formula. By a change of variables and using Λ is strictly increasing and continuous (see Theorem 11*a* of Widder 1972) we also obtain

$$\mathbb{E}\left(\int_0^{\Lambda^{-1}(\Lambda(\tau)\wedge(1-q)^{-1}\mathbf{T}_n)} \exp(-\alpha t) d\Lambda(t)\right) = \mathbb{E}\left(\int_0^{\Lambda(\tau)\wedge(1-q)^{-1}\mathbf{T}_n} \exp(-\alpha\Lambda^{-1}(t))dt\right).$$

This finally shows

$$\mathbb{E}\left(\int_0^{\tau\wedge\sigma_n} \exp(-\alpha t) d\mathbf{N}_\Lambda(t)\right) = \mathbb{E}\left(\int_0^{\Lambda(\tau)\wedge(1-q)^{-1}\mathbf{T}_n} \exp(-\alpha\Lambda^{-1}(t))dt\right)$$

and we have verified the result. □

Finally we still need to evaluate $J_3(\alpha, n, \tau)$.

Lemma 4. *For $\alpha > 0$ and σ_n the hitting time of the process $\mathbf{N}_{\Lambda_1}$ in n, we have*

$$J_3(\alpha, n, \tau) = \exp(-\alpha\tau)\mathbb{E}(\mathbf{N}_{\Lambda_1}(\tau)\mathbf{1}_{\{\mathbf{N}_{\Lambda_1}(\tau)\leq n-1\}}) + n\mathbb{E}(\exp(-\alpha\Lambda_1^{-1}(\mathbf{T}_n))\mathbf{1}_{\{\mathbf{T}_n\leq\Lambda_1(\tau)\}}) \tag{2.25}$$

Proof. Clearly it follows that

$$\mathbb{E}(\exp(-\alpha(\tau\wedge\sigma_n))\mathbf{N}_{\Lambda_1}(\tau\wedge\sigma_n)) = \sum_{k=0}^{n}\mathbb{E}(\exp(-\alpha(\tau\wedge\sigma_n))\mathbf{N}_{\Lambda_1}(\tau\wedge\sigma_n)\mathbf{1}_{\{\mathbf{N}_{\Lambda_1}(\tau\wedge\sigma_n)=k\}}) \tag{2.26}$$

with $\mathbf{1}_A$ denoting the indicator random variable of the event A. Since σ_n denotes the random time that the process $\mathbf{N}_{\Lambda_1}$ hits level n we obtain for every $0 \leq k \leq n-1$ that

$$\{\mathbf{N}_{\Lambda_1}((\tau\wedge\sigma_n)) = k\} \subseteq \{\sigma_n > \tau\}.$$

This shows for every $0 \leq k \leq n-1$ that

$$\begin{aligned}
\mathbb{E}(\exp(-\delta(\tau\wedge\sigma_n))\mathbf{N}_{\Lambda_1}(\tau\wedge\sigma_n)\mathbf{1}_{\{\mathbf{N}_{\Lambda_1}(\tau\wedge\sigma_n)=k\}}) &= k\mathbb{E}(\exp(-\delta(\tau\wedge\sigma_n))\mathbf{1}_{\{\mathbf{N}_{\Lambda_1}(\tau\wedge\sigma_n)=k\}}) \\
&= k\exp(-\delta\tau)\mathbb{P}\{\mathbf{N}_{\Lambda_1}(\tau\wedge\sigma_n) = k\} \\
&= k\exp(-\delta\tau)\mathbb{P}\{\mathbf{N}_{\Lambda_1}(\tau) = k\}.
\end{aligned} \tag{2.27}$$

Also, using $\{\mathbf{N}_{\Lambda_1}(\tau\wedge\sigma_n) = n\} = \{\sigma_n \leq \tau\}$, we obtain

$$\begin{aligned}
\mathbb{E}(\exp(-\delta(\tau\wedge\sigma_n))\mathbf{N}_{\Lambda_1}(\tau\wedge\sigma_n)\mathbf{1}_{\{\mathbf{N}_{\Lambda_1}(\tau\wedge\sigma_n)=n\}}) &= n\mathbb{E}(\exp(-\delta(\tau\wedge\sigma_n))\mathbf{1}_{\{\sigma_n\leq\tau\}}) \\
&= n\mathbb{E}(\exp(-\delta\sigma_n)\mathbf{1}_{\{\sigma_n\leq\tau\}})
\end{aligned} \tag{2.28}$$

Combining relations (2.26),(2.27) and 2.28) we obtain

$$\mathbb{E}(\exp(-\delta(\tau\wedge\sigma_n))\mathbf{N}_{\Lambda_1}(\tau\wedge\sigma_n) =$$

$$\exp(-\delta\tau)\sum_{k=0}^{n-1}k\mathbb{P}\{\mathbf{N}_{\Lambda_1}(\tau) = k\} + n\mathbb{E}(\exp(-\delta\sigma_n)\mathbf{1}_{\{\sigma_n\leq\tau\}}) =$$

$$\exp(-\delta\tau)\mathbb{E}(\mathbf{N}_{\Lambda_1}(\tau)\mathbf{1}_{\{\mathbf{N}_{\Lambda_1}(\tau)\leq n-1\}}) + n\mathbb{E}(\exp(-\delta\sigma_n)\mathbf{1}_{\{\sigma_n\leq\tau\}})$$

This shows the desired result. □

By applying (2.20), (2.21) and Lemmas 3 and 4, the total discounted cost of a (n, τ) policy is given by

$$C_{\delta,\gamma}(n,\tau) = \begin{cases} \beta_1 \mathbb{E}\left(\int_0^{\Lambda(\tau)\wedge(1-q)\mathbf{T}_n} \exp(-\delta\Lambda^{-1}(t)dt\right) + \beta_2 \mathbb{E}\left(\int_0^{\Lambda(\tau)\wedge(1-q)\mathbf{T}_n} \exp(-\gamma\Lambda^{-1}(t)dt\right) \\ +\beta_3 \mathbb{P}\{\mathbf{T}_n > (1-q)\Lambda(\tau)\} + \beta_4 \mathbb{E}(\mathbf{N}_{\Lambda_1}(\tau)\mathbf{1}_{\{\mathbf{N}_{\Lambda_1}(\tau)\le n-1\}}) + K(n,\tau) \end{cases} \tag{2.29}$$

with $\beta_1 = (c_s - h\delta^{-1})(1-q)$, $\beta_2 = -(c_a + p)(1-q)$, $\beta_3 = n(c_{scr} - h\delta^{-1})\exp(-\delta\tau)$ and $\beta_4 = (h\delta^{-1} - c_{scr})\exp(-\delta\tau)$.

Hence, we have reduced the computation of the discounted cost to elementary integrals, which can be calculated.

2.3 End-of-Life Inventory Policies

Using the results of the previous section, we now propose a variety of end-of-life policies based on various settings. Firstly, these settings consider the possibility of implementing a scrapping operation. In general, the company is unwilling to scrap parts. Therefore, in our first policy, this unwillingness is taken into account and we assume that an alternative policy is triggered once the serviceable inventory is depleted. In this case, the only decision variable is the final order quantity, n. In the second policy, the serviceable inventory can be scrapped at the switching time, τ. Accordingly, the decision variables are n and τ. The second setting is related to the inclusion of a review process. The first two policies are intrinsically static decision making processes, meaning that the decision is made once at the beginning of the horizon and values of the decision variables are set based on the outcome of the optimization procedure. However, during the course of the final phase, demand may fluctuate more or less than expected. Therefore, we add a review process to the (n, τ) policy (the second one) and we re-asses the available serviceable inventory on-hand at the beginning of each period and then re-optimize the policy switching time (as implemented in the third policy). In the fourth policy, we keep the switching time fixed, as obtained in the second policy, and find the optimal inventory level at the beginning of each period. Furthermore, we consider the option that the system can partially scrap the excessive inventory if it exceeds the optimal inventory level. The latter two policies are inherently rolling-horizon types of policies which aim at improving the second one.

It is worth mentioning that the time-line in the proposed policies is divided into equi-spaced intervals to which we limit our attention. In the second and third policies, we consider each interval to be continuous in time and use the lemmas presented in the previous section in each interval to calculate the corresponding cost terms.

2.3.1 One-time Buy, without Review or Scrapping

If the company is not willing to dispose of any serviceable inventory then the alternative policy is triggered once the inventory depletes. Thus, no scrapping cost occurs before T, and it may happen only at the end of the horizon if there is any stock left. This policy resembles the Teunter and Fortuin (1998) end-of-life inventory problem since the only decision variable is the final order quantity. We can apply a marginal cost analysis in order to find the optimal n. We define $\mathbb{E}\Delta C_{\delta,\gamma}(n,T) = \mathbb{E}(C_{\delta,\gamma}(n,T)) - \mathbb{E}(C_{\delta,\gamma}(n-1,T))$ as the cost difference of ordering $n-1$ instead of n. Then, we can find $\mathbb{E}\Delta C_{\delta,\gamma}(n,T)$ by conditioning on σ_n. If the inventory level drops to zero before the end of the horizon, $\sigma_n \leq T$, the overage cost of carrying n items instead of $n-1$ includes purchasing, holding, service and repair cost, but the system may benefit from a lower alternative policy cost. Hence we have the following

$$\mathbb{E}(\Delta C_{\delta,\gamma}(n,T)|\ \sigma_n < T) = c_p + h\int_0^{\sigma_n} \exp(-\delta t)dt - c_a \exp(-\gamma\sigma_n) + (qc_r + c_s)\exp(-\delta\sigma_n). \tag{2.30}$$

Next, we consider the case when $\sigma_n \geq T$ which happens when the system keeps serviceable inventory available for the entire final phase. In order to calculate expected marginal cost in this case, we have to include extra purchasing cost for one unit, holding cost for period $(0,T)$ and extra scrapping cost at time T. Therefore we have

$$\mathbb{E}(\Delta C_{\delta,\gamma}(n,T)|\ \sigma_n \geq T) = c_p + h\int_0^{T} \exp(-\delta t)dt + c_{scr}\exp(-\delta T). \tag{2.31}$$

Using (2.30) and (2.31), we have

$$\begin{aligned}
\mathbb{E}(\Delta C_{\delta,\gamma}(n,T)) &= \mathbb{E}(\Delta C_{\delta,\gamma}(n,T), \sigma_n < T) + \mathbb{E}(\Delta C_{\delta,\gamma}(n,T), \sigma_n \geq T) \\
&= c_p + \tfrac{h}{\delta} + (qc_r + c_s - \tfrac{h}{\delta})\int_0^T \mathbb{P}\{\sigma_n = t\}\exp(-\delta t)dt \\
&\quad - c_a\int_0^T \mathbb{P}\{\sigma_n = t\}\exp(-\gamma t)dt - (\tfrac{h}{\delta} - c_{scr})\mathbb{P}\{\sigma_n > T\}\exp(-\delta T).
\end{aligned} \tag{2.32}$$

Considering time to be continuous and using a simple search algorithm, we can find n as the integer number that satisfies $\mathbb{E}(\Delta C_{\delta,\gamma}(n,T)) \leq 0$ and $\mathbb{E}(\Delta C_{\delta,\gamma}(n+1,T)) \geq 0$.

2.3.2 One-time Buy, with Scrapping but without Review

In this policy, we assume that the system is allowed to scrap items at policy switching time. In other words, if the system carries stock at the time to switch to the alternative policy, all available inventory should be scrapped at that time. We aim at finding the optimal final order quantity, n, and the time to switch to the alternative policy, τ.

Dynamic Programming Approach

In this section, we develop a backward dynamic program to find the optimal arguments of a (n, τ) policy. We first divide the time-line into equi-spaced intervals such as $[0,1), \ldots, [T-2, T-1), [T-1, T]$. The starts of intervals and stock on hand at time t are considered as stages and system state respectively. Assume that the stock on hand at time l is y, $y = 0, 1, 2, \ldots$. Let $C_l(y, \tau)$ be the total expected cost, corresponding to a (y, τ) policy in interval $[l,\, T]$, discounted back to time l. Obviously, considering a backward dynamic program, the cost function $C_l(y, \tau)$ is dependent on the decision made at time $l+1$. If the system keeps on repairing at time $l+1$, it is allowed only to repair in period l since it cannot switch from the alternative policy to the repair policy later. Moreover, if the system decides to switch to the alternative policy at time $l+1$, it can either execute the repair policy during the l^{th} period and switch to the alternative policy at time $l+1$ or start the alternative policy at time l. Therefore, in order to derive the iterative function for each stage, the system needs to decide whether to launch the alternative policy or keep on servicing customers by the repair policy and hence postpone the decision of launching the alternative policy to the next period. If the system switches to the alternative policy, the available stock must be scrapped. Therefore, the expected alternative policy cost from time l up to time T is given by

$$C_{ALT}(y, l) = c_{scr}\mathbb{E}(\exp(-\delta l)\mathbf{IN}(l)) + c_a\mathbb{E}\left(\int_l^T \exp(-\gamma t) d\mathbf{N}_\Lambda(t)\right). \tag{2.33}$$

If the system keeps on repairing and the decision to switch to the alternative policy is deferred to the next period, we have (2.34) as the expected repair policy cost for the period $[l,\, l+1]$. It is the sum of expected holding, service, repair and forced alternative policy exchange costs.

$$\begin{aligned} C_R(y,l) = \;& h\mathbb{E}\left(\int_l^{l_f} \exp(-\delta t)\mathbf{IN}(t)dt\right) + c_s\mathbb{E}\left(\int_l^{l_f} \exp(-\delta t)d\mathbf{N}_\Lambda(t)\right) \\ & + c_s\mathbb{E}\left(\int_{l_f}^{l+1} \exp(-\delta t)d\mathbf{N}_{\Lambda_2}(t)\right) + c_r\mathbb{E}\left(\int_l^{l+1} \exp(-\delta t)d\mathbf{N}_{\Lambda_2}(t)\right) \\ & + (c_a+p)\mathbb{E}\left(\int_{l_f}^{l+1} \exp(-\gamma t)d\mathbf{N}_{\Lambda_1}(t)\right). \end{aligned} \tag{2.34}$$

In this formula l_f is the minimum time wherein either the system runs out of stock or enters the next stage and it is defined as

$$l_f = (l+1) \wedge \min\{t \geq l : \mathbf{N}_{\Lambda_1}(t) \geq n\}. \tag{2.35}$$

Hence, the iterative objective function can be defined as

$$C_l(y,\tau) = \min\{C_{ALT}(y,l), C_R(y,l) + C_{l+1}(y\prime,\tau)\} : y = 0,1,2,\ldots \tag{2.36}$$

where $y\prime$ is the expected stock on hand at the beginning of the next period. It is worth noting that the provisioning cost should also be incorporated in the expected total cost function at the beginning of the final phase. Therefore, the repair policy cost at the beginning of the final phase, time 0, needs to be reformulated as follows

$$\begin{aligned} C_R(y,0) = \;& h\mathbb{E}\left(\int_0^{l_f} \exp(-\delta t)\mathbf{IN}(t)dt\right) + c_s\mathbb{E}\left(\int_0^{l_f} \exp(-\delta t)d\mathbf{N}_\Lambda(t)\right) \\ & + c_s\mathbb{E}\left(\int_{l_f}^{1} \exp(-\delta t)d\mathbf{N}_{\Lambda_2}(t)\right) + c_r\mathbb{E}\left(\int_0^{1} \exp(-\delta t)d\mathbf{N}_{\Lambda_2}(t)\right) \\ & + (c_a+p)\mathbb{E}\left(\int_{l_f}^{1} \exp(-\gamma t)d\mathbf{N}_{\Lambda_1}(t)\right) + c_p y. \end{aligned} \tag{2.37}$$

Where $l_f = 1 \wedge \min\{t \geq 0 : \mathbf{N}_{\Lambda_1}(t) \geq n\}$. Relations (2.33), (2.34) and (2.37) can be simplified using Lemmas 1-4. The time-line is divided into equi-spaced intervals and we consider the beginning of each interval as the potential switching time to the alternative policy. Then each interval is analyzed in a continuous time way by applying the results obtained in section 3.3.

So far, we have proposed two policies that can switch to an alternative policy to deal with the end-of-life inventory problem. However, the drawback of these approaches is that there is no further review to revise decision variables based on the state of the system as demand is realized. In the next two subsections, we propose two more policies which incorporate review.

2.3.3 One-time Buy, with Review and Scrapping

In this case, the system starts with the optimal arguments for a (n, τ) policy, as set out in the second approach. However, as demand is materialized during the course of the final phase, the system is given the option to adjust the optimal switching time based on the available serviceable inventory. For example, if it is realized that the inventory level is low then the system may decide to push forward the policy switching time in order to avoid extra forced swapping policy. The one-time buy, with review and scrapping policy is a rolling-horizon one in which the optimal switching time is recalculated as demand is realized in each period. In each period for a given inventory level y at time $t \leq T$, we can determine all possible switching times and find the optimal solution. This can be implemented because the expected total cost function of an (n, τ) policy can be calculated using Lemmas 1-4. If the system is at the beginning of period t and the serviceable inventory on-hand is y, we can calculate the expected total discounted cost for all possible values of τ, $\tau = t, t+1, \ldots, T$ by

$$\begin{aligned} C_{\delta,\gamma}(y,l) &= \textstyle\sum_{l=t}^{\tau} \Bigg((h\mathbb{E}\left(\int_l^{l_f} \exp(-\delta t)\mathbf{IN}(t)dt\right) + c_s\mathbb{E}\left(\int_l^{l_f} \exp(-\delta t)d\mathbf{N}_{\Lambda}(t)\right) \\ &+c_r\mathbb{E}\left(\int_l^{l_f} \exp(-\delta t)d\mathbf{N}_{\Lambda_2}(t)\right) + (c_a+p)\mathbb{E}\left(\int_{l_f}^{\tau} \exp(-\gamma t)d\mathbf{N}_{\Lambda_1}(t)\right)) \Bigg) \\ &+c_{scr}\mathbb{E}(\exp(-\delta\tau)\mathbf{IN}(\tau)) + c_a\mathbb{E}\left(\int_{\tau}^{T} \exp(-\gamma t)d\mathbf{N}_{\Lambda}(t)\right). \end{aligned} \tag{2.38}$$

Then, the value for τ that leads to the least total cost is selected as the new policy switching time. In this case l_f is defined as the minimum time that the system faces a stock-out, enters the next stage or reaches the policy switching time. It is defined by $l_f = \min\{t \geq l : \mathbf{N}_{\Lambda_1}(t) \geq n\} \wedge (l+1) \wedge \tau$.

2.3.4 One-time Buy, with Review and Partial Scrapping

As mentioned earlier, in the second policy, decisions about the values of n and τ are just made once at the beginning of the horizon. During the course of the final phase, the system may encounter less demand than expected, which means that excess stock has to be carried over time. To avoid a build-up of excessive net stock, the system is given the option to scrap down to level s, $s < \mathbf{IN}(t_0)$, if the inventory level at time t_0 is $\mathbf{IN}(t_0)$. This is called *partial scrapping* since the system can scrap a portion of the serviceable inventory. The system starts with the optimal solution, n and τ, obtained by the second policy and the optimal inventory level is derived by a marginal cost analysis approach while τ is kept constant. It is a type of newsvendor formulation in which the marginal profit of scrapping down to level s should compensate the cost of its implementation. If some parts are scrapped, the system benefits from less holding and service costs for the rest of the period but might incur more scrapping and forced policy exchange cost.

Defining σ_s as the time that inventory level hits zero, we derive the newsvendor equation by conditioning on σ_s. $\mathbb{E}\Delta(C_{\delta,\gamma}(s,\tau)) = \mathbb{E}(C_{\delta,\gamma}(s,\tau)) - \mathbb{E}(C_{\delta,\gamma}(s-1,\tau))$ is defined as the cost difference of scrapping to $s-1$ instead of s. In a situation that inventory level drops to zero before τ, $\sigma_s \leq \tau$, the system benefits from less scrapping and forced policy exchange costs but incurs more repair, service and holding costs as shown in the following relation

$$\begin{aligned}\mathbb{E}(\Delta_{\delta,\gamma}(s,\tau) \mid \sigma_s \leq \tau) = \quad & h\mathbb{E}\left(\int_{t_0}^{\sigma_s} \exp(-\delta t)dt\right) + (qc_r + c_s)\exp(-\delta\sigma_s) \\ & -(c_a+p)\exp(-\gamma\sigma_s) - c_{scr}\exp(-\delta t_0).\end{aligned} \tag{2.39}$$

If $\sigma_s > \tau$, the system incurs more holding cost but benefits from less scrapping cost at the policy switching time, hence

$$\mathbb{E}(\Delta C_{\delta,\gamma}(s,\tau) \mid \sigma_s > \tau) = h\mathbb{E}\left(\int_{t_0}^{\tau} \exp(-\delta t)dt\right) - c_{scr}\left(\exp(-\delta t_0) - \exp(-\delta\tau)\right). \tag{2.40}$$

Therefore s is the value satisfying $\mathbb{E}\Delta C_{\delta,\gamma}(s+1,\tau) \geq 0$ and $\mathbb{E}\Delta C_{\delta,\gamma}(s,\tau) \leq 0$ where $\mathbb{E}\Delta C_{\delta,\gamma}(s,\tau)$ is given by

$$\begin{aligned}\mathbb{E}\Delta(C_{\delta,\gamma}(s,\tau)) &= \mathbb{E}\Delta(C_{\delta,\gamma}(s,\tau) \mid \sigma_s \leq \tau)\mathbb{P}\{\sigma_s \leq \tau\} + \mathbb{E}\Delta(C_{\delta,\gamma}(s,\tau) \mid \sigma_s > \tau)\mathbb{P}\{\sigma_s > \tau\} \\ &= \exp(-\delta t_0)(\tfrac{h}{\delta} - c_{scr}) + (qc_r + c_s - \tfrac{h}{\delta})\int_{t_0}^{\tau} \mathbb{P}\{\sigma_s = t\}\exp(-\delta t)dt \\ &\quad -(c_a+p)\int_{t_0}^{\tau} \mathbb{P}\{\sigma_s = t\}\exp(-\gamma t)dt - (\tfrac{h}{\delta} - c_{scr})\mathbb{P}\{\sigma_s > \tau\}\exp(-\delta\tau).\end{aligned} \tag{2.41}$$

2.4 Numerical Experiments

We hope to achieve three goals with our numerical experiments. First, we investigate the cost improvement of each policy compared to the worst one. Secondly, we evaluate how different cost terms affect the optimal solutions and thirdly, we assess the cost efficiency that can be achieved by an accurate demand forecasting. The data originate from a case study on a typical CE service part, namely the Cathode Ray Tube, which was an important and expensive part in the former generation of TVs and monitors. The cost structure of the base case scenario is shown in Table 2.2. It is worth noting that in this case swapping is considered as the alternative policy. Accordingly, after policy switching time, the defective product is not repaired but customers are offered a new product.

2.4.1 Effects of Cost Parameters

We first evaluate the performance of the proposed policies and analyze the sensitivity of the solutions to the different variations of the base case scenario parameters. The planning horizon covers more than five years which is divided into 66 periods, each of which is assumed to represent one month. Costs are all discounted to the beginning of the final phase. According to the demand analysis (Sigar, 2007), the parameters a and b in the poly-exponential intensity function, given by $\lambda(t) = t^2 exp(a - bt)$, have the values 0.2 and 2 respectively. These parameters match the data of the demand for CRT over an eight-year period. The mean value function, $\Lambda(s) = \int_0^s \lambda(t)dt$, is linearized in each period (month). To this end, after dividing the time-line into equi-spaced intervals, the upper and lower points in each interval are extracted and the mean value function is approximated by the line crossing those two points. This linearization allows us to analytically calculate the cost terms.

Since the third and fourth policies are rolling-horizon approaches, we implemented a simulation program replicating 100 times. The choice of 100 is made on the basis of maintaining a small standard deviation for the expected total cost that reduces the length of the confidence interval to 1000, in a 90% confidence interval. Moreover, in order to generate arrival times that follow a non-stationary Poisson process, we use the approach proposed by Cinlar (1975, pp. 94-101). This approach can be implemented due to the linear approximation of $\Lambda(t)$ that makes the $\Lambda^{-1}(t)$ easy to calculate. We investigate the

Table 2.2: Parameter setting of the base case scenario

Notation	**Definition**	**Cost**
c_p	Provisioning cost of each part	225
h	Holding cost per item per time	3.25
c_s	Service cost per item	30
c_r	Repair cost per repairable item	20
p	Penalty cost per item	20
c_a	Alternative policy cost per item	645
c_{scr}	Scrapping cost per item	30
γ	Price erosion factor per month	0.02
δ	Discounting factor per month	0.005

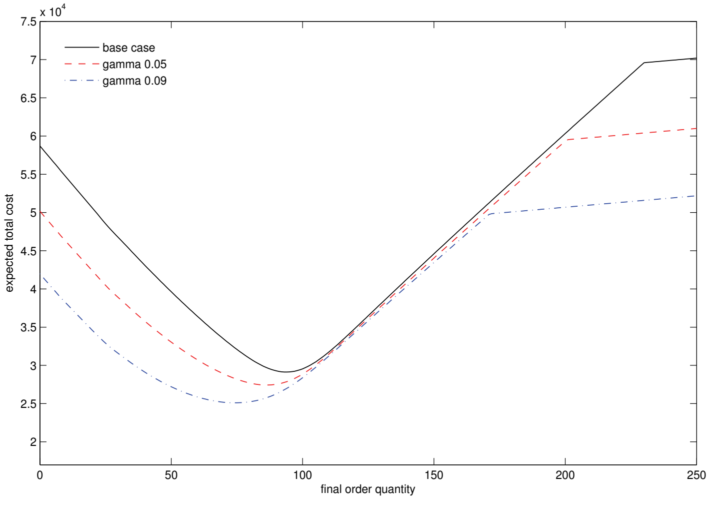

Figure 2.1: expected total cost versus final order quantity

effect of discounting, price erosion and repair yield factors as well as purchasing, holding, alternative policy, repair, scrapping and service costs. Results are shown in Table 2.2.

Before discussing the results of the numerical analysis, we proceed by studying the behavior of the expected total cost function. It is difficult to analytically prove the joint or component-wise convexity or quasiconvexity of the total cost function over n and τ. However, Figure 2.1 illustrates the total cost function versus the final order quantity using the the parameter setting of the base case scenario for different discounting and price erosion factors. Apparently the expected total cost function shows a quasiconvex behavior over the final order quantity values for different discounting and price erosion rates. We examined the behavior of the expected total cost function versus final order quantity for a wide range of parameters and observed a similar pattern.

It is observed that the first policy, *one time buy without review and without scrapping*, shows the worst performance. Therefore, it is considered as a benchmark for the performance of the other policies. The percentage of relative cost improvement that can be achieved by implementing each of the policies compared to the benchmark policy is shown in the $\Delta\%$ column. It can be observed that the policy with partial scrapping outperforms all other policies. The primary factor is that the system avoids additional holding and service costs by partially scrapping serviceable inventory down to the optimal level in each period.

The effect of discounting and price erosion factors on decision variables is illustrated in Figure 2.1. Figures 2.2.a and 2.2.b show that when the discounting factor increases the time to switch as well as the final order quantity increase. A high discount rate makes the future repair related costs cheaper and thus the system tends to run the repair policy for a longer period. Therefore, the associated final order quantity increases and the switch to the alternative policy is postponed to a later time. Increasing δ from 0.005 to 0.03 results in a rise in final order quantity from 93 to 107 and consequently switching time changes from 22 to 41. Figure 2.2.c and 2.2.d show the effect of increasing price erosion factor on the final order quantity and the time to switch to the alternative policy. As intuition dictates, Figure 2.2.d illustrates that when the price erosion rate increases, the system tends to start the alternative policy earlier and consequently the final order quantity decreases (Figure 2.2.c). For instance, when γ is increased from 0.02 to 0.25, the time to switch is pushed forward to 11 from 22 and the final order quantity shrinks to 42 from 93.

It seems that the repair yield factor, q, has a high impact on the final order quantity optimal values. Basically, when the repair yield increases, the system resorts to ordering less in anticipation of facing more repairable parts. In this case, the effect of purchasing cost is alleviated. Consequently, this makes the whole repair policy cheaper compared to the alternative policy and thus the system allows the repair policy to run for a longer period. In other words, when the repair yield rises the policy switching time increases as well.

Table 2.3: Sensitivity analysis

		1st Policy		**2nd Policy**			**3rd Policy**		**4th Policy**
Parameter	Value	n	cost	n	τ	$(\Delta)\%$	τ	$(\Delta)\%$	$(\Delta)\%$
δ	0.001	79	31408	92	21	6.9	23	7.5	8.2
	0.005	83	30460	93	22	4.4	27	5.8	6.7
	0.015	85	29889	97	24	3.5	33	4.9	5.3
	0.025	86	29444	102	34	3.2	35	4.4	4.7
γ	0.02	83	30460	93	22	4.4	27	5.8	6.7
	0.05	79	27856	87	19	1.5	23	4.1	5.5
	0.09	72	25346	75	16	1.0	19	3.2	4.3
	0.13	61	22881	64	15	0.4	14	2.7	3.7
q	0.1	83	30460	93	22	4.4	27	5.8	6.7
	0.2	71	28204	85	23	4.3	27	6.4	6.9
	0.4	50	22719	64	26	4.2	30	5.5	7.1
	0.8	24	11153	39	32	5.5	33	7.2	8.6
c_p	100	87	18130	101	26	6.0	27	6.3	7.8
	225	83	30460	93	22	4.4	27	5.8	6.7
	350	78	42210	89	22	4.1	24	5.8	6.7
	500	67	53736	72	16	2.0	19	4.1	5.1
c_a	345	71	27185	79	19	3.2	25	4.5	7.1
	645	83	30460	93	22	4.4	27	5.8	6.7
	945	87	32464	99	24	7.1	27	8.5	9.1
	1245	90	33647	101	25	7.3	30	9.3	9.5
c_s	0	84	27725	96	22	5.8	33	6.4	7.8
	10	83	28636	95	22	5.3	32	7.5	7.6
	30	83	30460	93	22	4.4	27	5.8	6.7
	50	83	32283	94	22	3.6	27	4.2	6.4
h	0.25	88	28340	98	41	3.3	63	4.1	5.7
	3.25	83	30460	93	22	4.4	27	5.8	6.7
	6.25	80	32072	92	18	4.4	27	5.8	6.6
	9.25	78	33388	90	16	4.8	23	6.2	7.8
c_r	0	83	30247	93	22	4.4	26	5.4	6.2
	5	83	30300	93	22	4.4	27	5.1	5.4
	20	83	30460	93	22	4.4	27	5.8	6.7
	35	83	30619	93	22	4.4	27	4.8	6.8
c_{scr}	-30	84	30451	96	22	4.7	25	5.2	6.7
	10	83	30457	95	22	4.5	25	5.1	7.1
	30	83	30460	93	22	4.4	27	5.8	6.7
	50	83	30462	93	22	4.3	27	5.5	6.7
p	0	83	30460	93	22	4.7	28	6.3	7.2
	20	83	30460	93	22	4.4	27	5.8	6.7
	80	83	30460	96	22	3.7	24	6.5	7.9

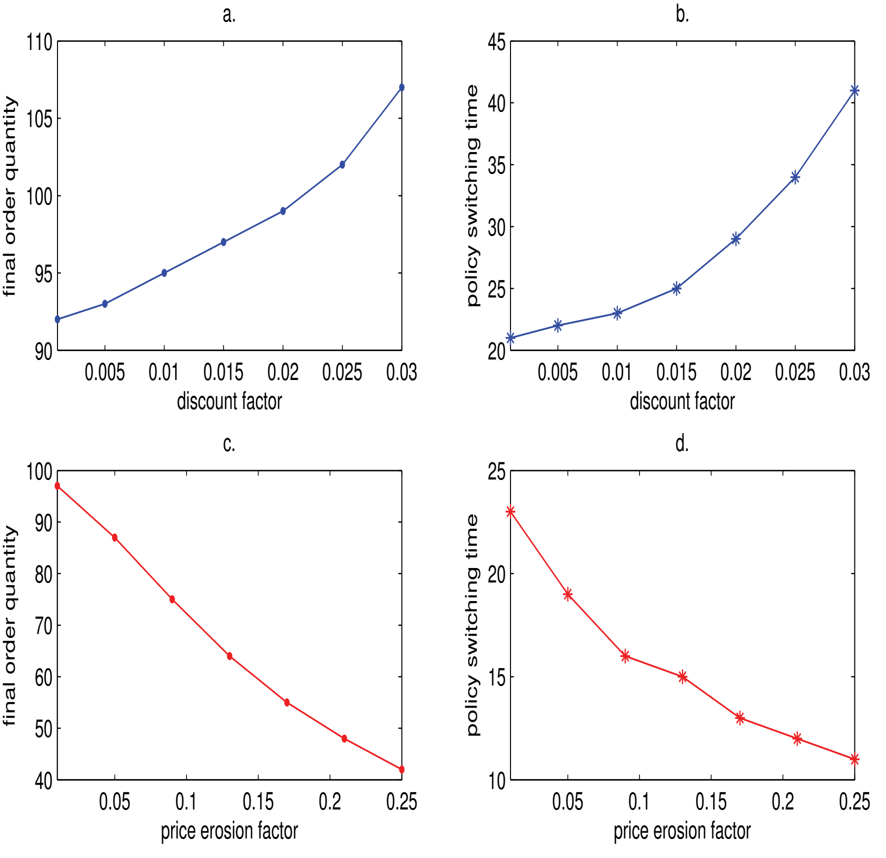

Figure 2.2: optimal final order quantity and time to switch versus price erosion and discount rates

We can infer from the numerical analysis that the holding and alternative policy costs are the important determinants for choosing between the repair and alternative policies. Intuitively, if holding is cheap, there is a preference to order more and switch to the alternative policy later in time. We observe when holding cost approaches zero ($h = 0.25$), n increases from 93 to 98 and τ increases from 22 to 41 in the base case. Similarly, if the alternative policy is cheap the system orders less and the alternative policy launches earlier in order to avoid expensive repair policy costs.

We observe that the repair cost does not play a major role. When the repair yield is 0.1, the repair cost just applies to a small portion of items which are repairable. Moreover, service cost does not affect the optimal value of policy switching time. The system just decides to place a slightly bigger final order quantity as it does if the service cost is cheaper. Penalty cost also has the same effect.

Interestingly, we also observe in Figure 2.1 that, at some point the expected total cost function starts to become linear. This can be explained by Figure 2.3. In general, when the final order quantity increases, we may expect the system to adjust the policy switching time by increasing it. However, this is not always the case. The system may either keep the policy switching time constant or push it forward. This happens because the repair policy costs go up considerably as the final order quantity increases. Accordingly, it becomes more cost efficient to switch to the alternative policy earlier in time and scrap the available stock on-hand. Therefore, when the final order quantity is higher than a certain value, the system scraps the available serviceable inventory and retains the policy switching time at a fixed time. As a consequence, the expected total cost function starts to increase linearly with the scrapping cost at some point. This can be seen on the right hand side of Figure 2.1.

From a practical standpoint, the observation in Figure 2.3 pinpoints a drawback of applying the third policy. In this policy, the system adjusts the optimal τ given the inventory level. However, depending on the inventory level, the policy switching time is likely to be pushed forward or postponed and thus causes planning difficulties for the start of the alternative policy. It is worth noting that such difficulties do not occur in the fourth policy since policy switching time is kept constant.

Another interesting observation is that the policy without scraping (first policy) always orders less than the one with scrapping (second policy). This happens because the system switches to the alternative policy, if the serviceable inventory is empty. The system decides

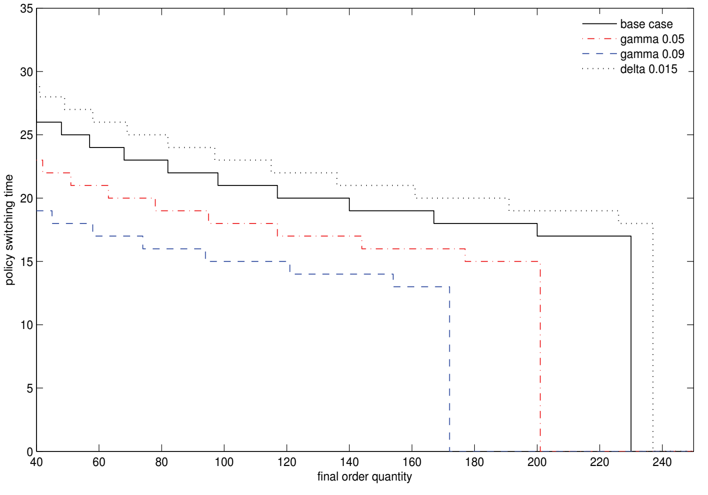

Figure 2.3: time to switch versus final order quantity

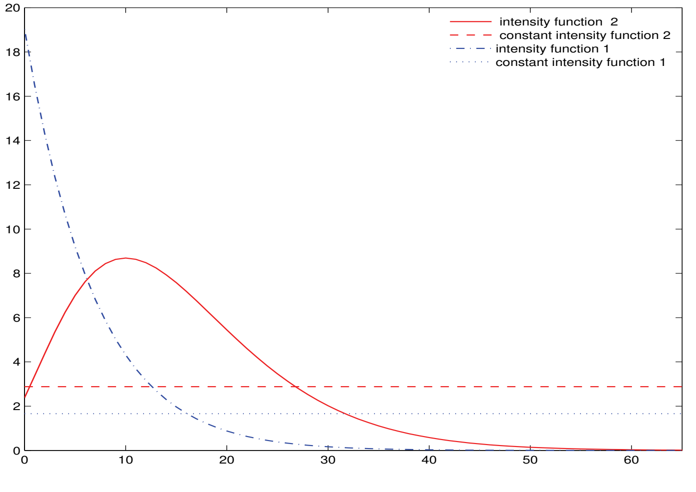

Figure 2.4: intensity functions

Table 2.4: Effect of demand

		const. intens. func. 1			intens. func. 2		const. intens. func. 2		
Parameter	Value	n	τ	$\Delta\%$	n	τ	n	τ	$(\Delta)\%$
δ	0.005	50	30	27.13	131	33	72	25	15.78
	0.010	52	31	26.20	134	36	75	26	17.91
	0.015	54	33	25.23	139	37	78	27	14.85
γ	0.01	80	50	7.49	138	36	115	43	6.43
	0.05	24	13	28.07	90	30	35	13	16.68
	0.09	15	7	30.09	52	27	21	5	25.47
q	0.2	46	34	25.74	117	36	66	28	18.25
	0.4	37	35	22.31	88	40	54	29	19.39
	0.8	15	37	9.06	30	54	21	31	6.85
c_p	100	73	47	19.30	140	38	105	39	15.11
	350	32	23	15.35	111	31	50	17	8.12
	500	14	9	6.60	48	12	26	8	5.58
c_a	345	18	9	12.12	71	34	28	10	9.40
	945	71	45	24.37	139	36	103	39	12.42
	1245	81	57	20.72	143	38	121	46	8.69
h	0.24	71	46	16.22	138	57	138	53	8.71
	3.25	40	26	29.75	123	30	123	48	18.16
	6.25	33	20	30.69	114	27	114	44	16.53

to order less than the second policy so that it can switch to the alternative policy once it becomes sufficiently cheap.

2.4.2 Effect of Demand Behavior

As explained earlier, we employ a non-stationary mean value function to explain demand behavior during the course of the final phase. The proposed models in the literature mostly consider a stationary demand pattern with a constant mean over time. We investigate the gain that could be achieved by including an accurate non-stationary demand pattern. Intensity function 1 in Figure 2.4 shows the strictly decreasing poly-exponential intensity function used for the base case scenario and the corresponding mean arrival rate. However, as mentioned earlier due to the spurt in technology and innovation, parts may enter the final phase while the demand rate is increasing. Therefore, we also look at an increasing and then decreasing pattern for the intensity function denoted by intensity function 2 in Figure 2.4.

The objective is to discover how a stationary demand intensity function rather than a non-stationary one would affect the expected total cost. We therefore use the second policy with a stationary Poisson process and a constant intensity function similar to the mean intensity rate 1(2) and find the optimal values for decision variables and associated expected total cost denoted by TC_s. These values are plugged into the model with a non-stationary arrival rate with intensity function 1(2) and the corresponding expected total cost is calculated, TC_{ns}. Results for different sets of parameters are shown in Table 2.4. $\Delta\%$ shows the percentage of the relative cost efficiency and is calculated according to $\Delta\% = \frac{TC_s - TC_{ns}}{TC_{ns}} \times 100$.

Table 2.4 shows that the cost efficiency is considerably impaired if we assume a stationary demand pattern, when the actual demand follows a non-stationary process. This major observation emphasizes the prominent role of accurate demand forecasting when dealing with the end-of-life inventory problem. Due to positive skewness of the intensity function, the system expects the major part of the demand earlier in the course of the final phase, when repair policy is still cheaper than the alternative policy. As a consequence, a larger final order quantity is always placed in case of non-stationary demand arrival.

2.5 Conclusion

In this paper, we build models to obtain the optimal final order quantity and time to switch to an alternative policy for a consumer electronics service part in the final phase of its life cycle. The final phase starts when the part production is terminated. However, a company is mandated to serve customers due to warranty or service contract obligations. The idea of adopting an alternative policy is triggered by the fact that consumer electronics prices erode considerably over time. Therefore, from some point in time it might be more cost effective to serve demands for service parts through an alternative channel such as swapping the defective product with a new one.

To deal with this, we first find a closed-form expression for the expected total discounted cost in terms of elementary functions using a martingale stochastic process and related optional sampling theorem property. We then propose four policies to deal with end-of-life inventory decision making and implement them. Numerical analysis shows that an alternative policy for repair is feasible and results in cost efficiency. Furthermore, it sheds light over the importance of various cost terms. Moreover, it shows that the final order quantity with review and partial scrapping outperforms all other policies in terms of cost efficiency. This system avoids a build-up of excessive stock and the associated costs by scrapping down the inventory level at each period. The final order quantity without review or scrapping shows to have the worst performance.

One of the advantages of our approach is that it inherently reduces the risk of obsolescence. All previous studies place the final order to cover the demand over the whole service period, while in our approach demand is partially serviced through part repair and therefore considerably lowers the part obsolescence risk.

Another significant finding is the importance of an accurate demand forecasting in the final phase. Comparisons highlight the danger of assuming a stationary demand process while demand follows a non-stationary process. Therefore, accurate demand forecasting before deciding over the final order quantity is of vital importance.

Chapter 3

End-of-Life Inventory Problem with Phase-out Returns*

3.1 Introduction

Due to the spurt of technology and innovation the service life cycle of both parts and products have become shorter. Consequently, managing the inventories of service parts in order to fulfill service obligations and avoid obsolescence risk has become a major challenge for companies. This is even more crucial as the production of a service part is discontinued when the part enters its final phase of service life cycle. In this phase, various strategic decisions can be made to keep the product in the market. These include substituting another part for the obsolete one, obtaining the obsolete part from an after market manufacturer, redesigning the product, discontinuing the product or purchasing a sufficient volume of the obsolete part to sustain production of the product for its remaining life time (Bradley and Guerrero, 2008). The quantity of the final order of capital-intensive service parts should be carefully decided as the costs of obsolescence and unavailability are typically very high. It is of vital importance to balance the risk of inventory shortage versus the risk of excess inventory. On the one hand, companies are mandated to serve customers in this phase and any failure to satisfy demand for service is very costly. On the other hand, excess inventory imposes carrying cost and increases the risk of obsolescence at the end of the final phase. Many companies, such as IBM, have reported huge write-offs of inventories at the end of the service life cycle (Bulkeley, 1999).

*This chapter is based on Pourakbar, Laan and Dekker (2011).

Besides the final order, a secondary source of spare parts is to repair defective returned items. These parts may be recovered and used to service customers during the final phase. Triggered by a real-life business case we consider an additional spare part acquisition option, namely phase-out returns. These are returns retrieved from customers that phase out one system platform to exchange it for a new platform. Phase-out systems, however, may still be exploited to meet the demand of customers who continue to use the old platform. Due to today's replacement rates, supply of phase-outs can abound and an OEM often faces multiple phase-out occurrences in the final phase. These returns are still often in good (repairable) condition and can be used to avoid cost and to improve system performance. Examples of phase-out returns are found in various industries including aviation technologies, medical devices and military equipments.

This study is motivated by a global player in industrial automation that produces and maintains distributed plant control systems; see (Krikke and van der Laan, 2011) for a detailed account. Plants are highly dependent on these control systems and therefore require prompt service when a system failure occurs. In this case, a service engineer is dispatched to the failure location immediately after the call from the customer. A spare part is taken out of the serviceable inventory to replace the failed part. The defective part is sent to a repair shop for repair. If the part is identified as repairable it may be restored with some repair effort and replenished to serviceable inventory. Recently, with the introduction of new technology, customers have been switching from existing mainframe systems to desktop based plant control systems. Therefore, planning for phase-out returns has become a challenging procedure for the OEM. The timing of system phase-outs is planned well in advance. When a customer replaces her mainframe system, the phase-out return may still serve as a source of spare parts for other customers still using the mainframe platform.

Service contracts typically run for three to five years. These predetermined service agreements oblige the company to provide its customers with a certain service level. Therefore, in case of stock-out, the company must acquire the part from a third party, thus incurring an extra cost. However, the main challenge arises when the final production quantity of a certain part/system is decided, since there are multiple sources of uncertainty including demand arrival, phase-out returns and arrival time of repairable items. The primary task is to set the final production quantity and repair policy so that it considers the possibility of phase-out returns and balances the risk of obsolescence with the risk of serviceable inventory stock-out.

Another reason for planning complications is the effect of phase-out returns on speculated future demand rates. Since each phase-out arrival reduces the number of installed bases in the market we expect to observe less demand for service in the future. To take this issue into account, we assume a non-stationary demand arrival process in our proposed model. Furthermore, the company is keen to glean an insight on when is the best timing to trigger a repair operation. The repair process is costly and repairing an item early causes excessive carrying cost whereas delaying repair increases the risk of shortage. Moreover, repaired and unused service parts are subject to the risk of obsolescence at the end of the final phase.

In summary, this chapter addresses the inventory planning challenges of a service part in its final phase, when serviceable parts can also be acquired from the repair of failed parts and the cannibalization of system phase-outs. This particular problem was first introduced and modeled by Krikke and van der Laan (2010), but they only considered heuristic policies and heuristic optimization rules, evaluated through simulation. We take a fully analytical approach in investigating the following research questions.

- What are the characteristics of an optimal repair control policy in the final phase and how are these influenced by phase-out returns?
- What is the impact of uncertainty in the timing and quantity of phase-outs on the performance of the system? In other words, how valuable is phase-out information?
- How do heuristic repair policies perform compared to the optimal policy?

We contribute to the literature in several ways. First, we characterize the structure of the optimal policy in the final phase of the service life cycle considering phase-out occurrence. Secondly, we show that repair operations should be controlled according to a time-varying threshold level by which the system decides to trigger a repair operation based on the time remaining to the end of the horizon and the level of serviceable and repairable inventory. Thirdly, we investigate the value of phase-out information by considering cases in which phase-out schedule and quantities are subject to randomness and show that phase-out uncertainty should be taken into account when negotiating service agreements. Fourthly, we show that there is a considerable gap between the optimal policy and the heuristic repair control policies that have been previously suggested in the literature.

The remainder of the chapter is organized as follows. Section 2 reviews the related literature. Section 3 describes the problem in detail and in section 4, we formulate the problem and characterize the structure of the optimal policy. Section 5 presents the numerical analysis and section 6 extends the primary formulation to other problems of interest considering phase-out associated uncertainties. Our conclusion and discussion can be found in section 7.

What distinguishes our work from the rest of the literature is that we incorporate phase-out returns as an extra source to acquire serviceable items. We discuss the complications results from phase-out returns. Moreover, we characterize the structure of the optimal policy in the final phase and show that the optimal repair policy is a time-varying decision. Numerical analysis shows the advantage of the optimal policy compared to previously developed heuristic policies, namely push and pull repair policies. Furthermore, we show that phase-out information is very valuable and significantly reduces costs.

3.2 Problem Framework

We explore the joint optimization problem of the repair control policy and final order quantity when phase-out returns occur. First, as the basic case, we consider a situation where we have perfect advance information about the schedule and the quantities of phase-outs. According to this case, n arrivals of phase-out returns occur at times $\tau_1, \tau_2, \ldots, \tau_n$ in quantities equal to $o_1, o_2, \ldots, o_n$. Later in section 6 we show that the results can easily be extended to cases where schedule or quantities are uncertain. The problem is analyzed for a finite horizon spanning time 0 to H. Time 0 is defined as the beginning of the final phase and represents the point in time at which the order for the final quantity should be placed. Procuring service parts is assumed to cost c_p per item. H signifies the end of the horizon and represents the time that the last service contract expires.

Demands arrive according to a Poisson process. Each phase-out return shrinks the market size of available installed-base size. Consequently, we expect a decrease in the future demand rate for service after each phase-out arrival. Therefore, the demand arrival for service parts is modeled as a non-homogenous Poisson process. The mean value function of this process is denoted by $\Lambda(t)$. After each phase-out arrival, the demand rate drops to a lower level but stays homogenous until the next phase-out occurs. Each demand for service is coupled with a return of a defective part. With probability q the returned item is repairable. Repair time is an exponential random variable and it costs c_r per item. Uncertainty in the repair time originates from the fact that repairable returned items are received in different quality and conditions. This assumption is common in modeling remanufacturing system. It is reasonable in systems with high service time variability where repair times are typically short but occasionally longer repair times occur too. Moreover, using the memoryless property of exponential distribution gives us the opportunity to model the system as a finite horizon Markov decision process (MDP) that facilitates the analysis and makes it tractable. In case of a stock-out, the system endures a lost sale cost c_l. The demand is assumed to be lost since the service provider needs to acquire the service part through a third party.

The holding cost rates are h_s and h_r respectively for each unit of serviceable and repairable item per time. Any stock left at the end of the horizon is considered redundant and thus the system should dispose of it. Many countries heavily tax the disposal of parts or products. Therefore, a disposal cost of c_d^r is applied for repairable items and c_d^s for serviceable items such that $c_d^s \geq c_d^r$. All costs are discounted back to the beginning of the final phase with a rate α. We note that in the formulation the cost parameters are set such that $c_l \geq \alpha c_d^s$. This basically means the lost sales cost is larger than the disposal. Thus, it is always optimal to satisfy demand when there are serviceable items.

Without loss of generality, the time $[0, H]$ is divided into time units so that the probability of having more than one demand arrival is negligible. These periods may correspond to a month, a week, a day or an hour in which both demand and phase-out arrivals happen at the beginning of each period. o_t defined below denotes the phase-out quantity at each period

$$o_t = \begin{cases} o_i & t = \tau_i \ , \quad i = 1, 2, \ldots, n \\ 0 & \qquad\qquad \text{otherwise} \end{cases}$$

Moreover, if an item is sent to the repair facility, the operation finishes in the same period with probability μ. In each period, the system has to decide whether to repair an item or not. Furthermore, at the beginning of the horizon, time 0, the system should decide how many items to order as the final order quantity.

3.3 Problem Formulation

We start with the case in which the schedule and quantities of phase-out returns are known in advance. Our objective is to find the starting inventory level at time 0, indicating the final order quantity, and the repair control policy during the period $[0, H]$. The state of the system at an arbitrary time t is defined by (t, x, y), where x and y correspond to levels of serviceable and repairable inventories, respectively. The optimality equation at time t is defined by $\nu(t, x, y)$, representing the minimum discounted cost from t to H with inventories x and y at time t. For $t \in [0, T]$ we have

$$\nu(t,x,y) = \begin{cases} \nu_{11}(t,x,y) & x \geq 1,\ y \geq 1 \\ \nu_{01}(t,x,y) & x = 0,\ y \geq 1 \\ \nu_{00}(t,x,y) & x = 0,\ y = 0 \\ \nu_{10}(t,x,y) & x \geq 1,\ y = 0 \end{cases} \tag{3.1}$$

In the rest of this section we define $\nu_{11}(t, x, y)$, $\nu_{01}(t, x, y)$, $\nu_{00}(t, x, y)$ and $\nu_{10}(t, x, y)$. First, for the ease of representation we define $\lambda(t)$ as the demand arrival probability in period t. Moreover, the operator $T\nu(t+1, x, y)$ is associated with the decision of whether or not to repair an item. This operator is defined as:

$$T\nu(t+1,x,y) = \min\{\alpha\nu(t+1,x,y), \mu\alpha(\nu(t+1,x+1,y-1)+c_r+h_s-h_r)+(1-\mu)\alpha\nu(t+1,x,y)\} \tag{3.2}$$

Therefore we have:

$$\begin{aligned} \nu_{11}(t,x,y) = \quad & (1-\lambda(t))\{h_s x + h_r y + T\nu(t+1, x+o_{t+1}, y)\} \\ & +(1-q)\lambda(t)\{h_s(x-1) + h_r y + T\nu(t+1, x+o_{t+1}-1, y)\} \\ & +q\lambda(t)\{h_s(x-1) + h_r(y+1) + T\nu(t+1, x+o_{t+1}-1, y+1)\} \end{aligned} \tag{3.3}$$

The first term on the right hand side of equation (3.3) represents a situation in which no demand is realized in period t. Therefore, the system has to decide whether to retain the state of the system or repair one item. The second term considers a situation where a non-repairable item arrives. In this case, the serviceable inventory level decreases by one unit and the system should make a decision over retaining the state of the system or repairing an item. Using the third term, the system decides on the optimal action when a repairable item arrives. In this case, the serviceable inventory decreases by one unit and the repairable inventory increases by one unit. When $x = 0$ and $y \geq 1$, we have

$$\begin{aligned} \nu_{01}(t,x,y) = \quad & (1-\lambda(t))\{h_r y + T\nu(t+1, o_{t+1}, y)\} \\ & +(1-q)\lambda(t)\{h_r y + c_l + T\nu(t+1, o_{t+1}, y)\} \\ & +q\lambda(t)\{h_r y + c_l + T\nu(t+1, o_{t+1}, y+1)\} \end{aligned} \tag{3.4}$$

When $x = 0$ and $y = 0$, in case of no demand arrival or return of a non-repairable item, the system has no option but to keep the current state of the system unchanged. However, when the returned item is repairable, the system should decide whether to send the item immediately to the repair shop or keep the current state intact. Thus, the value function in this case is defined as

$$\begin{aligned} \nu_{00}(t,x,y) = \quad & (1-\lambda(t))\{\alpha\nu(t+1, o_{t+1}, 0)\} \\ & +\big\{(1-q)\lambda(t)\big\{c_l + \alpha\nu(t+1, o_{t+1}, 0)\big\} \\ & +q\lambda(t)\{h_r + c_l + T\nu(t+1, o_{t+1}, 1)\}\big\} \end{aligned} \tag{3.5}$$

when $x \geq 1$ and $y = 0$ we have:

$$\begin{aligned} \nu_{10}(t,x,y) = \quad & (1-\lambda(t))\big\{h_s x + \alpha\nu(t+1, x+o_{t+1}, 0)\big\} \\ & +(1-q)\lambda(t)\big\{h_s(x-1) + \alpha\nu(t+1, x+o_{t+1}-1, 0)\big\} \\ & +q\lambda(t)\big\{h_s(x-1) + T\nu(t+1, x+o_{t+1}-1, 1) \end{aligned} \tag{3.6}$$

Since all leftover stocks are disposed of at the end of the horizon, time H, the terminal value is expressed by

$$\nu(H,x,y) = c_d^s x + c_d^r y. \tag{3.7}$$

One should note that (3.2) implies that the system decides to repair one repairable part if the following condition holds:

$$\nu(t+1,x,y) \geq \nu(t+1,x+1,y-1) + c_r + h_s - h_r \tag{3.8}$$

The simple interpretation of (3.8) is that the system decides to repair one item if the future cost is less than the discounted cost of retaining the state of the system. This condition is useful in establishing the structural properties of an optimal policy.

3.3.1 Structure of the Optimal Policy

In this section, we characterize the structure of an optimal policy. To do so, we first show that the optimal value function $\nu(t, x, y)$ satisfies certain properties enlisted in the following lemma at a specific time t. Next, we demonstrate that this set of properties results in a specific rule for optimal repair action which should be taken in each state. The following lemma is very helpful in characterizing the optimal policy.

Lemma 5. *If v is defined by equation (1) on $[\tau_i, \tau_{i+1}) \times \mathbb{Z}^+ \times \mathbb{Z}^+$, then it satisfies the following properties*

i) $\nu(t, x+1, y) - \nu(t, x, y)$ *is non-decreasing in* x

ii) $\nu(t, x, y+1) - \nu(t, x, y)$ *is non-decreasing in* y

Proof. First, for the sake of brevity we define $\xi(t, x, y) = \nu_{11}(t, x, y) - \nu_{11}(t, x-1, y)$. Then, we need to show that $\xi(t, x, y)$ is non-decreasing in x. Moreover, we define $\xi(t, 0, y) = \alpha/c_l$. We follow an induction approach in order to show the desired results.

From the terminal value definition we have $\nu_{11}(H, x, y) = c_d^s x + c_d^r y$, thus, $\xi(H, x, y) = c_d^s$. From assumption (1) we have $c_l \geq \alpha c_d^s$ which can be immediately translated to $\xi(H, 1, y) \geq \xi(H, 0, y)$. Therefore, $\xi(H, x, y)$ is non-decreasing in x.

Following the induction, we assume $\xi(t, x, y)$ is non-decreasing in x, then we need to show that $\xi(t-1, x, y)$ is non-decreasing in x. From (3.8) and the induction assumption we know that there exists a x^* such that if $x \geq x^*$ then it is optimal not to repair and repair otherwise. It is worth nothing that $\lambda(t) = \lambda$ for $t \in [\tau_i, \tau_{i+1})$. Then from equation

(3.3) we have

$$\xi(t-1,x,y) =$$

$$(1-\lambda)\{h_s + \alpha\xi(t,x,y)\mathbf{1}_{\{x \geq x^*\}}\}$$

$$+(1-q)\lambda\{h_s + \alpha\xi(t,x-1,y)\mathbf{1}_{\{x-1 \geq x^*\}}\}$$

$$+q\lambda\{h_s + \alpha\xi(t,x-1,y+1)\mathbf{1}_{\{x-1 \geq x^*\}}\}$$

$$+(1-\lambda)\{h_s + (1-\mu)\alpha\xi(t,x,y)\mathbf{1}_{\{x<x^*\}} + \mu(\alpha\xi(t,x+1,y-1) + c_r)\mathbf{1}_{\{x<x^*\}}\}$$

$$+(1-q)\lambda\{h_s(1-\mu)\alpha\xi(t,x-1,y)\mathbf{1}_{\{x-1<x^*\}} + \mu(\alpha\xi(t,x,y-1) + c_r)\mathbf{1}_{\{x-1<x^*\}}\}$$

$$+q\lambda\{h_s + (1-\mu)\alpha\xi(t,x-1,y+1)\mathbf{1}_{\{x-1<x^*\}} + \mu(\alpha\xi(t,x,y) + c_r)\mathbf{1}_{\{x-1<x^*\}}\}$$

since $\xi(t-1,x,y)$ is a linear expression of $\xi(t,x,y)$ and using induction assumption we know that $\xi(t-1,x,y)$ is non-decreasing in x therefore $\xi(t-1,x,y)$ is non-decreasing in x. The same can be established for expressions (6), (8) and (10).

Using the same approach and the fact that $h_s \geq h_r$ we can show that $\xi(t,x,y)$ is non-decreasing in y. □

Property *i*) implies that the marginal cost difference due to increasing the serviceable inventory (for a fixed level of repairable inventory) is non-decreasing. Similarly, *ii*) implies that the marginal cost difference due to increasing the repairable inventory (for a fixed level of serviceable inventory) is non-decreasing. In other words, *i* and *ii* indicate that the optimal cost function is component-wise convex in x and y. In order to describe the optimal policy implied by the above properties, we define the following time-varying and state dependent repair threshold, $r^*(t,y)$ as:

$$r^*(t,y) = \min\{x|\nu(t,x+1,y-1) + c_r + h_s - h_r - \nu(t,x,y) \geq 0,\ y \geq 1\} \tag{3.9}$$

The simple interpretation of the above threshold level is that the system triggers a repair operation as soon as the cost of repair of one unit together with the future cost of the system becomes smaller than retaining the current state of the system. Using lemma 1 and the definition of the repair threshold level, the main results are stated by the following theorem.

Theorem 1. *There exists an optimal time and state dependent policy that can be determined in terms of state and time dependent threshold level $r^*(t, y)$ as follows*

I. *repair an item to increase on-hand serviceable inventory if $x < r^*(t, y)$ and do not repair otherwise*

II. *$r^*(t, y)$ is non-increasing in time, $t \in [\tau_i, \tau_{i+1})$.*

Proof. **I**. The results are intuitive considering the definition of the repair threshold and component-wise convexity properties.

II. We show this by induction where the induction assumption is $r^*(t, y) \leq r^*(t-1, y)$ and $\beta(t-1, x, y) \geq \beta(t, x, y)$, where $\beta(t, x, y) = \nu_{11}(t, x+1, y-1) - \nu_{11}(t, x, y)$. It is straightforward to show the results for $t = H$, since intuitively $r^*(H, y) = 0 \leq r^*(H-1, y)$.

Then, assuming the induction assumption holds at time $t-1$ we need to show that it holds at time t. In order to show that the induction assumption holds we employ a contradiction approach. Suppose for contradiction that $r^*(t-1, y) < r^*(t, y)$. Using the definition of repair threshold it immediately implies that $\beta(t, r^*(t-1, y), y) + c_r + h_s - h_r \geq 0$. Using (3.3), we should note that

$$
\begin{aligned}
\beta(t-1, x, y) = \; & (1-\lambda)\{\alpha\beta(t, x, y)\mathbf{1}_{\{x \geq r^*(t,y)\}}\} \\
& +(1-q)\lambda\{\alpha\beta(t, x-1, y)\mathbf{1}_{\{x-1 \geq r^*(t,y)\}}\} \\
& +q\lambda\{\alpha\beta(t, x-1, y+1)\mathbf{1}_{\{x-1 \geq r^*(t,y+1)\}}\} \\
& +(1-\lambda)\{(1-\mu)\alpha\beta(t, x, y)\mathbf{1}_{\{x < r^*(t,y)\}} + \mu\alpha\beta(t, x+1, y-1)\mathbf{1}_{\{x < r^*(t,y)\}}\} \\
& +(1-q)\lambda\{(1-\mu)\alpha\beta(t, x-1, y)\mathbf{1}_{\{x-1 < r^*(t,y)\}} + \mu\alpha\beta(t, x, y-1)\mathbf{1}_{\{x-1 < r^*(t,y)\}}\} \\
& +q\lambda\{(1-\mu)\alpha\beta(t, x-1, y+1)\mathbf{1}_{\{x-1 < r^*(t,y+1)\}} + \mu\alpha\beta(t, x, y)\mathbf{1}_{\{x-1 < r^*(t,y)\}}\}
\end{aligned}
$$

For the ease of representation we define $\Delta_t\beta(t,x,y) = \beta(t,x,y) - \beta(t+1,x,y)$, Then we have

$$\Delta_t\beta(t-1, r^*(t,y), y) = (1-\lambda)\{\alpha\Delta_t\beta(t, r^*(t,y), y)\mathbf{1}_{\{r^*(t,y)\geq r^*(t+1,y)\}}\}$$

$$+(1-q)\lambda\{\alpha\Delta_t\beta(t, r^*(t,y)-1, y)\mathbf{1}_{\{r^*(t,y)-1\geq r^*(t+1,y)\}}\}$$

$$+q\lambda\{\alpha\Delta_t\beta(t, r^*(t,y)-1, y+1)\mathbf{1}_{\{r^*(t,y+1)-1\geq r^*(t+1,y+1)\}}\}$$

$$+(1-\lambda)\{(1-\mu)\alpha\Delta_t\beta(t, r^*(t,y), y)\mathbf{1}_{\{r^*(t,y)<r^*(t+1,y)\}}\}$$

$$+(1-\lambda)\mu\alpha\Delta_t\beta(t, r^*(t,y)+1, y-1)\mathbf{1}_{\{r^*(t,y)<r^*(t+1,y)\}}$$

$$+(1-q)\lambda\{(1-\mu)\alpha\Delta_t\beta(t, r^*(t,y)-1, y)\mathbf{1}_{\{r^*(t,y)-1<r^*(t+1,y)\}}\}$$

$$+(1-q)\lambda\mu\alpha\Delta_t\beta(t, r^*(t,y), y-1)\mathbf{1}_{\{r^*(t,y)-1<r^*(t+1,y)\}}$$

$$+q\lambda\{(1-\mu)\alpha\Delta_t\beta(t, r^*(t,y)-1, y+1)\mathbf{1}_{\{r^*(t,y+1)-1<r^*(t+1,y+1)\}}\}$$

$$+q\lambda\mu\alpha\Delta_t\beta(t, r^*(t,y), y)\mathbf{1}_{\{r^*(t,y)-1<r^*(t+1,y)\}}$$

Using the induction assumption, we have the terms $\Delta_t\beta(t,x-1,y+1)$, $\Delta_t\beta(t,x-1,y)$ and $\Delta_t\beta(t,x,y)$ are all non-negative. Therefore, $\Delta_t\beta(t-1,x,y) = \beta(t-1,x,y) - \beta(t,x,y) \geq 0$. Thus,

$$\beta(t-1,x,y) + c_r + h_s - h_r \geq \beta(t,x,y) + c_r + h_s - h_r \geq 0$$

which implies that $r^*(t,y) \leq r^*(t-1,y)$, it is a contradiction.

Next, we show $\beta(t-1,x,y) \geq \beta(t,x,y)$ given that $r^*(t,y) \leq r^*(t-1,y)$, $t \in (0,H]$. We separate the interval $(0, r^*(t-1,y)]$ into the following subintervals $(0, r^*(t+1,y)]$, $(r^*(t+1,y), r^*(t,y)]$ and $(r^*(t,y), r^*(t-1,y)]$. For each of these intervals we show the results. It is worth mentioning that we use the notation $\Delta_t\beta(t,x,y)$ as defined previously. Moreover, we just show the results for the case that $x \geq 1$ and $y \geq 1$, a similar analysis can be applied to other cases.

Case 1. $\forall x \in (0, r^*(t+1,y)]$

In this case we have

$$\Delta_t\beta(t-1,x,y) =$$

$$(1-\lambda)\{(1-\mu)\Delta_t\beta(t,x,y)\mathbf{1}_{\{r^*(t,y)<r^*(t+1,y)\}} + \mu\Delta_t\beta(t,x+1,y-1)\mathbf{1}_{\{r^*(t,y)<r^*(t+1,y)\}}\}$$

$$+(1-q)\lambda\{(1-\mu)\Delta_t\beta(t,x-1,y)\mathbf{1}_{\{r^*(t,y)-1<r^*(t+1,y)\}} + \mu\Delta_t\beta(t,x,y-1)\mathbf{1}_{\{r^*(t,y)-1<r^*(t+1,y)\}}\}$$

$$+q\lambda\{(1-\mu)\Delta_t\beta(t,x-1,y+1)\mathbf{1}_{\{r^*(t,y+1)-1<r^*(t+1,y+1)\}} + \mu\Delta_t\beta(t,x,y)\mathbf{1}_{\{r^*(t,y)-1<r^*(t+1,y)\}}\}$$

Following an approach similar to the previous case we can show that the right hand side are all non-negative and therefore $\Delta_t\beta(t-1,x,y) \geq 0$.

Case 2. $\forall x \in (r^*(t+1,y), r^*(t,y)]$

$$\begin{aligned}\Delta_t\beta(t-1,x,y) = \;& (1-\lambda)\{\Delta_t\beta(t,x,y)\mathbf{1}_{\{r^*(t,y)\geq r^*(t+1,y)\}}\} \\ & +(1-q)\lambda\{\Delta_t\beta(t,x-1,y)\mathbf{1}_{\{r^*(t,y)-1\geq r^*(t+1,y)\}}\} \\ & +q\lambda\{\Delta_t\beta(t,x-1,y+1)\mathbf{1}_{\{r^*(t,y+1)-1\geq r^*(t+1,y+1)\}}\}\end{aligned}$$

Following an approach similar to the previous case we can show that the right hand side are all non-negative and therefore $\Delta_t\beta(t-1,x,y) \geq 0$.

Case 3. $\forall x \in (r^*(t,y), r^*(t-1,y)]$

In this case we have $r^*(t,y) < x \leq r^*(t-1,y)$, then according to the definition of $r^*(t,y)$ we have $\beta(t-1,x,y) + c_r + h_s - h_r \geq 0$ and $\beta(t,x,y) + c_r + h_s - h_r \leq 0$ therefore $\beta(t-1,x,y) - \beta(t,x,y) \geq 0$.

These show the desired results for $x \geq 1$ and $y \geq 1$. We can follow a similar approach for other cases. □

Figure 3.1 illustrates an example of the optimal repair policy structure for a case without phase-out returns. As we can see, the optimal policy defines two regions in the state space. The contour of this region is determined by the threshold function $r^*(t,y)$. The area under the contour represents the subset of the state space where the optimal decision is to repair and the area above the contour shows the portion of state space where the optimal decision is to retain the state of the system.

Figure 3.2 illustrates the optimal repair threshold for a case with three phase-out occurrences scheduled to arrive at times 30, 85 and 145 with quantities 7, 4 and 9 re-

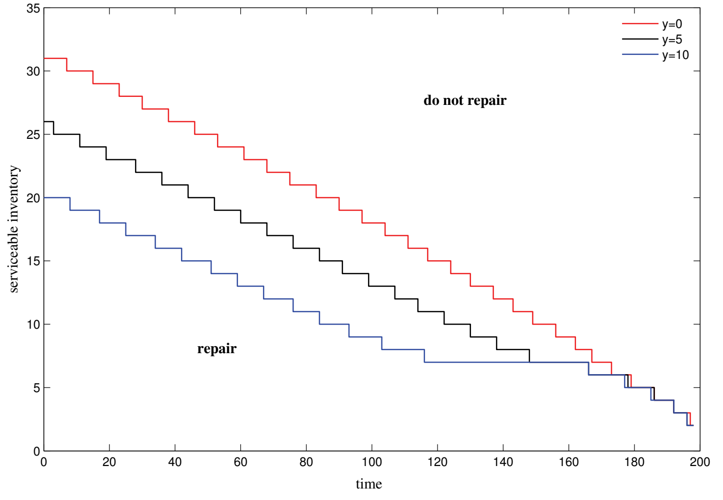

Figure 3.1: Optimal time and state dependent repair threshold without phase-out occurrence

spectively. We observe that when it is closer to the end of the horizon the system prefers to have less serviceable inventory and therefore the optimal threshold shows a decreasing pattern. Moreover, having more repairable items in stock results in a smaller repair threshold. In other words, the repair threshold seems to be non-decreasing in y. Another observation is that the motivation for repair becomes weaker as the system approaches the next phase-out arrival and thus a lower repair threshold is set. Intuitively, the system sets a lower threshold since it is expected to receive serviceable inventory from phase-out returns.

Figures 3.3 and 3.4 show that the repair threshold is monotonic with regard to parameters h_s and c_l. It is observed that when h_s increases, the system tends to keep less serviceable inventory in stock. Similarly, when the stock-out penalty c_l increases the system avoids incurring lost sale cost by increasing the repair threshold level that consequently triggers repair for higher levels of x.

The provisioning cost is considered a sunk cost when making decisions about repair operations. However it needs to be incorporated in the model as we have to decide upon the optimal final order quantity. As an immediate result of the convexity of $\nu(t, x, y)$ with

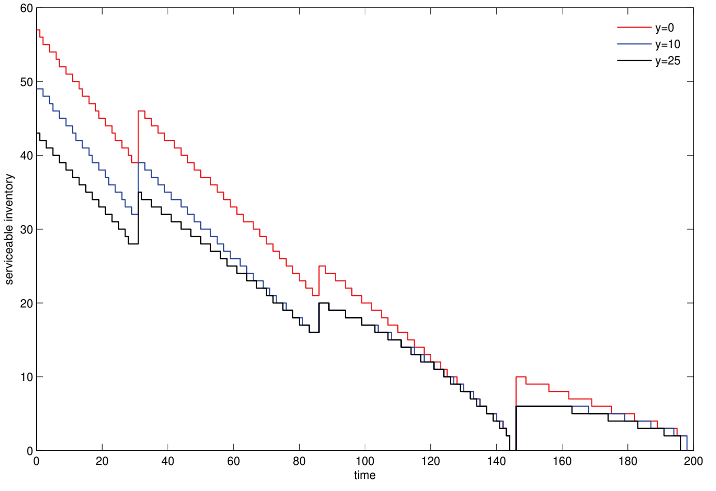

Figure 3.2: Optimal time and state dependent repair threshold with phase-out occurrence

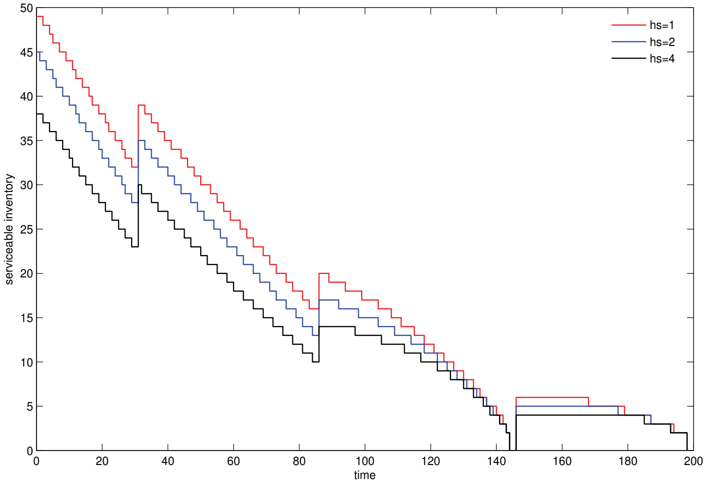

Figure 3.3: Effect of serviceable inventory holding cost rate on repair threshold

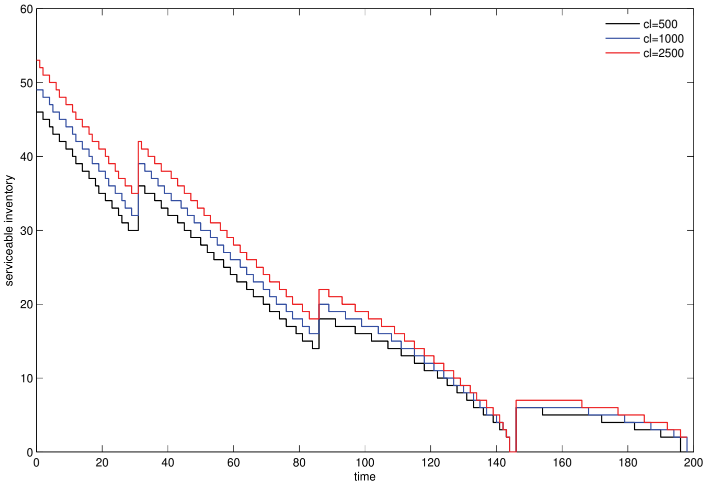

Figure 3.4: Effect of lost sale cost on threshold levels

respect to x the following proposition holds. Proposition 3 allows us to find the optimal final order quantity by using a simple search algorithm.

Proposition 2. *The optimal order quantity is the x that minimizes the following expression*

$$\nu_0(0, x, y) = \mathbb{E}\nu(0, x, y) + c_p x \tag{3.10}$$

Proof. It is a direct result of the convexity of $\nu_0(0, x, y)$ in x. □

The system manager is interested in the effect of the phase-out schedule on the expected total cost. Intuitively, it is not clear how postponing or pushing forward phase-out returns affects the expected total cost. Thus, we carry out an analysis in which the quantity of the first phase-out return is fixed, but the arrival schedule is varied over time. As can be observed in Figures 3.5 and 3.6, there is an optimal time to receive phase-out items. The corresponding diagram shows the effect of the phase-out schedule on the expected total cost for different quantities of the phase-out returns. When the phase-out quantity increases, the system first prefers to postpone the arrival of phase-out returns. However, when a large quantity of phase-out returns are planned to arrive the optimal schedule will push forward to the beginning of the horizon (Figure 3.6). Furthermore,

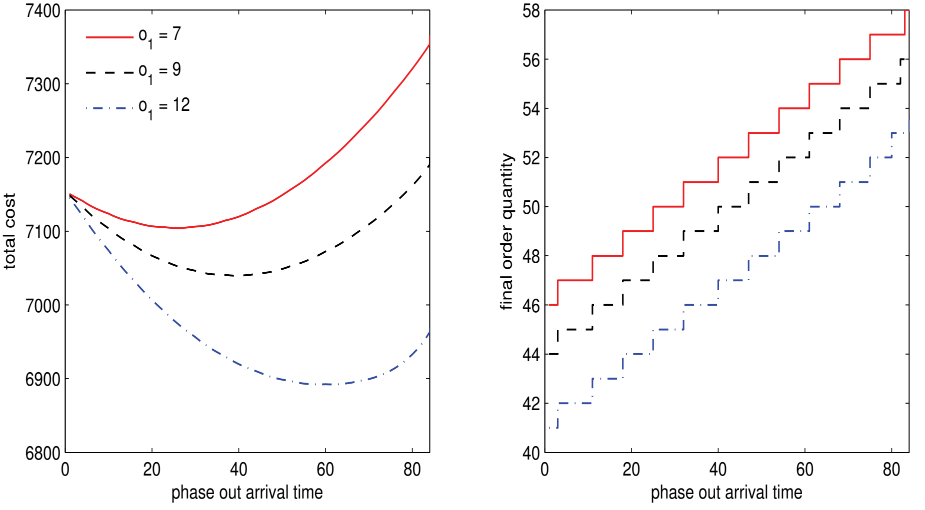

Figure 3.5: Effect of phase-out schedule on expected total cost

as we expect intuitively increasing the phase-out quantity results in smaller final order quantities. These effects are better represented in Figure 3.7. As we observe for different values of c_l, when the phase-out quantities are very low or very high, the system prefers to receive them very early in time.

Therefore, when planning the inventory in the final phase, it is beneficial if the system manager can plan the schedule of phase-out arrivals and force the customers to return phase-out returns in the vicinity of the optimal schedule.

3.4 Numerical Analysis

In this section, we compare the performance of some heuristic policies already developed in the literature for hybrid systems to the performance of the optimal policy for the general problem described in section 4. Our aim is to assess the value of implementing the optimal policy instead of simpler heuristics. We focus on heuristics that involve fixed (non-state dependent) parameters, since they are simpler to communicate and implement and, perhaps, are more common in practice. Below we provide a description of each of the heuristics we consider.

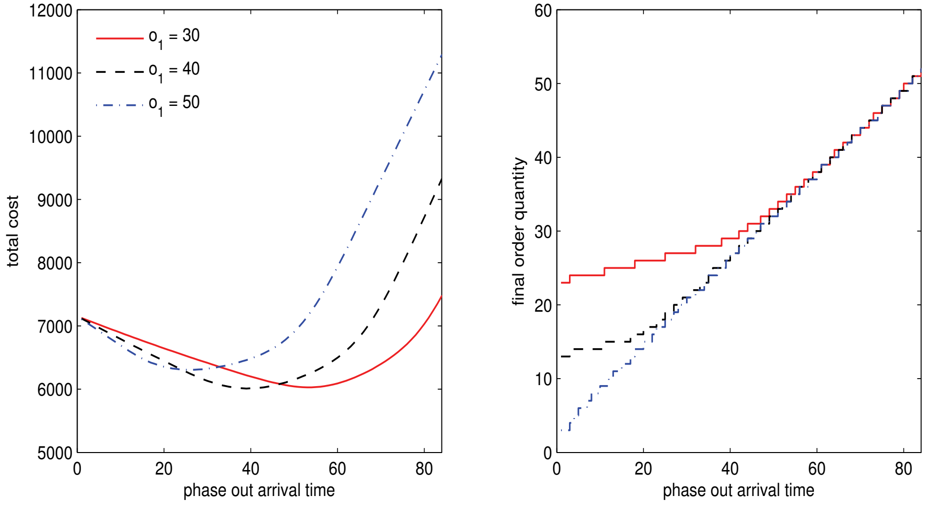

Figure 3.6: Effect of phase-out schedule on expected total cost

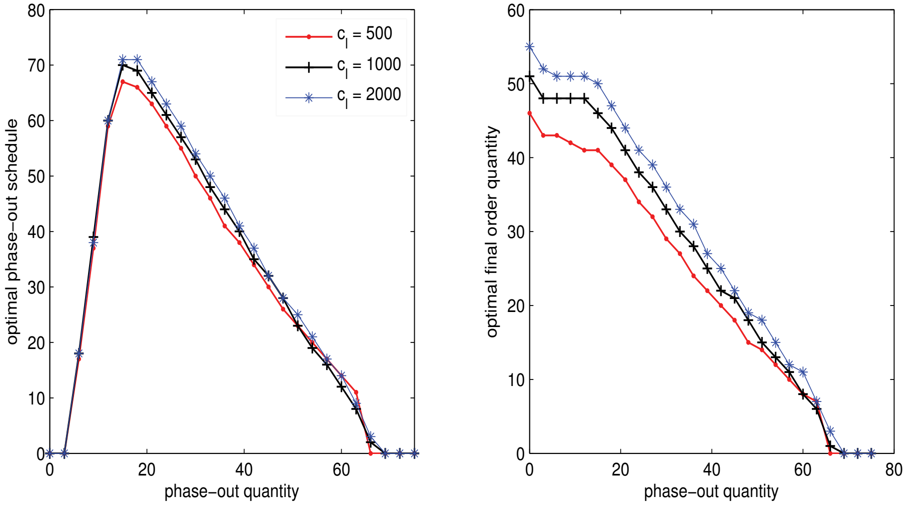

Figure 3.7: Effect of phase-out quantity on optimal schedule and final order quantity

3.4.1 Heuristic 1: Push Policy

Under heuristic 1, in each period t, if there is repairable item the system triggers repair or in other words the repairable items are immediately sent to repair shop as soon as they arrive. In this case the optimality equation where $x \geq 1$ and $y \geq 1$ can be expressed as

$$\begin{aligned}
\nu_{11}(t,x,y) = \quad & (1-\lambda(t))\mu\{h_s(x+1) + h_r(y-1) + c_r + \alpha\nu(t+1, x+o_{t+1}+1, y-1)\} \\
& +(1-q)\lambda(t)\mu\,\{h_s x + h_r(y+1) + c_r + \alpha\nu(t+1, x+o_{t+1}, y-1)\} \\
& +q\lambda(t)\mu\big\{h_s x + h_r y + c_r + \alpha\nu(t+1, x+o_{t+1}, y)\big\} \\
& +(1-\lambda(t))(1-\mu)\{h_s x + h_r y + \alpha\nu(t+1, x+o_{t+1}, y)\} \\
& +(1-q)\lambda(t)(1-\mu)\{h_s(x-1) + h_r y + \alpha\nu(t+1, x+o_{t+1}-1, y)\} \\
& +q\lambda(t)(1-\mu)\{h_s(x-1) + h_r(y+1) + \alpha\nu(t+1, x+o_{t+1}-1, y+1)\}
\end{aligned} \tag{3.11}$$

Relations 3.4-3.6 need to be modified based on this policy similar to (3.11).

3.4.2 Heuristic 2: Pull Policy with a Fixed Repair Threshold

In contrast to push, under heuristic 2 the system just repairs an item if the level of serviceable inventory is below a ceratin threshold S. Relation (3.3) according to this policy is rewritten as follows:

$$\nu_{11}(t,x,y) = \begin{cases} \nu_p(t,x,y) & 1 \leq x \leq S,\ y \geq 1 \\ \nu_l(t,x,y) & x > S,\ y \geq 1 \end{cases} \tag{3.12}$$

If $1 \leq x \leq S$, the system operates according to a push policy. Therefore, $\nu_p(t,x,y)$ can be calculated according to a relation similar to relation (3.11). Moreover, where $x > S,\ y \geq 1$ the system does not trigger any repair operations and thus we have

$$\begin{aligned}
\nu_l(t,x,y) = \quad & (1-\lambda(t))\big\{h_s x + h_r y + \alpha\nu(t+1, x+o_{t+1}, y)\big\} \\
& +(1-q)\lambda(t)\big\{h_s(x-1) + h_r y + \alpha\nu(t+1, x+o_{t+1}-1, y)\big\} \\
& +q\lambda(t)\big\{h_s(x-1) + h_r(y+1) + \alpha\nu(t+1, x+o_{t+1}-1, y+1)\big\}
\end{aligned} \tag{3.13}$$

3.4.3 Experimental Design

In our numerical test, the planning horizon is 200 periods, i.e. $H = 200$. We assume that there are three planned phase-outs arriving at times 30, 85 and 145 with a size of 7, 4 and 9 respectively. The demand arrival rates are set at 0.9, 0.7, 0.4 and 0.2 respectively between each two consecutive phase-out returns. The other system parameters are chosen from the following sets, which generate a total of 64 different combinations. Sets are as follows $\mu \in \{0.3, 0.8\}$, $q_0 \in \{0.1, 0.7\}$, $c_l \in \{1000, 2500\}$, $c_r \in \{25, 125\}$, $c_{ss} \in \{40, 120\}$, $h_s \in \{0.5, 1.5\}$, $h_r = 0.5$ and $c_{sr} = 40$.

We compute the cost and final order quantity for each instance with different parameters under optimal and heuristic policies. We report the average, minimum and maximum cost increase resulting from each heuristic policy compared to the optimal policy. We define the cost increase by the following expression

$$\Delta_{cost} = \frac{TC_h - TC_{opt}}{TC_{opt}} \times 100\%$$

where, TC_h and TC_{opt} are expected cost according to heuristic and optimal policies, respectively.

The numerical results in Table 3.1 show that on average the pull policy outperforms the push policy, as intuition might dictate. This is because while repair is triggered according to a push policy, the system does not utilize any information regarding time and state of the system. However, the pull policy benefits from deliberately postponing the repair operation. The average cost increase for a pull policy is 6.83% compared to 20.75% for a push policy. Moreover, in some cases implementing a push or pull policy instead of an optimal policy can impair the performance of the system as much as 43.68% or 31.10%, respectively. Moreover, on average the pull policy tends to place a larger final order quantity than the optimal policy, whereas push always places a smaller final order quantity. This can be easily justified considering the structure of each policy. Basically, the system expects to yield more serviceable items through repair when it operates according to a push rather than a pull policy. Therefore, the final order quantity is smaller when the repair operation is controlled according to a push structure.

Table 3.1: The Value of the Optimal Policy

	$\Delta_{cost}\%$	Max $\Delta_{cost}\%$	Min $\Delta_{cost}\%$
Push	20.75	43.68	3.70
Pull	6.83	31.10	0.35

Table 3.2: Final order quantity

	Average n	Max n	Min n
Optimal	61.76	83	39
Push	59.78	82	37
Pull	64.75	85	42

3.4.4 Impact of Cost Terms

In this section, we first aim at exploring the impact of various cost parameters on the value of the optimal control policy and secondly at understanding better the performance of push and pull policies. To achieve this, we assign different values to a specific parameter and keep other variables constant. For the base case scenario the parameters are set as shown in Table 3.3. Figure 3.8 suggests that there are many situations for which a push might outperform a pull policy. Figure 3.8.a implies that as the holding cost for repairable items increases, the average error of a push policy decreases whereas it increases for a pull policy. This is because it becomes more costly to hold repairable items which makes push more appealing. Therefore, for larger values of h_r push becomes superior to pull. Moreover, as the serviceable item holding cost rate increases push becomes less attractive and therefore pull outperforms push for larger h_s, as shown in Figure 3.8.b.

Next, we examine the impact of the repair rate on the value of the optimal policy (Figure 3.8.c). As the repair rate increases, pull tends to outperform push policy. This is because when the repair rate is high, the repair operation becomes more reliable and therefore the system prefers to postpone the repair operation and trigger it when the serviceable inventory hits a certain level. Since repairable items are cheaper to hold, the

Table 3.3: Base case parameters

c_p	c_l	c_r	h_r	h_n	c_d^s	c_d^r	q	μ
200	1000	75	0.5	1	80	40	0.3	0.4

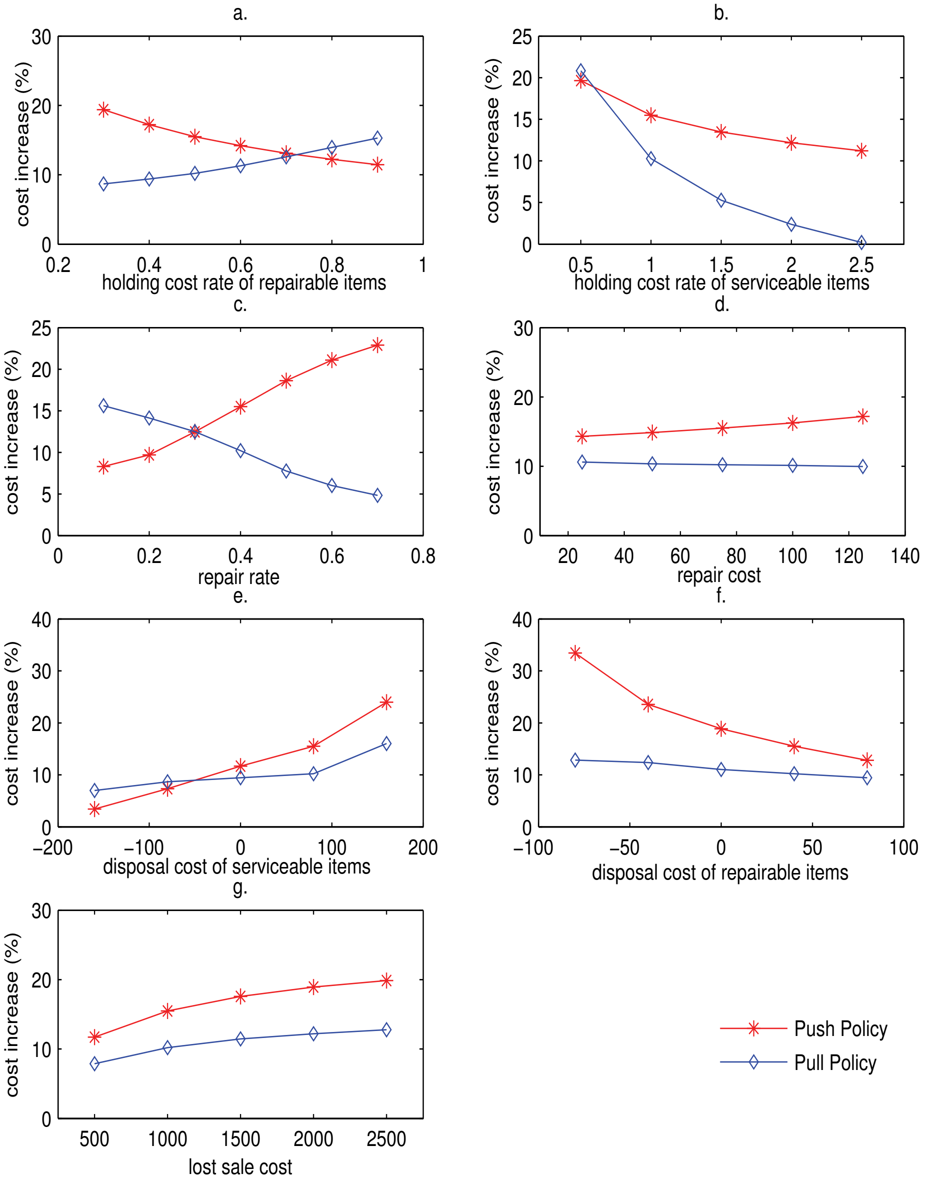

Figure 3.8: Impact of various parameters on the performance of heuristic policies

system can benefit more from pull than push when repair can be completed more swiftly. Furthermore, the increase in repair cost seems to impair the performance of the push more than pull policy (Figure 3.8.d). This is mainly due to the fact that pull can adjust S in order to avoid extra repair cost.

As intuition dictates, push policy outperforms pull when the disposal of the serviceable item generates a large revenue (Figure 3.8.e). As the serviceable item disposal cost increases, push loses its advantage and therefore pull tends to be a more effective policy. When it becomes more costly to dispose of repairable items, then having less repairable stock at the end of the horizon becomes more advantageous. Hence, we observe that the performance of the push policy improves when c_d^r increases (Figure 3.8.f). Figure 8.g suggests that with the increase of the lost sale cost, both push and pull policies impair performance significantly.

3.5 Extension to the Other Cases

Our model and approach can accommodate several related problems of interest as simple extensions. In this section, we describe some of these cases. The main interest lies with phase-out uncertainty. In practice, the phase-out arrival schedule is subject to considerable uncertainty. This is because in order to switch from an old platform to a new one, the customer has to take many sequential steps including purchasing, testing, personnel training etc. All of these activities are subject to randomness that might render an uncertain phase-out arrival schedule. Furthermore, in some cases, the OEM is not fully aware of the condition of platforms in use and therefore the phase-out quantity is also subject to randomness. First, we extend the model to a case with phase-out schedule uncertainty and then to a case with uncertain schedule as well as uncertain quantity.

3.5.1 Phase-out Schedule is Stochastic While Quantities are Deterministic

In this case, the arrival of phase-out returns are subject to uncertainty, but we can limit the arrival time, τ_i, to the interval $[\underline{\tau}_i, \overline{\tau}_i]$ with arrival probability $\mathbb{P}\{\tau_i = t\} = p_i$. In order to calculate the policy cost, we define the function $\omega(\tau_i, \tau_{i+1}, x, y)$ as the cost function of running the policy from time τ_i to τ_{i+1}. Therefore, the expected total cost function from

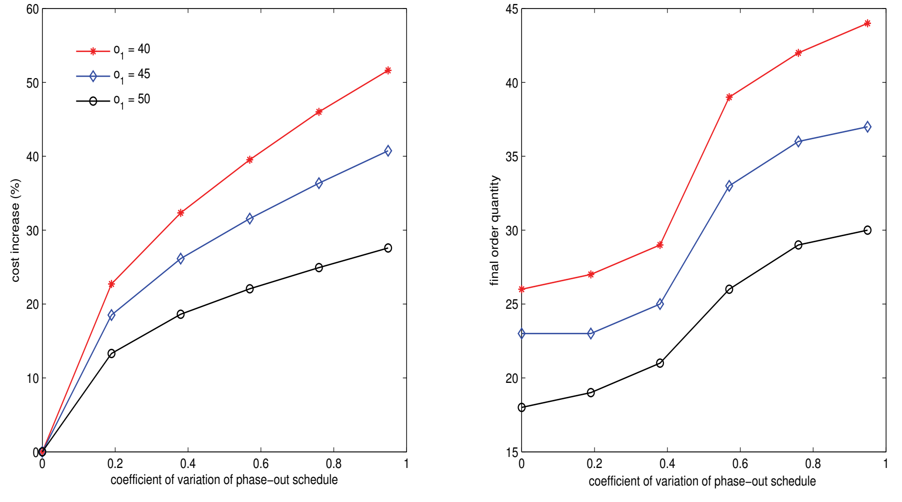

Figure 3.9: Effect of phase-out arrival uncertainty on expected total cost

time 0 to H is obtained by

$$\mathbb{E}\omega(x,y) = \sum_{i=0}^{n} \sum_{\tau_i=\underline{\tau}_i}^{\overline{\tau}_i} \sum_{\tau_{i+1}=\underline{\tau}_{i+1}}^{\overline{\tau}_{i+1}} p_i(\tau_i)p_{i+1}(\tau_{i+1})\omega(\tau_i,\tau_{i+1},x,y) \tag{3.14}$$

where $\tau_0 = 0$ and $\tau_{n+1} = T$. Moreover, $\omega(\tau_i, \tau_{i+1}, x, y)$ for $\tau_i \le t < \tau_{i+1}$ is defined as

$$\omega(\tau_i,t,x,y) = \begin{cases} \omega_{11}(\tau_i,t,x,y) & x \ge 1, y \ge 1 \\ \omega_{01}(\tau_i,t,x,y) & x = 0, y \ge 1 \\ \omega_{00}(\tau_i,t,x,y) & x = 0, y = 0 \\ \omega_{10}(\tau_i,t,x,y) & x \ge 1, y = 0 \end{cases} \tag{3.15}$$

which can be calculated in the same fashion as (3.3) and (3.4).

In order to investigate the effect of phase-out uncertainty, we limit our attention to the first phase-out arrival and use the variance in the arrival schedule as a measure for uncertainty. As intuition dictates, more variation around the optimal phase-out schedule results in a higher expected total cost. The results are shown in Figure 3.9. It is observed that the system places a larger final order quantity in order to hedge against uncertainty when the coefficient of variation of the phase-out schedule increases.

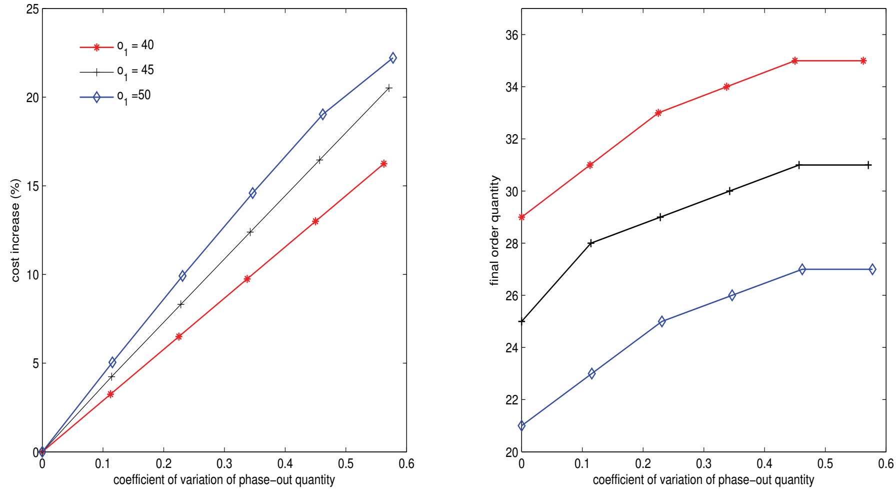

Figure 3.10: Effect of phase-out quantity uncertainty on expected total cost

3.5.2 Both Phase-out Schedule and Quantities are Stochastic

In this situation, the quantity of phase-out returns is also subject to uncertainty. With probability $q_i(k)$, k parts out of o_i can immediately be added to the serviceable inventory and the rest should undergo repairs. In this case, the expected total cost function from time 0 to H is obtained by

$$\mathbb{E}\omega(x,y) = \sum_{i=0}^{n} \sum_{\tau_i=\underline{\tau}_i}^{\overline{\tau}_i} \sum_{\tau_{i+1}=\underline{\tau}_{i+1}}^{\overline{\tau}_{i+1}} \sum_{k=0}^{o_i} \sum_{j=0}^{o_i-k} q_i(k) p_i(\tau_i) p_{i+1}(\tau_{i+1}) \omega(\tau_i, t+1, x+k, y+j) \quad (3.16)$$

where $\omega(\tau_i, t+1, x+k, y+j)$ can be calculated similar to (3.15)

In order to investigate the effect of phase-out quantity uncertainty, we keep the standard deviation of the phase-out schedule at a fixed level and change the coefficient of variation of the phase-out quantity while its expected value is fixed. The results are shown in Figure 3.10. As can be observed, more randomness in phase-out quantities results in an increase of final order quantity and consequently impairs the performance of the system.

3.6 Discussion and Conclusion

In this chapter we address the end-of life inventory and repair planning for service parts in their final phase. In particular, we focus on the final order quantity, taking into account product returns due to failures and phase-outs and (optimal) repair policy.

When the schedule and quantities of phase-out returns are known in advance we proved that the structure of the optimal policy is characterized in terms of state and time dependent threshold levels $r^*(t, y)$, where t is time and y is the remanufacturable inventory. So, whenever the level of serviceable inventory x is below $r^*(t, y)$, a part, if available, is sent to the repair shop.

Varying the arrival time of phase-outs, we see that there is an optimal timing of phase out returns for a given phase-out quantity. When phase-out quantities are higher, the optimal timing first moves later in time, but eventually moves earlier in time. Therefore, in constructing service contracts it is important to take the timing of phase-outs into account or even negotiate optimal timing.

The optimal policy combines push and pull in one policy. Simpler policies have previously been developed and are widely used in practice, such as push (push repairable items upon arrival) and pull (pull repairable items relative to a fixed serviceable inventory level). Our numerical study suggests that push only outperforms pull when the holding cost rates for serviceable and remanufacturable items are very close or when the repair rate is very small. The difference between push and pull becomes smaller as the disposal cost for a remanufacturable part increases. For our parameter setting, the optimal policy outperforms pull by up to 31.10% (6.83% on average). When the serviceable holding cost rate or the probability that a part is remanufacturable is high, the performance of pull is close to optimal. With respect to the final order quantity decision we see that push always underestimates the optimal final order quantity, whereas pull always overestimates it.

Another finding highlight the vital importance of phase-out information. We show that uncertainties about the phase-out schedule and quantity can impair the performance of the system. Having accurate information over phase-out returns can lead to considerable cost savings.

Chapter 4

End-of-Life Inventory Problem with Customer Differentiation*

4.1 Introduction

With the rapid technology development, life cycles of products have become shorter. As a consequence, managing the inventories of service parts in order to fulfill service obligations and avoid obsolescence risk becomes a major challenge for companies. This becomes even more crucial as the production of a service part is discontinued when the part enters its final phase of service life cycle. One of the main tactics adopted by various industries to cope with the end-of-life inventory problem is placing a "final order quantity" at the beginning of the final phase. The final order should be placed in a quantity such that it balances the risk of obsolescence at the end of horizon versus the risk of failure to meet service agreements.

The service agreements oblige the company to provide its customers with a certain service level. It has been common in practice that companies offer different service levels versus different prices. As a result, customers are segmented according to the service level they choose. This introduces the idea of rationing available inventories for some customer classes. The practice of rationing inventory (or capacity) among different customer classes is an increasingly important tool for balancing supply with demand in environments where requirements for service vary widely. Basically a rationing policy issues stock to some customers while refuses or delays demand fulfillment for others. It is analogous to the highly successful yield management policies adopted by airlines and hotels. In

*This chapter is based on Pourakbar and Dekker (2011).

capital-intensive goods industry there are several examples of implementing a customer differentiation scheme, for example defense systems (Deshpande et al. 2003a and 2003b), semiconductor manufacturing equipment (Kranenberg and Van Houtum 2008), and mobile phone operating systems (Möllering and Thonemann 2008). Essentially, there are various situations that illustrate the importance of customer differentiation for inventory control, namely demand criticality based differentiation or service contract based differentiation. The criticality of the demand for the spare parts can be due to various reasons. First, a spare part can be critical in one place and non-critical in another. For example, breaking down of a mainframe computer at a stock exchange has more severe financial impact than when a mainframe computer in a library goes down. Another example is given by Dekker et al. (1998). They consider the case of a petrochemical plant in which one could distinguish between vital, essential and auxiliary equipments. Demands for service parts originating from equipments in each of these classes are given a different level of criticality. Another situation wherein demand criticality arises is identified where demands happen for both regular replenishment and emergency orders. Obviously, a demand for an emergency order is given a higher priority than a regular replenishment order.

In environments in which manufacturers of complex goods sell directly to customers, service parts are distributed primarily through service contracts. For OEMs and service providers that handle performance-based service contracts for customers, service payments are based on up-time performance or equipment availability, rather than actual support cost. This includes companies in the aerospace and defense, industrial chemical, semi-conductor equipment, and networking and telecom industries (Aberdeen Group, 2005). Service providers offer an array of service contracts for a single product. These service contracts impose different service requirements for service providers against different prices. Murthy and Blischke (2005) discuss the factors that form the distinction among various service contracts. In general one could argue that the distinctions are induced by varying: 1) Service responses and/or repair time commitments; and 2) Price and/or cost structures. The response times vary significantly from situation to situation. For example in mission critical situations, the service provider is always present on-site whereas in the same day delivery, the response time varies from 2 to 24 hours. Cohen et al. (2006) highlight that consumer products such as TVs and PCs have lower response time requirements. On the other hand, businesses computing machines, construction equipment and aircraft have typically very high response time requirements. The failure to meet service obligations may results in penalties that are negotiated during the contract formalization. In such a setting, service contract based differentiation has been an increasing trend for after-sale service providers.

With the technology developments and shortening of products life cycles, service parts enter the end-of-life phase sooner. Consequently, companies face a huge service responsibility while the parts are in the final phase and parts provisioning is not guaranteed any longer. Therefore, companies are mandated to take into account various types of service obligations they have while making the final order quantity decisions. Considering this aspect, in the sequel of this chapter, we study the inventory control problem of a capital-intensive product service part when the part production is discontinued. We proceed by characterizing the structure of an optimal inventory control policy in the final phase where customers are differentiated. We consider both demand criticality based differentiation and contract based differentiation schemes. Using Markov decision processes, we show that in these settings inventories should be controlled according to time dependent threshold levels that consider the level of available inventory. Moreover, we study the advantages of incorporating the critical level policies in this problem.

The rest of this chapter is structured as follows. Section 2 proceeds by a brief overview of the literature on end-of-life inventory decisions and inventory problems with customer differentiation. Next, in section 3 we describe the problem. Section 4 formulates the problem when customers are differentiated based on demand criticality. Section 5 considers a service contract-based differentiation and section 5 concludes the chapter.

Besides the end-of-life inventory related literature, another stream of research related to this work is the issue of customer differentiation. In traditional inventory systems all customer demands are treated equally and fulfilled based on a first come first serve policy. However, in practical settings, managers often differentiate customers by assigning a priority based on the level of service customers are expecting. A very common approach employed in this setting is critical level policy. According to a critical level policy the system reserves some inventory for the higher priority customer. In other words, given the current level of inventory, the system may deliberately decide to deny some lower priority customers access to the inventory in anticipation of higher priority demand arriving in the future. It is shown that this type of policy has considerable advantage over the traditional inventory policies in which it is assumed that all customers receive the same level of service.

These types of problem have been studied extensively under various assumptions, see for example Veinott (1965), Topkis (1968), Ha (1997), Cattani and Souza (2002), Dekker et al. (2002), De Vericourt et al. (2002), Deshpande et al. (2003), Jalil et al (2011), Frank et al. (2003), Kranenburg and Van Houtum (2007, 2008), Teunter, Klein Haneveld (2008) and Benjaafar et al. (2010).

However, to the best of our knowledge the issue of a customer differentiated inventory system in the final phase has not been dealt with in the literature. There are certain aspects that make this problem paramount. First of all, the end-of-life phase is considered the longest in the service parts life cycle. Therefore, we expect that service responsibilities are mostly stretched to this phase as well. However, another major complication in this phase is that the opportunity of ordering parts is not guaranteed and therefore companies should consider various service obligations at the moment the final order is placed. What distinguishes our work from the rest of the literature is that first, we consider customer differentiation in the final phase of the service life cycle. Next, we characterize the structure of the optimal inventory policy in this phase for demand criticality based differentiation and service contract based differentiation. Using a finite horizon Markov decision process, we show that in case of demand criticality based differentiation inventories should be controlled according to some time and state-dependent criticality levels. Moreover, for service contract based differentiation we show that we also need some time dependent contract extension thresholds. Characterizing the optimal policy structure, we study the value of the optimal policy by investigating similar systems without critical level or contract extension thresholds.

4.2 Problem Description

We consider the End-of-Life inventory decisions associated with a spare part used by different classes of customers in a finite horizon $[0, H]$. 0 denotes the time that the last time procurement decision for service parts should be made . Parts can be either produced or purchased with a cost c_p per item. After this time, parts acquisition is not guaranteed any more. H signifies the end of the horizon and it is the time that the last service or warranty contract expires. All parts left at the end of the horizon are considered obsolete and should be disposed of. While deciding on the final order quantity, one should note that overage stock of service parts imposes high carrying and obsolescence costs while underage stock results in service failure. Therefore, one primary challenge is to balance the risk of obsolescence versus failure to meet service commitments.

We assume that customers are differentiated into S different categories. Demands of each category arrive according to a non-stationary Poisson distribution with mean value function $\Lambda_i(t)$. The non-stationarity in demand arrival is due to the fact that in this phase, the size of the installed-base available in the market is shrinking and so does the demand rates for spare parts.

We assume unmet demands are lost with a cost c_s where $s \in \{1, 2, \ldots, S\}$. The lost sale assumption stems from the fact that as long as the system is in the final phase ordering parts is not guaranteed. Therefore if shortages are backlogged there is no assurance that the system could satisfy them later in the course of final phase. Thus, assuming lost-sales is more reasonable. Furthermore, the higher the priority of a customer the larger is the lost sale cost, $c_s > c_{s+1}$ for $s \in \{1, 2, \ldots, S-1\}$. For each unit of serviceable inventory the system incurs a holding cost of h per unit per time . Moreover, all cost terms are discounted back to the beginning of the horizon with a rate α. All the remaining serviceable inventory at the end of the final phase are considered obsolete and should be disposed of with a cost d_s per unit.

One popular tactic in such a case to mitigate the risk of service failure is to ration the serviceable inventory. According to a rationing scheme the system might decide to deliberately avoid serving a lower priority customer in order to save the inventory in anticipation of future demand for higher priority customers. Moreover, if customers are segmented according to service contracts then denying to offer contract renewal to less valuable customers is another tactic, introduced in this chapter, to ensure higher priority customers demand satisfaction.

4.3 Demand Criticality-Based Differentiation

In this setting customers are differentiated based on the criticality of their demands. One example is the case where a specific part is critical in one equipment and non-critical in another one. Another example is identified where there are demands for both emergency and regular replenishment shipment. Emergency shipment might be due to machine failure and therefore are signified more critical than regular shipment orders. In our model, we assume there are S different categories of demand and servicing a type i

demand result in a revenue of amount r_i. Moreover, higher priority customers generate a larger revenue than lower priority ones, $r_i > r_{i+1}$ for $i \in \{1, 2, \ldots, S-1\}$.

Upon arrival of a customer of type i, the system should decide whether to satisfy or decline service in order to preserve the serviceable items for future demand of higher priority customers. In the rest of this section we formulate this problem as a finite horizon Markov decision process and using this formulation we characterize the structure of the optimal policy. First, without loss of generality we assume that the time interval $[0, H]$ is divided into periods of length one unit such that the probability of having more than one demand of any type i is negligible. This time unit can represent a month, a week, a day or an hour. Then the optimality equation at time t for a specific serviceable inventory level x is denoted by $\nu(t, x)$. In a case where $x \geq 1$ and $t < H$, it is formulated as

$$\begin{aligned} \nu(t,x) = \; & (1 - \textstyle\sum_{i=1}^{S} \lambda_i(t)) \{hx + \alpha\nu(t+1,x)\} \\ & + \textstyle\sum_{i=1}^{S} \lambda_i(t) \{hx + \min\{\alpha\nu(t+1,x) + c_i, \alpha\nu(t+1,x-1) - h - r_i\}\} \end{aligned} \tag{4.1}$$

The first term represents a situation in which no demand occurs during period t, and the second term explains a situation wherein a demand of type i arrives during t for which the system manager should decide whether to accept or deny it. In case $x = 0$ and $t < H$, all incoming demands are lost therefore we have

$$\nu(t,0) = (1 - \sum_{i=1}^{S} \lambda_i(t))\alpha\nu(t+1,0) + \sum_{i=1}^{S} \lambda_i(t) \{\alpha\nu(t+1,0) + c_i + r_i\} \tag{4.2}$$

At time H all available serviceable inventory should be disposed of therefore the terminal value function is given by

$$\nu(H,x) = d_s x \tag{4.3}$$

We assume that it is always optimal to use a part to satisfy a demand than to dispose of it, i.e. $h + r_S + c_S > \alpha d_s$ where S corresponds to the least valuable customer. Note when there is on-hand serviceable stock, i.e. $x > 0$, at any time t it is optimal to satisfy an incoming class i demand if the increase in the system costs due to having one less unit of inventory is less than the associated unit lost sales cost and the generated revenue. The system rejects the class i incoming demand otherwise. This condition is formulated as

$$\alpha \left[\nu(t+1,x-1) - \nu(t+1,x)\right] \leq c_i + r_i + h \tag{4.4}$$

This condition identifies the rationing threshold and has a simple interpretation. The system keeps satisfying demands from customers of type i as long as the discounted future loss from having one less unit of the serviceable inventory is less than the costs incurred by rationing. The following lemma is useful in characterizing the structure of the optimal policy.

Lemma 6. $\nu(t,x) - \nu(t,x-1)$ *is non-decreasing in* x.

Proof. We prove this by induction. First, for the ease of exposition we define $\Delta_x\nu(t,x) = \nu(t,x)-\nu(t,x-1)$ we note that $\Delta_x\nu(t,x)$ non-decreasing in x is equivalent to $\nu(t,x)$ being discretely convex. We also define $\Delta_x\nu(t,0) = \alpha/(c_i + r_i + h)$. From the terminal value definition, $\nu(H,x) = d_s x$, we have $\Delta_x\nu(H,x) = d_s$. From the assumption ($h + r_S + c_S > \alpha d_s$) we immediately have $\Delta_x\nu(H,x) > \Delta_x\nu(H,1) > \Delta_x\nu(H,0),\ x \geq 1$. Therefore, $\Delta_x\nu(H,x)$ is non-decreasing in x.

Following the induction, we assume that $\Delta_x\nu(t,x)$ is non-decreasing in x, then we need to show that $\Delta_x\nu(t-1,x)$ is non-decreasing in x. Relation (4.4) implies that $\exists r_i(t)$ such that it is optimal to deny an arriving demand of type i if $x < r_i(t)$ and fulfill it otherwise. Then using equation (4.1) we have

$$\begin{aligned}\Delta_x\nu(t-1,x) = \ & (1-\textstyle\sum_{i=1}^{S}\lambda_i(t))\,[h+\alpha\Delta_x(t,x)] \\ & +\textstyle\sum_{i=1}^{S}\lambda_i(t)\begin{cases} h+\alpha\Delta_x\nu(t,x) & x < r_i(t) \\ h+\alpha\Delta_x\nu(t,x-1) & x \geq r_i(t)\end{cases}\end{aligned} \tag{4.5}$$

Given that $\Delta_x\nu(t,x)$ is non-decreasing in x, it is clear from the above relation that $\Delta_x\nu(t-1,x)$ is also non-decreasing in x at any time t. □

This lemma establishes that the value function $\nu(t,x)$ is convex in x for all time t. This lemma together with condition (4) leads to the optimality of a time-varying threshold policy as follows:

Theorem 3. *The optimal end-of-life inventory control policy when customers are differentiated based on demand criticality is a time-varying threshold policy. It can be characterized as follows:*

i. There exist threshold levels $r_1(t), r_2(t), \ldots, r_S(t)$ *such that if* $x \geq r_s(t)$ *an incoming demand of class* s *is satisfied and rejected otherwise.*

ii. At each time t we have $0 = r_1(t) \leq r_2(t) \leq \cdots \leq r_S(t)$

iii. $r_s(t)$ is non-increasing in t, $s \in \{1, 2, \ldots, S\}$

Proof. i. We note that $\nu(t, x)$ is convex. Considering (4.4) for an arbitrary class i if $x \geq r_i(t)$ the minimizer of the objective function is to satisfy demand of class i. If $x < r_i(t)$ the minimizer is to reject any arriving demand of class i.

ii. This can be proved using the definition of $r_i(t)$ in relation (4.4). If $j \leq i$, $j, i \in \{1, 2, \ldots, S\}$ then $\alpha [\nu(t+1, x-1) - \nu(t+1, x)] \leq c_i + r_i + h \leq c_j + r_j + h$. Thus $r_j(t) \geq r_i(t)$.

iii. We consider an arbitrary class i and show that $r_i(t)$ is non-increasing in t. The induction assumption in this case is $r_i(t) \geq r_i(t+1)$ and $\Delta_x \nu(t, x) \geq \Delta_x \nu(t+1, x)$, $\forall x \in [1, r_i(t)]$. Then we need to show that $r_i(t-1) \geq r_i(t)$ and $\Delta_x \nu(t-1, x) \geq \Delta_x \nu(t, x)$, $\forall x \in [1, r_i(t-1)]$. Considering the definition of $r_i(t)$ (4.4), we have $\alpha \Delta_x(t, x) \leq c_i + r_i + h$ if $x < r_i(t)$.

Using a contradiction approach we assume that $r_i(t-1) < r_i(t)$. Then we have $\alpha \Delta_x(t, r_i(t-1)) \leq c_i + r_i + h$ if $x < r_i(t)$. Then using equation (4.5), we have

$$\alpha \Delta_x(t-1, r_i(t)) - \alpha \Delta_x(t, r_i(t)) = (1 - \sum_{i=1}^{S} \lambda_i(t)) \left[\alpha \Delta_x(t, r_i(t)) - \alpha \Delta_x(t+1, r_i(t))\right]$$
$$+ \sum_{i=1}^{S} \lambda_i(t) \begin{cases} \alpha \Delta_x \nu(t, r_i(t)) - \alpha \Delta_x \nu(t+1, r_i(t)) & r_i(t) < r_i(t+1) \\ \alpha \Delta_x \nu(t, r_i(t) - 1) - \alpha \Delta_x \nu(t+1, r_i(t) - 1) & r_i(t) \geq r_i(t+1) \end{cases} \tag{4.6}$$

By induction assumption, we know that the terms $\alpha \Delta_x \nu(t, r_i(t)) - \alpha \Delta_x \nu(t+1, r_i(t))$ and $\alpha \Delta_x \nu(t, r_i(t) - 1) - \alpha \Delta_x \nu(t+1, r_i(t) - 1)$ are non-negative. Thus $\alpha \Delta_x(t-1, r_i(t)) - \alpha \Delta_x(t, r_i(t))$ is also non-negative. Consequently $\alpha \Delta_x(t-1, r_i(t)) > \alpha \Delta_x(t, r_i(t)) > c_i + r_i + h$ which implies that $r_i(t-1) > r_i(t)$ which is a contradiction. Thus the desired result is shown.

Next, we show that $\Delta_x \nu(t-1, x) \geq \Delta_x \nu(t, x)$, $\forall x \in [1, r_i(t-1)]$. Given that $r_i(t-1) \geq r_i(t)$, we can distinguish the following cases

Case I. $1 \leq x \leq r_i(t+1)$

In this case, we have

$$\alpha \Delta_x(t-1, r_i(t)) - \alpha \Delta_x(t, r_i(t)) = (1 - \sum_{i=1}^{S} \lambda_i(t)) \left[\alpha \Delta_x(t, r_i(t)) - \alpha \Delta_x(t+1, r_i(t))\right]$$
$$+ \sum_{i=1}^{S} \lambda_i(t) \left[\alpha \Delta_x \nu(t, r_i(t)) - \alpha \Delta_x \nu(t+1, r_i(t))\right] \tag{4.7}$$

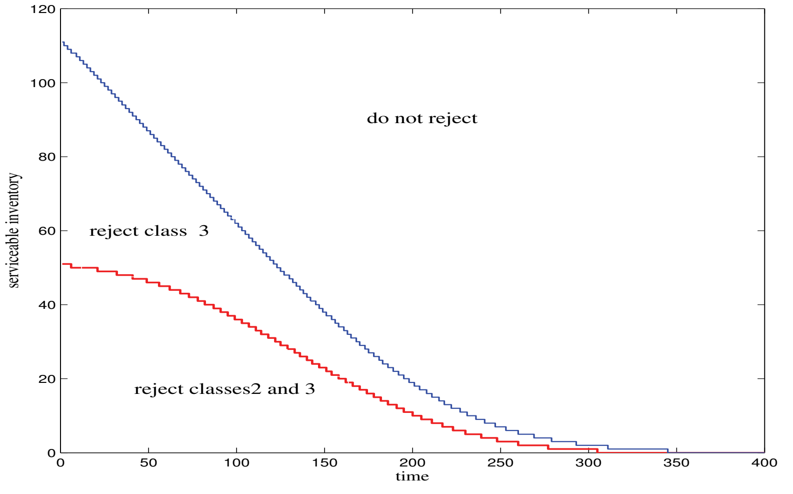

Figure 4.1: rationing threshold for a system with three classes of customers

The right-hand side is non-negative therefore, $\alpha\Delta_x(t-1,x) - \alpha\Delta_x(t,x) \geq 0$ which shows the desired result.

Case II. $r_i(t+1) < x \leq r_i(t)$

The results can be shown similar to the previous case.

Case III. $r_i(t) < x \leq r_i(t-1)$

In this case we have according to the definition of the rationing levels, equation (4.4), $\alpha\Delta_x\nu(t,x) \leq c_i + r_i + h$ and $\alpha\Delta_x\nu(t-1,x) \geq c_i + r_i + h$ therefore $\Delta_x(t-1,x) - \Delta_x(t,x) \geq 0$.

We also need to show that the results hold for $t = H$. It is straightforward since intuitively $0 = r_i(H) \leq r_i(H-1)$. $\square$

Figure 4.1. demonstrates the optimal rationing policy for a system with three different customer classes. As it is observed the state space is divided into three different regions. The contour of each region is the rationing threshold. We observe that, when it is closer to the end of the horizon, the system tends to set a lower rationing level. The system denies the demand from a lower priority class if the level of inventory is very low. In other words, the rationing levels are non-increasing in time. Moreover, if class i is more critical than class j, then the system sets a lower rationing threshold for class i than class j.

4.3.1 Final Order Quantity

So far the procurement and production costs are not accounted in the formulation since these can be considered sunk cost in making the rationing decisions. However this cost needs to be considered when we make decision over the final order quantity. The unit provisioning cost which is either the cost of purchasing or production is denoted by c_p. Then the net total cost at time 0 is defined by

$$TV(x) = \nu(0, x) + c_p x \tag{4.8}$$

As an immediate result from convexity of $\nu(t, x)$, we have $TV(x)$ is also convex and the optimal final order quantity can be obtained using a simple search algorithm.

4.3.2 Numerical Analysis

By conducting this numerical analysis we aim at quantifying the value of having a rationing decision in the course of the final phase. To do so, we consider a system without rationing. In other words, in case of available serviceable inventory the system always fulfill demands from all types of customers. For the base case scenario, we assume there are three different equipment criticality levels for which the associated total shortage and lost sale costs are $c_1 = 250$, $c_2 = 150$ and $c_3 = 50$. Holding cost is set as 0.05 per unit per time. Moreover, demand is a non-homogenous Poisson process with rates $\lambda_1(t) = 0.45/(1 + \exp(0.025(t - 200)))$, $\lambda_2(t) = 0.25/(1 + \exp(0.025(t - 200)))$ and $\lambda_3(t) = 0.20/(1 + \exp(0.025(t - 200)))$ respectively for class 1, 2 and 3 customers and $H = 400$. In order to study the value of rationing we compare the results of the system with rationing with the results of of a similar system without rationing. To do so the cost of a system without rationing is denoted by C_r and the one with rationing is denoted by C_{opt}. Then, the value of a rationing decision is calculated according to

$$\Delta\% = \frac{C_r - C_{opt}}{C_{opt}} \times 100 \tag{4.9}$$

Figure 4.2. depicts the effect of holding cost rate on the value of rationing and also the final order quantity. As we observe in this case, the final order quantity decreases as it becomes more expensive to hold inventory. Moreover, a system with rationing tends

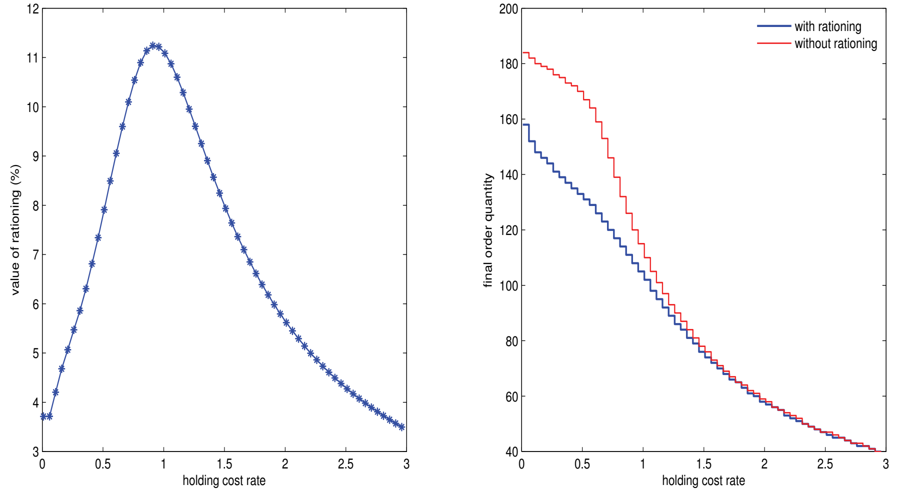

Figure 4.2: the value of a rationing option and its effect on final order quantity

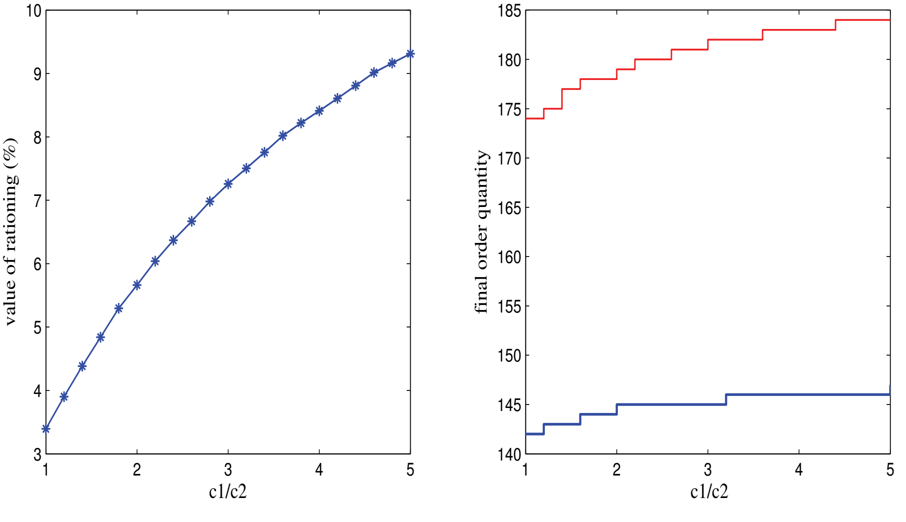

Figure 4.3: the value of rationing and its effect on final order quantity

to place a smaller final order quantity than a system without rationing. As holding cost rate increases at first the value of rationing increases. It is due to the fact that the more expensive the items are to hold, the less inventory level is preferred and as a consequence rationing plays a more vital role. However, as the holding cost rate becomes higher it might become more advantageous to stock less and therefore deny demands for service rather than satisfying them thus, rationing loses its value.

Furthermore, as intuition dictates when the lost-sale ratio c_1/c_2 increases, the importance of meeting class 1 demands becomes more vital. As a consequence, having a rationing decision gains more value. We again observe that a system without rationing places a much larger order than a system with rationing. Therefore, an inherent consequence of a rationing option in the final phase would be an alleviated risk of obsolescence. By placing a smaller final order quantity while we have rationing, the system not only avoids extra carrying cost but also hedges upon the risk of obsolescence at the end of the final phase.

4.4 Service Contract-Based Differentiation

As mentioned earlier, over the past few decades, after-sale service contracts have become a common practice in service industries. It is due to the fact that in a highly competitive environment with increased and differentiated customer demands, service organizations pay more attention to service contracts as a source of predictable and renewable revenue streams. Once customers have signed or renewed their contracts, the service organization must meet its commitments consistently and cost effectively. In this setting, customers are differentiated based on the service contracts they choose. The service provider offers S different types of contracts such that type i contract generates a revenue of magnitude R_i and $R_1 \geq R_2 \geq \cdots \geq R_S$ for a specific duration (for example a year). Customers with a more valuable service contract are given a higher priority. In such a setting the revenue is generated not per service given to the customer but per contract that runs for a certain period.

At the end of the service period the system should decide whether to offer a contract extension to a customer of type i or terminate this type of contract. Essentially the system should make this decision according to the level of serviceable inventory and the time remaining to the end of the horizon. If the inventory level is seen as critically low to satisfy the forthcoming demands for all active service contracts then it might be beneficial to consider not renewing lower priority service contracts in order to preserve the inventory for higher priority ones. If it is decided not to extend a specific type of contract then the corresponding customers are not offered a renewal option once their contracts are expired. The times at which these decisions are made is denoted by $T = \{t_1, t_2, \ldots, t_n\}$. Moreover, we should note that if the system decides not to extend a certain type of contract then from that time on, the demand rate for service decreases accordingly. In addition to the contract extension decision, the system also needs to decide whether to deny an arriving demand even if the associated service contract is running or satisfy it. In other words, the system needs to make rationing decision as well.

During the service period the service provider is mandated to satisfy customers demands. Demands which are unmet or denied, while the corresponding contract is active, are considered lost and a penalty cost is incurred. Moreover, failure to service higher priority customers leads to a higher lost sale cost, i.e. $c_1 \geq c_2 \geq \cdots \geq c_S$.

The demand originated from each category of service contracts follows a non-homogenous Poisson process with intensity function $\lambda_s(t), s \in \{1, 2, \ldots, S\}$. It is worth mentioning that, similar to the previous model we assume that satisfying a demand is always more beneficial than disposing of an item, i.e. $c_s > \alpha d_s$.

The optimality equation at time t, $\nu_s(t, x, \mathbf{s})$, is a function of inventory level, x and the status of various contract types, $\mathbf{s}$, where $\mathbf{s}$ is a binary vector and $s_i = 1$ if the type i contract is active and 0 otherwise. The optimality equation at $t \in T$ where $x > 0$ is formulated as

$$
\begin{aligned}
&\nu(t, x, \mathbf{s}) = \\
&\min_{1 \leq j \leq \phi(\mathbf{s})} \Big\{ (1 - \textstyle\sum_{i=1}^{j} \lambda_i(t)) \Big\{ hx - \sum_{k=1}^{j} R_k + \alpha\nu(t+1, x, \mathbf{s} - \sum_{h=j+1}^{\phi(\mathbf{s})} \mathbf{e}_h) \Big\} \\
&+ \textstyle\sum_{i=1}^{j} \Big\{ \lambda_i(t) \Big\{ h(x-1) - \sum_{k=1}^{j} R_k + \min \Big\{ \alpha\nu(t+1, x, \mathbf{s} - \sum_{h=j+1}^{\phi(\mathbf{s})} \mathbf{e}_h) + c_i + h, \\
&\qquad\qquad \alpha\nu(t+1, x-1, \mathbf{s} - \textstyle\sum_{h=j+1}^{\phi(\mathbf{s})} \mathbf{e}_h) \Big\} \Big\} \Big\} \Big\}
\end{aligned} \tag{4.10}
$$

where $\phi(\mathbf{s}) = \max\{\, i \mid s_i = 1, 1 \leq i \leq S\}$ finds the active type of contract with the lowest priority. The first term deals with the decision of which contract types to extend in period t where no demand arrives. The second term deals with the same decision together with a rationing decision. Meaning that whether an arriving demand of type i should be denied or admitted even though the corresponding contract is still running. Furthermore, for $x = 0$ we have

$$\nu(t,0,\mathbf{s}) = \min_{1\le j\le \phi(\mathbf{s})} \Big\{ (1-\textstyle\sum_{i=1}^{j}\lambda_i(t)) \Big\{ -\sum_{k=1}^{j} R_k + \alpha\nu(t+1,0,\mathbf{s}-\sum_{h=j+1}^{\phi(\mathbf{s})}\mathbf{e}_h) \Big\} + \sum_{i=1}^{j} \Big\{ \lambda_i(t) \Big\{ -\sum_{k=1}^{j} R_k + \alpha\nu(t+1,0,\mathbf{s}-\sum_{h=j+1}^{\phi(\mathbf{s})}\mathbf{e}_h) + c_i \Big\}\Big\}\Big\} \tag{4.11}$$

Moreover, $\nu(t,x,\mathbf{s})$ where $t \in [0,H]$ and $t \notin T$ is defined similar to (4.1) and (4.2) as follows where $x \ge 1$

$$\nu(t,x,\mathbf{s}) = (1-\textstyle\sum_{i=1}^{\phi(\mathbf{s})}\lambda_i(t))\{hx+\alpha\nu(t+1,x,\mathbf{s})\} + \sum_{i=1}^{\phi(\mathbf{s})}\lambda_i(t)\{hx+\min\{\alpha\nu(t+1,x,\mathbf{s})+c_i, \alpha\nu(t+1,x-1,\mathbf{s})-h\}\} \tag{4.12}$$

and when $x = 0$ we have

$$\nu(t,0,\mathbf{s}) = (1-\sum_{i=1}^{\phi(\mathbf{s})}\lambda_i(t))\alpha\nu(t+1,0,\mathbf{s}) + \sum_{i=1}^{\phi(\mathbf{s})}\lambda_i(t)\{\alpha\nu(t+1,0,\mathbf{s})+c_i\} \tag{4.13}$$

In this setting we need a condition similar to (4.4) to assure that the system keeps satisfying incoming demand of type i as long as the discounted future loss from having one less unit of serviceable inventory is less than the lost sale cost, i.e.

$$\alpha\,[\nu(t+1,x-1,\mathbf{s})-\nu(t+1,x,\mathbf{s})] \le c_i + h\ , \quad i\in\{1,2,\dots,S\}\ , \quad t\in[0,H] \tag{4.14}$$

Moreover, at contract extension decision times, $t \in T$, a specific contract of type i is extended only if the revenue generated is more than the future discounted cost of renewing the contract. This condition implies the contract extension thresholds and is formulated as

$$\alpha\,[\nu(t+1,x,\mathbf{s})-\nu(t+1,x,\mathbf{s}-\mathbf{e}_i)] \le R_i \quad i\in\{1,2,\dots,S\}\ , \quad t\in T \tag{4.15}$$

Lemma 7. $\nu(t,x,\mathbf{s})$ *is convex in* x $\forall t \in [0,H]$.

Proof. In order to show this lemma we follow an induction approach similar to lemma 1. Thus, at time $t = H$ the result holds. We assume that the $\nu(t,x,\mathbf{s})$ is convex at time t and inductively establish the result for time $t-1$. if time $t_j < t-1 < t_{j+1}$ then the proof is similar to lemma 1. Therefore we assume that $t-1 \in T$. $\Delta_x\nu(t,x,\mathbf{s}) =$

$\nu(t, x, \mathbf{s}) - \nu(t, x-1, \mathbf{s})$ similar to the previous definition. Using (4.10) we assume that an arbitrary index j is the minimizer, therefore we have

$$\Delta_x \nu(t, x, \mathbf{s}) = (1 - \sum_{i=1}^{j} \lambda_i(t)) \left\{ h + \alpha \Delta_x \nu(t+1, x, \mathbf{s} - \sum_{h=j+1}^{\phi(\mathbf{s})} \mathbf{e}_h) \right\}$$
$$+ \sum_{i=1}^{j} \lambda_i(t) \begin{cases} h + \alpha \Delta_x \nu(t+1, x, \mathbf{s} - \sum_{h=j+1}^{\phi(\mathbf{s})} \mathbf{e}_h) & x < r_i(t) \\ h + \alpha \Delta_x \nu(t+1, x-1, \mathbf{s} - \sum_{h=j+1}^{\phi(\mathbf{s})} \mathbf{e}_h) & x \geq r_i(t) \end{cases}$$

which establishes the convexity property at time $t-1$. □

Having established that the value function is convex in x, together with conditions (4.14) and (4.15) we can show that a set of time dependent rationing and contract extension thresholds characterize the optimal policy as stated in the following theorem.

Theorem 4. *The optimal end-of-life inventory control policy when customers are differentiated based on service contracts is characterized by time-varying thresholds as follows:*

i. *There exists threshold levels $r_1(t), r_2(t), \ldots, r_S(t)$ such that if $x \geq r_s(t)$ an incoming demand of class s is satisfied and rejected otherwise.*

ii. *There exists threshold levels $e_1(t), e_2(t), \ldots, e_S(t)$ such that if $x \geq e_s(t)$ a contract of type s is extended and expired otherwise at time $t \in T$.*

iii. *At each time t we have $0 = r_1(t) \leq r_2(t) \leq \cdots \leq r_S(t)$*

iv. *At each time $t \in T$ we have $0 = e_1(t) \leq e_2(t) \leq \cdots \leq e_S(t)$*

v. *$r_s(t)$ is non-increasing in t, $s \in \{1, 2, \ldots, S\}$*

vi. *$e_s(t)$ is non-increasing in t, $s \in \{1, 2, \ldots, S\}$*

Proof. The proof is similar to the proof of theorem 2. □

In this setting, the optimal policy can be characterized by a set of rationing and a set of contract extension thresholds. The contract extension thresholds are shown in Figure 4.4 for an instance of the problem. It is assumed that at every 50 periods the system has to revisit the decision of contract extensions. If at time t the serviceable inventory is above the blue contour and $\mathbf{s} = (1, 1, 1)$ then the contracts of type 2 and 3 are extended and if

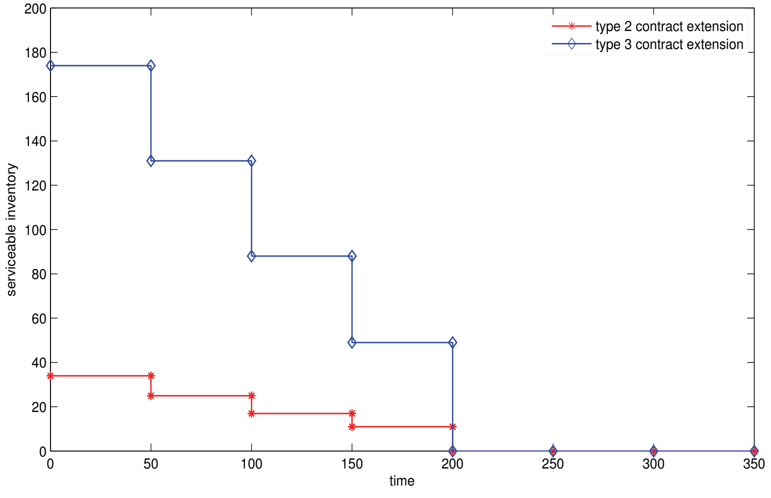

Figure 4.4: contract extension thresholds for a system with three classes of customers

the level of serviceable inventory is below the blue threshold then the contracts os type 3 should not be extended any more and $\mathbf{s}$ becomes $(1, 1, 0)$. The red contour represents the contract extension threshold for contracts of type 2. If at any time t serviceable inventory on-hand falls below this contour then the system does not offer contract renewal to both types 2 and 3. We observe that when it becomes closer to the end of the horizon, the system decides to stop extending contracts if the level of serviceable inventory is very low. In other words, the contract extension thresholds are non-increasing in time.

Moreover, the rationing thresholds are used to decide whether to service or decline a customer of type s when the corresponding service contract is still active. These rationing thresholds are also dependent on the remaining time to the end of the horizon and the level of serviceable inventory and show similar behavior as in the previous model.

4.4.1 Numerical Analysis

The cost parameters are considered similar to the customer differentiation based on equipment criticality. Every 50 periods the system should decide which contracts to renew. The revenues associated with the extension of different service contracts are $R_1 = 150$, $R_2 = 100$ and $R_3 = 50$. In order to study the value of having a contract extension decision included in the model we consider a similar system but without contract extension decision in which service contracts are always extended. If we denote the expected total cost of the optimal policy by C_{opt} and that of the policy without contract extension decision with C_{nce} then the value of having a contract extension decision in the model can be calculated according to

$$\Delta\% = \frac{C_{nce} - C_{opt}}{C_{opt}} \times 100$$

As we observe in Figure 4.6, with the increase of the holding cost rate the value of contract extension decision increases significantly. It is because, when the items are more expensive to hold the system decides to keep less items available in stock and resorts to not extending less profitable contracts when inventory level diminishes. Therefore, having a contract extension decision is more valuable for higher values of holding cost rate. Moreover, having a contract extension decision leads to setting a lower final order quantity inherently and together with rationing can be considered as tools to tame the risk of obsolescence. In Figure 4.6 we also observe a jump down in the final order quantity diagram . This point represents the value of holding cost rates in which the system decides not to extend some contracts at the beginning of the final phase. Therefore, there is a step down in the size of the final order quantity.

In order to study the effect of R_i and c_i on the value of service contract extension decision, we define a coefficient k. Then all R_i and c_i are multiplied by k and the results are shown in Figures 4.6 and 4.7. Figure 4.6 shows that with the increase of R_i the contract extension decision loses its value due to the fact that the system tends to extend all contracts. As a result, the system places a larger final order quantity in order to assure sufficient serviceable items available during the course of the final phase. As intuition dictates, the final order quantity does not show any sensitivity to the service contract revenues where the system always extends the service contracts.

Figure 4.7 shows the value of having a contract extension decision with respect to different values of lost sale cost. With the increase of the lost sale costs, the value of having a contract extension decision first intuitively increases and then starts to decrease slowly. The reason for the contracts extension decision losing its value is that the shortage cost becomes so expensive that the system decides not to extend low priority contracts very early in the final phase. As a result, less contract extension decisions are made during the course of the final phase and therefore, the value of contract extension decision

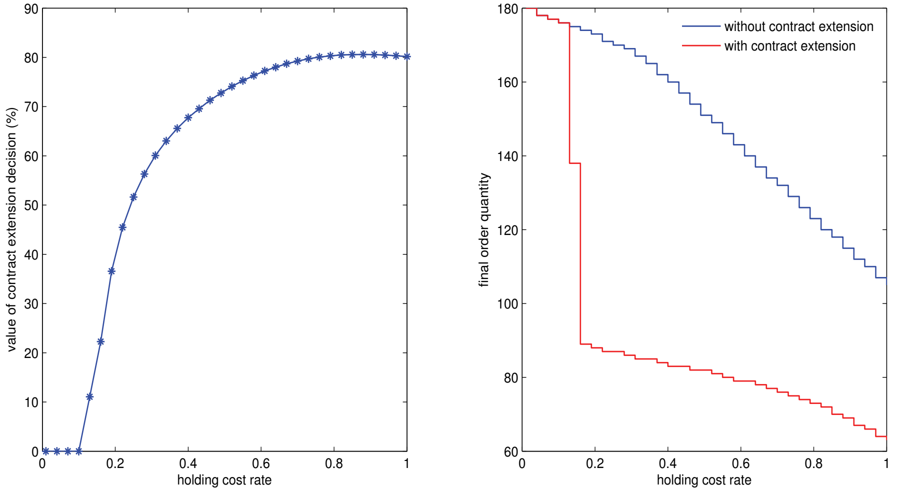

Figure 4.5: value of contract extension decision and its effect on final order quantity

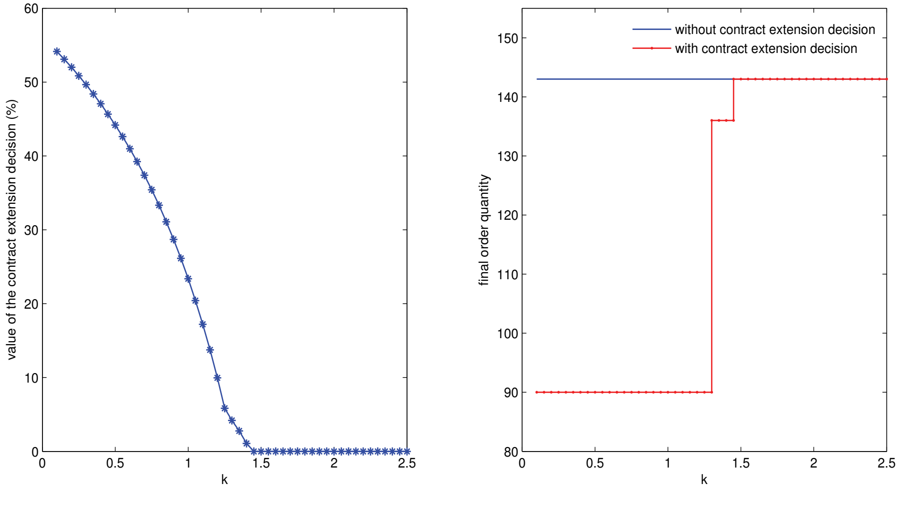

Figure 4.6: value of contract extension decision w.r.t. to R_i

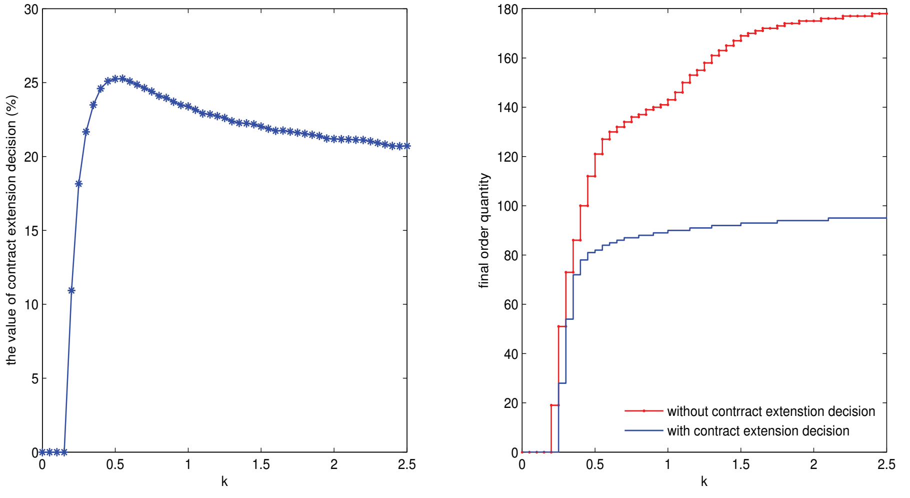

Figure 4.7: value of contract extension decision w.r.t. to c_i

diminishes slowly with the increase of shortage costs. Moreover, as we expect with the increase of the lost sale cost the system places a higher final order quantity to avoid the shortage risk.

4.4.2 Service Contracts for Multiple Parts

In practice, service contracts might apply to a certain equipment. For example, OEM agrees a certain uptime for a machine or is obliged to meet a specific availability for a specific machine service parts. In such a situation, the system manager needs to deal with a multiple part problem. Accordingly, while deciding upon extension of a specific contract we need to take into account the level of serviceable inventory on-hand for all parts. In other words, the system might resort to terminate a low priority contract because of low inventory level of some parts even though the on-hand stock of some other service parts abounds. We assume that the equipment considered has M different parts each one cost h_m, $m \in \{1, 2, \ldots, M\}$ to hold per unit per time. λ_i^m denotes the demand intensity function of service contract of type i for part m. The state of the system is denoted by a m-dimensional vector, $\mathbf{x}$ where the m-th element represent the inventory level of m-th part. The rest of the notations is similar to the previous model. In this setting the

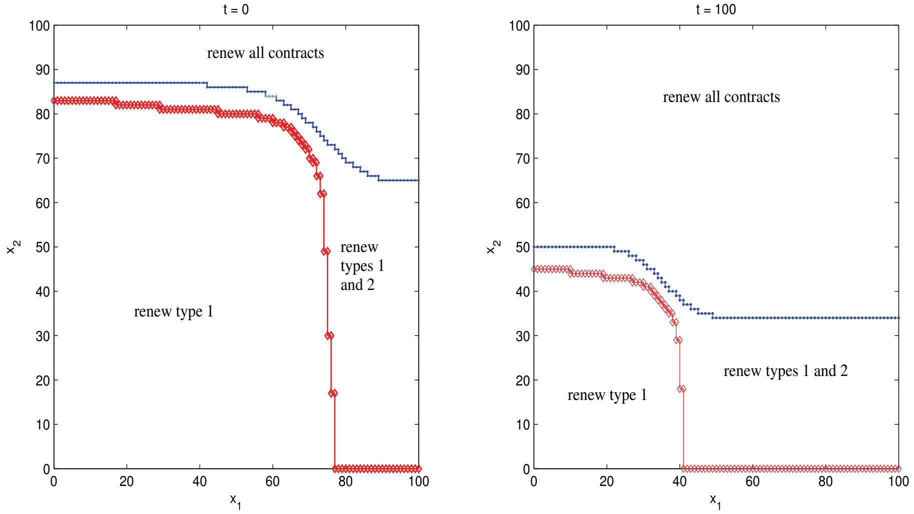

Figure 4.8: instances of contract extension thresholds

optimality equation is denoted by $\nu(t, \mathbf{x}, \mathbf{s})$ and is expressed according to (4.16), which can be obtained following the same logic as the previous case.

$$\begin{aligned}
&\nu(t, \mathbf{x}, \mathbf{s}) = \\
&\min_{1 \le j \le \phi(\mathbf{s})} \Big\{ (1 - \textstyle\sum_{m=1}^{M} \sum_{i=1}^{j} \lambda_i^m(t)) \Big\{ \sum_{m=1}^{M} h_m x_m - \sum_{k=1}^{j} R_k + \alpha \nu(t+1, \mathbf{x}, \mathbf{s} - \sum_{h=j+1}^{\phi(\mathbf{s})} \mathbf{e}_h) \Big\} \\
&+ \textstyle\sum_{m=1}^{M} \sum_{i=1}^{j} \Big\{ \lambda_i^m(t) \Big\{ h_m(x_m - 1) - \sum_{k=1}^{j} R_k \\
&+ \min \Big\{ \alpha \nu(t+1, \mathbf{x}, \mathbf{s} - \textstyle\sum_{h_m=j+1}^{\phi(\mathbf{s})} \mathbf{e}_h) + c_i + h_m, \alpha \nu(t+1, \mathbf{x} - \mathbf{e}_m, \mathbf{s} - \sum_{h=j+1}^{\phi(\mathbf{s})} \mathbf{e}_h) \Big\} \Big\} \mathbf{1}_{\{x_m > 0\}} \\
&+ \Big\{ - \textstyle\sum_{k=1}^{j} R_k + \alpha \nu(t+1, \mathbf{x}, \mathbf{s} - \sum_{h_m=j+1}^{\phi(\mathbf{s})} \mathbf{e}_h) + c_i + h_m \Big\} \mathbf{1}_{\{x_m = 0\}} \Big\}
\end{aligned} \tag{4.16}$$

In this case it can be shown that at each time t the inventory should be controlled according to threshold levels $r_i^m(t)$ and $e_i(t)$, as rationing and contract extension thresholds, respectively. $r_i^m(t)$ and $e_i(t)$ are defined similar to relations (13) and (14).

Figure 4.8 shows an instance of contract extension thresholds at times 0 and 100. As it is observed at each time the state space is divided into three regions. When the inventory levels of both parts are low the optimal decision is just to extend the highest priority contract type. In rather higher inventory levels the second highest priority contract is also renewed. In higher inventory levels all types of contracts are offered an extension. Furthermore, when it becomes closer to the end of the horizon, these contract extension hresholds are set lower. In other words, it is observed that contract extension thresholds are non-increasing in x_1 and x_2.

4.5 Conclusion

In this chapter we study the end-of-life inventory problem while customers are differentiated. Nowadays, technology development happens with a fast pace that leads to shorter product life cycle. As a result, parts and products enter their final phase earlier and system managers need to make a final order decision to mitigate the risk of obsolescence at the end of this phase. Customers differentiation has become a common practice in order to fulfill customer demands more efficiently. With the shortened product life cycle we expect a prominent share of service obligations be met while the production of parts is discontinued. Therefore, considering customer differentiation in the final phase can be of vital importance. We consider customer differentiation for both demand-criticality and service contracts-based differentiation. We show that inventory should be optimally controlled according to threshold levels that consider both remaining time to the end of the horizon and the level of serviceable inventory. We show that considering these decisions in the final phase inventory management leads to remarkable cost improvements as well as obsolescence risk mitigation.

Chapter 5

The Floating Stock Policy in Fast Moving Consumer Goods Supply Chains*

5.1 Introduction

Fast delivery is used in many retail supply chains. The advantages are enjoyed mainly by the retailers as they can operate in a just-in-time mode: they need fewer inventories on-site which reduces operational costs (both holding and storage costs) and investment costs (through less amount of warehouse space required). When they call orders, they can rely on rapid fulfillment. This works well if the order lead times and production time allow the manufacturer to operate on a make-to-order basis. If this option is not available and substantial batches are made, the burden of keeping inventory is shifted from the retailer to the supplier. In this case, the supplier has to either store it close to the retailer or use fast transport in order to meet the required order lead time (Ochtman et al. 2004). This leads to many transport movements with few opportunities for loaded return trips. The considered distribution concept in this paper, intermodal floating stocks, supports just-in-time delivery with short order lead times for manufacturers who follow a make-to-stock strategy.

The floating stock concept exploits the opportunities intermodal transport offers to deploy inventories in the supply chain. The idea is that, by advanced deployment and carefully tuning demand with transport modes, we can reduce non-moving inventories,

*This chapter is based on Pourakbar, Sleptchenko and Dekker (2009).

shorten lead times and improve the order fill rate. Although the term floating stock is relatively new, the concept has been used for a long time. It is used when shippers send their containers in advance of demand from Asia to Europe or to the US and the final destination is determined only in the final port. Another example is North American lumber, where lumber producers would ship loads to north, central and eastern customers before demand had finalized (Sampson et al. 1985). The flatcars or boxcars were held at transit yards in the Mid-West until a customer order was received. This practice enabled western US producers to compete in the eastern markets against their southern competitors in terms of lead times. Yet, almost no literature is available on floating stocks, as the terminology is not yet standardized. The exceptions are Teulings and van der Vlist (2001) who do not deal with inventories and a companion paper by Ochtman et al. (2004) which applies a simulation approach for studying the floating stock concept, but does not propose a mathematical optimization model to deal with this policy.

To position our contribution in the literature, we further relate it to three streams, viz., intermodal studies, inventory management and outbound dispatch policies. Intermodal transport can be defined (ECMT 1993) as the movement of goods in one and the same loading unit or vehicle by successive modes of transport without handling of the goods themselves during transfers between modes, e.g. container transport via rail and road. The transfer points offer short- term storage to decouple the successive steps in the transport chain and they often feature a limited amount of free time for which no storage costs are charged. Nowadays, this transport method is strongly advocated by many European governments in order to reduce road congestion and pollution. However, intermodal transport is, on short distances more costly than road transport, since it requires more handling. Furthermore, its transit time is often longer than that of direct road transport and its reliability is not always high (Konings 1996). Transport studies, such as Bookbinder and Fox (1998) and Rutten (1995) typically make such comparisons between road transport and intermodal transport, but in these studies inventories are left out of consideration.

Inventory management is another important topic in supply chains (Chopra and Meindl 2004). The main emphasis here is on determining how much inventory should be kept at which stocking locations, while typically only one lead time (and hence transportation mode) is considered. A well-known result is that centralization or pooling can reduce inventories if demands are uncorrelated, at the expense of higher transportation costs and a longer response time. This has led to the creation of European Distribution Centers, from which goods are trucked to clients throughout Europe directly upon client's calls. Different transport modes are considered primarily in the case of emergency shipments to take care of stock-outs (Moinzadeh and Schmidt 1991, Moinzadeh and Nahmias 1988). Some studies also consider lateral transshipments in multi-echelon chains, but mostly just in case of stock-outs (Minner 2003 and Diks et al. 1996). Herer et al. (2002) is an exception, as it considers lateral transshipments to enhance postponement and hence leagility (i.e. a combination of lean and agility) in supply chains. There are a few studies that integrate transportation and inventory control (see for example Tyworth and Zeng (1998)), but they focus on the relation between either transport frequency or transit time reliability and inventory control. A negative effect of the floating stock concept is that few possibilities exist for pooling, as products are shipped already towards their destination. Evers (1996), (1997) and (1999) study risk pooling of demand and lead times in relation to transshipments. However, these studies do not consider transport costs. No studies seem to exist on integration of intermodal transport and inventory control, according to recent reviews on intermodal research, such as Bontekoning et al. (2004) and Macharis and Bontekoning (2004).

The ideas in this paper can also be related to outbound dispatch policies for integrated stock replenishment and transportation decisions. The logistics literature reports that two different types of such policies are popular in current practice. These are *time-based* and *quantity-based* dispatch policies. Under a time-based policy, each order is dispatched by a pre-specified shipment release date, even though the dispatch quantity does not necessarily realize transportation scale economies. On the other hand, under a quantity-based policy, the dispatch quantity assures transportation scale economies, but a specific dispatch time cannot be guaranteed. Considering the case of stochastic demand, it has been shown that the quantity-based policy has substantial saving over the time-based policy. An alternative to these two policies is a hybrid routine aimed at balancing the trade-off between the timely delivery advantages of time-based policies and the transportation cost savings associated with quantity-based policies. Under a hybrid policy, the objective is to consolidate an economical dispatch quantity, denoted by q_H. However, if this quantity does not accumulate within a reasonable time window, denoted by q_H, then a shipment of smaller size may be released. A dispatch decision is made either when the size of a consolidated load exceeds q_H, or when the time since the last dispatch exceeds T_H (Cetinkaya et al. 2006).

The main difference between the problem discussed in this paper and the previously discussed outbound dispatch logistics is that in those models demand is realized first and then a shipping is done by either time-based or quantity-based policies. But in the problem discussed in this paper, it is intended to ship before demand realization. It is worth nothing that when intermodal transport is used, the shipment time increases considerably and the order lead time will be usually exceeded if the order is shipped after it is received. Increasing the order lead time forms a great problem, especially in the retail industry in which even the short delays are not acceptable. To avoid this problem the shipment should be sent in advance, before the order is placed, and then in this case the system can be benefited from a fast delivery time to the customer and saving in factory holding costs.

In this study we consider a Fast Moving Consumer Goods supply chain and we will present mathematical models for a floating stock policy in that supply chain. These models address the question of how to schedule shipment of containers through intermodal channels. Next, we will compare the results of our models with other distribution strategies.

This paper is organized as follows. In section 2 the problem environment is explained, and based on that a quick review on possible distribution strategies for this problem is presented. This review is carried to enable comparison of the result of developed policies with the previously developed distribution strategies. Then in section 3 the floating stock policy is formulated and two different approaches to deal with this problem are developed. Section 4 focuses on the calculation of safety stock for the case of decentralized storage with centralized safety stock(DS/CSS) strategy. In section 5 some numerical results of applying the developed policies for a real world case are shown and the results are compared with possible distribution strategies introduced in section 2. Finally, section 6 concludes the paper.

5.2 Problem definition

In this paper we consider a Fast Moving Consumer Goods (FMCG) supply chain with two echelons (the manufacturer's warehouse and the intermodal terminals) and one type

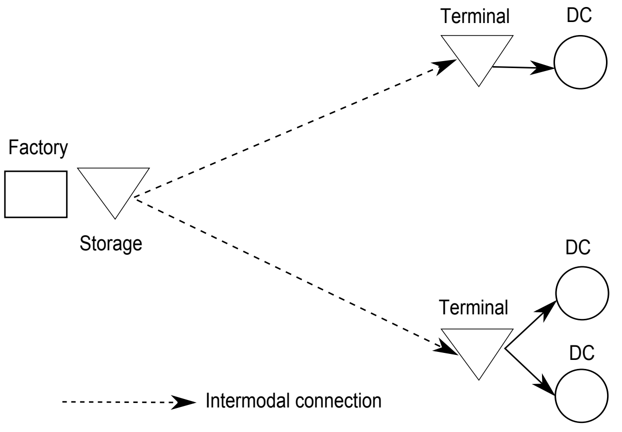

Figure 5.1: Conceptual representation of an FMCG supply chain with intermediary stocking points.

of product (or aggregated mix). The products can be stored in a storage location near the factory (which we call the factory storage) or can be transported to an intermodal terminal where they can wait before being sent to the final destination (see Figure 5.1). The advantage of factory storage is that it is cheaper than that of the intermodal terminal, but the traveling time from that terminal to customer is shorter than in case of factory storage.

Generally Fast Moving Consumer Goods (FMCG), also known as Consumer Packaged Goods (CPG), is a business term with different interpretations. The main characteristic of these products is having a high turnover and relatively low cost. Though the absolute profit margin made on FMCG products is relatively small, the large numbers in which they are sold can yield a substantial cumulative profit. Examples of FMCG include a wide range of frequently purchased consumer products, such as cosmetics, batteries, paper products and plastic goods. FMCG may also include pharmaceuticals, consumer electronics, packaged food products and drinks. What is essential in our analysis is that a batch production is applied and full containers are used for transportation. If turnover is low and product cost is high, then typically smaller shipments are sent. This is the reason we focus on FMCG.

We assume that in each production run a batch of containerized products is produced and they are packaged in the factory. Determining the set of products that are packed into one container is left out of consideration. Moreover, we assume that the finishing of the production batch can be adjusted to the shipment of the last container from the factory.

In practice, intermodal terminals are not meant for long-time storage, since they have been designed for transshipment, but they benefit from a short delivery time to customers. That is, delivering the whole production batch directly to the terminal will cause higher storage costs but will also guarantee very fast delivery to the customers and will lower backorder costs. In addition, once containers have arrived, it is common in practice that intermodal terminals offer a holding-cost-free period for each delivery (e.g. due to discounts given by the terminal authorities), this feature is included in the proposed model. Moreover, we assume that when a customer arrives while there is no container available in the terminal, the demand is backlogged and will be satisfied as soon as a container becomes available. In this case, the system endures shortage cost.

Total cost consists of transportation, shortage and storage costs. Transportation costs differ per transportation mode and contain all costs resulting from using a specific transportation mode. Therefore, transportation costs can cause differences in the total costs of each strategy, but these are independent of the inventory levels during a production cycle. The storage costs are the direct costs for storing a certain number of products for a certain period. These costs depend on the storage tariff at the specific point, the storage time, and volume of the products (or load units) stored. Shortage cost is stock- out cost, and is calculated based on the customer waiting time for a container to arrive.

The main question in this paper is how to schedule the shipments of products from the factory, such that the total cost is minimized. In the next section, all the possible strategies for this problem are briefly reviewed.

5.3 Distribution strategies

For an FMCG supply chain with the aforementioned characteristics, we consider four distribution strategies. These strategies are based on two decisions. First, if every container will be stored in a centralized or a decentralized location, and second, if road or intermodal is used for transportation.

Among these strategies, the first strategy is based on the just-in-time concept and applies direct road transport only. This is frequently used in FMCG-supply chains. The second strategy is completely based on distributed storage: all transports are intermodal.

This strategy is especially popular in supply chains where an intermodal connection has lower transport costs than a road connection. The third and fourth strategies aim at taking as much advantage of floating stock as possible. Below we will explain these strategies in detail.

Strategy CS: *Centralized storage and unimodal transport*: Using this just-in-time based strategy means that the whole production batch and a possible safety stock are stored on-site at the factory storage. When an order arrives, it is always fulfilled using road transport from the on-site inventory. In this strategy, the emphasis is on fast transportations and easy coordination.

Strategy DS: *Decentralized storage and intermodal transport*: The complete production batch is shipped to regional terminals using intermodal transport. The safety stock is also stored in these regional terminals. This batch cannot be used to fulfill orders until it has arrived at the regional terminal. Any order which comes in during this transit time is assumed to be backlogged. This increases storage time and costs. A demand prediction is used to determine the split of the production batch over the regional terminals. Orders are delivered by truck from these terminals to the DCs. The emphasis is on using intermodal transportation and short order lead times (because the order lead time from the terminal will be shorter than from the factory). If the safety stocks are depleted at a terminal, lateral transshipments from other terminals are made.

Strategy DS/CSS: *Decentralized storage, intermodal transport, and centralized safety stock*: In this case the safety stock is stored at the factory storage, whereas the production batch is shipped to the terminals using intermodal transport and stored there. The safety stock takes care of demands during shipment of the batch to the intermodal terminal. As soon as batches reach to terminals, regular deliveries to the retailers are fulfilled from the terminals. The emergency deliveries from factory are done by road, because the intermodal transit time is much longer.

The safety stock storage costs will probably be lower in the DS/CSS strategy when compared to the DS strategy. This is because long storage on-site is in general cheaper than long storage in an intermodal terminal. Furthermore, demand fill rate increases if the safety stock is stored in a central location.

Strategy FS: *Floating Stock with staged arrivals* : The Floating Stock strategy stores part of the production batch in the factory storage (centralized) and part of the production batch is stored in decentralized terminals. The shipment to the terminals is done by intermodal transport. Once the products have arrived at the terminal, they are shipped to the retailer from that point upon demand occurrence with a shorter order lead time. This strategy is designed to benefit from costs advantages of floating stock storage without having to increase the total inventory level in the supply chain. The FS strategy we consider here has staged arrivals, viz., for each container a shipment time is determined. This differs from the FS strategies in Ochtman et al. (2004) where the containers are sent together.

Note that if we assume that the batching decision is made beforehand and that the timing of the finishing of the batch coincides with the shipment of the last container, then the CS strategy needs no safety stock. For the DS/CSS strategy we still need to determine the amount of safety stock needed. This can be done with standard approaches such as marginal cost analysis and the approach will be described in section 4. For the Floating Stock strategy however, we need to determine when to ship each container, which is the problem this paper focuses on.

5.4 Formulation of the container shipping scheduling problem

The shipment process can be explained as follows: when the last container has been sent out of the factory storage, say at time t, a batch of size m is produced (the production time is neglected) and therefore we have m containers ready for shipment at the production facility. Customers demand containers according to a stochastic processe. Production planning is outside the scope of this paper, and thus we assume the value of m is given. To fulfill the demand, containers are shipped according to FS strategy from the manufacturer site to the terminal before demand actually occurs. It takes T_{fi} days to deliver from factory to the intermodal terminal and during these days and the initial period at the terminal, T_{nh}, no storage costs occur. If a customer requests his container after termination of the free-of-charge period, the system incurs storage cost h_i at the intermodal terminal per container per time unit. If, however, a customer requests his container before the end of the free-of-charge period, the container had spent long time at the factory and factory storage costs could be reduced by sending it earlier to the terminal. If a customer arrives while there is no container at the terminal, the demand would be backlogged until the container arrives. This shortage cost is denoted by c_b per container per time unit.

We assume an Erlang(k, λ) renewal process for demand, since the Erlang(k, λ) distribution can be interpreted as the batching of k exponentially distributed demands, which is simply treatable. Moreover, it is straightforward to calculate the convolution of the same Erlang random variables. Other processes may need more computational effort to calculate the convolution.

In the rest of this section, we present two approaches to deal with the FS strategy. The first one is a time-based policy, that tries to find the optimal shipping time, and the second one is a quantity-based policy that ships a new container whenever the total number of containers in the pipeline and terminal drops down to a certain level. It is worth noting that, without loss of generality, the supply network is decomposed into serial chains including an intermodal terminal and a warehouse, and each chain is treated independently.

5.4.1 Time-based policy

As we have already mentioned, we aim at the optimization of shipping moments, such that the average expected costs are minimized. As mentioned earlier, we assume a repetitive fixed batch of size m, the long-term average costs equal the expected costs per manufacturing batch. That is, for each batch we will optimize the shipment moments $r_1, r_2, \ldots, r_m$ of the containers in the batch such that the average cost per container is minimized:

$$\min_{r_1, r_2, \ldots, r_m \geq 0} C(r_1, r_2, \ldots, r_m) = \frac{\mathbb{E}\left[\text{batch cost}\,(r_1, r_2, \ldots, r_m)\right]}{\text{batch size}} \tag{5.1}$$

Let us construct now this cost function.

Cost function

The assumed cost structure incorporates factory and intermodal terminal storage and shortage costs. It is worth noting that during shipment of a container, the system does not endure a holding cost. To formulate the total cost, assume that *k-1* demands have been realized so far and A_k is the arrival time of the k^{th} container arriving to the intermodal and it is planned to satisfy the k^{th} demand (D_k). We assume a full backlogging scheme. Considering this situation, three possible circumstances are likely to happen

Case 1. $D_k \leq A_k$

In this case, demand occurs before the arrival of the container, i.e., the demand is backlogged and the customer has to wait for the container to arrive. Total cost in this case consists of backlogging costs for the length of delay and holding costs at the factory until the shipment moment.

Case 2. $A_k < D_k \leq A_k + T_{nh}$

Here, demand happens after arrival of the container and before the end of the intermodal terminal free of holding charge period. Therefore, no holding cost is incurred at the intermodal terminal, and total cost in this case includes only the holding costs at the factory until the shipment moment.

Case 3. $A_k + T_{nh} < D_k$

In this circumstance, the container arrives at the intermodal terminal, spends the entire free holding period at the terminal and then the demand is realized. This case leads to holding cost at the intermodal terminal plus the holding costs at the factory until the shipment moment. Due to deterministic transportation time, the arrival moments A_k can be immediately computed from the shipment moment r_k as $A_k = r_k + T_{fi}$.

Note now that, due to the backlogging assumption, each shipped container will be in fact "assigned" to a certain demand moment D_k. Therefore, optimizing the shipment moments $r_1, r_2, \ldots, r_m$ of the containers in a certain batch, we can ignore the demand moments that were "assigned" to other containers. This allows us to separate the function of the total expected cost of a batch and rewrite it as:

$$E\left[C\left(r_1,\, r_2,\, ...,\, r_m\right)\right] = \sum_{k=1}^{m} E\left[C_k\left(r_k\right)\right] \tag{5.2}$$

Taking into account the demand model, the cost functions $C_k\left(r_k\right)$ for each container will be computed as:

$$C_k\left(r_k\right) = \begin{cases} h_f r_k + c_b\left(r_k + T_{fi} - D_k\right), & \mathbb{P}\left\{D_k \leq r_k + T_{fi}\right\} \\ h_f r_k, & \mathbb{P}\left\{r_k + T_{fi} < D_k \leq r_k + T_{fi} + T_{nh}\right\} \\ h_f r_k + h_i\left(D_k - r_k - T_{fi} - T_{nh}\right), & \mathbb{P}\left\{D_k > r_k + T_{fi} + T_{nh}\right\} \end{cases} \tag{5.3}$$

Then, the expected cost for each container is the following:

$$\begin{aligned} \mathbb{E}[C_k(r_k)] = \quad & h_f r_k + c_b \int_0^{r_k+T_{fi}} \left(r_k + T_{fi} - D_k\right) f_{D_k}\left(\tau\right) d\tau \\ & + h_i \int_{r_k+T_{fi}+T_{nh}}^{\infty} \left(D_k - r_k - T_{fi} - T_{nh}\right) f_{D_k}\left(\tau\right) d\tau \end{aligned} \tag{5.4}$$

Since total cost function is separable, to minimize the total expected cost of the batch, we need to minimize the expected cost of each container$\mathbb{E}[C_k(r_k)]$. In this case the following lemma is valid.

Lemma 8. *Given a continuous distribution of the demand time D_k, optimal shipment moments r_k, that minimize the expected cost for each container $\mathbb{E}[C_k(r_k)]$ either solve equation:*

$$\mathbb{P}\{D_k \leq r_k + T_{fi}\} + \frac{h_i}{(c_b + h_i)}\mathbb{P}\{r_k + T_{fi} \leq D_k \leq r_k + T_{fi} + T_{nh}\} = \frac{h_i - h_f}{c_b + h_i} \tag{5.5}$$

or should be set equal to the production moment, when there is no optimal r_k after the production moment.

Proof. Assuming continuous distribution of the demand D_k, the expected cost function is continuous in r_k. Therefore, we can find the optimal shipment moment r_k by analyzing the first derivative of the cost function:

$$\begin{aligned}
\partial\mathbb{E}[C_k(r_k)]/\partial r_k &= h_f + c_b\mathbb{P}\{D_k \leq r_k + T_{fi}\} - h_i\mathbb{P}\{D_k \geq r_k + T_{fi} + T_{nh}\} \\
&= h_f + c_b\mathbb{P}\{D_k \leq r_k + T_{fi}\} - h_i\left(1 - \mathbb{P}\{D_k \leq r_k + T_{fi} + T_{nh})\right\} \\
&= h_f - h_i + (c_b + h_i)\,\mathbb{P}\{D_k \leq r_k + T_{fi}\} \\
&\quad + h_i\mathbb{P}\{r_k + T_{fi} \leq D_k \leq r_k + T_{fi} + T_{nh}\}
\end{aligned} \tag{5.6}$$

From this expression it is easy to see that the first derivative is always greater than or equal to *0* in cases with $h_i \leq h_f$:

$$\begin{aligned}
&h_f + c_b\mathbb{P}\{D_k \leq r_k + T_{fi}\} - h_i\mathbb{P}\{D_k \geq r_k + T_{fi} + T_{nh}\} \\
&\qquad \geq\ h_f - h_i\mathbb{P}\{D_k \geq r_k + T_{fi} + T_{nh}\}\ \geq h_f - h_i \geq 0
\end{aligned} \tag{5.7}$$

That is, the cost function $\mathbb{E}[C_k(r_k)]$ is continuously increasing in r_k. Then, in order to minimize the costs, we have to set r_k as low as possible. In other words, we get a very natural conclusion that in the case with the holding cost at the factory higher than the holding cost at the terminal, it will be cheaper to send everything to the terminal as soon as it is produced. To find optimal shipping time r_k for the other case ($h_i > h_f$), we apply the standard method of optimization of convex functions and set the first derivative of the cost function $\frac{dE[C(r_k)]}{dr_k}$ to *0*, i.e. we have to solve the following equation:

$$h_f + c_b\mathbb{P}\{D_k \leq r_k + T_{fi}) - h_i\mathbb{P}(D_k \geq r_k + T_{fi} + T_{nh}\} = 0 \tag{5.8}$$

It is easy to see that the first derivative is continuous non-decreasing function, since the second derivative

$$\partial^2\mathbb{E}[C_k(r_k)]/\partial r_k^2 = c_b\mathbb{P}\{D_k = r_k + T_{fi}\} + h_i\mathbb{P}\{D_k = r_k + T_{fi} + T_{nh}\} \geq 0 \tag{5.9}$$

is always greater than or equal to 0.

This means that the solution of the equation (5.5) minimizes the expected cost for each container $\mathbb{E}[C_k(r_k)]$ if r_k is unbounded. However, in real life situations it is not possible to ship an order that is not produced yet. Therefore, optimal shipment moments, r_k, that minimize the expected cost for each container $\mathbb{E}[C_k(r_k)]$ either solve equations $\partial\mathbb{E}[C(r_k)]/\partial r_k = 0$ or should be set equal to the production moment (in cases when there is no optimal r_k after the production moment).

Note here, that for certain probability distributions, there is a possibility of multiple solutions for the equation $\partial\mathbb{E}[C(r_k)]/\partial r_k = 0$. However, since the first derivative is non-decreasing, all solutions of $\partial\mathbb{E}[C(r_k)]/\partial r_k = 0$ will belong to one compact set and all of them will in fact produce the same value of $\mathbb{E}[C(r_k)]$. The optimal solution can be easily found by a bisection search or an enumeration method. □

5.4.2 Quantity- based policy

To deal with this approach, we make one extra assumption that the demand moments D_k are modeled as $D_k = D_{k-1} + \eta_k$, where D_{k-1} is the arrival moment of previous demand and η_k is stochastic demand inter-arrival time. As the second proposed policy, we will look for a shipment schedule defined by the system state. Namely, the schedule in which the shipment moments are defined by the total number of containers in the delivery "pipeline" and intermodal terminal, i.e., shipped but not picked-up yet by customers.

The cost function in this case can be defined similarly to the cost function (5.2) in the previous section. However, estimation and minimization of the expectation of the total cost for each container C_k requires different approach. First of all, we assume here that the container k will be shipped after the number of containers in the "pipeline" dropes from S_k to S_{k-1}. where S_k is the optimal total number of containers in the pipeline and intermodal terminal before realization of demand k. Since backorders are allowed, customers $k - S_k + 1, \ldots, k - 1$ will pick up their containers from the terminal before the customer k's arrival. That is, we know exactly that $S_k - 1$ customers will come to the

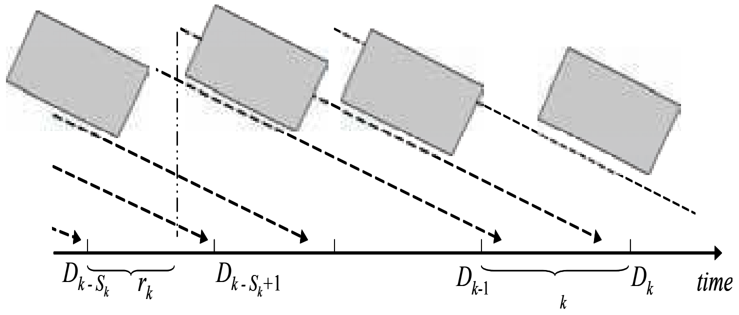

Figure 5.2: Arrivals of the customers (moments Dt) and of the containers to the terminal.

terminal before customer D_k. Then, the time from the moment of the system changes from S_k to $S_k - 1$ until the moment of arrival of customer k will be distributed as $\sum_{i=0}^{S_k-1} \eta_{k-i}$.

Taking into account these assumptions about shipment policy, the total cost for container k can be defined as:

$$C(r_k, S_k) =$$

$$\begin{cases} h_f r_k + c_b \left(r_k + T_{fi} - \sum_{i=0}^{S_k-1} \eta_{k-i} \right), & \mathbb{P}\left\{ \sum_{i=0}^{S_k-1} \eta_{k-i} \le r_k + T_{fi} \right\} \\ h_f r_k, & \mathbb{P}\left\{ r_k + T_{fi} < \sum_{i=0}^{S_k-1} \eta_{k-i} \le r_k + T_{fi} + T_{nh} \right\} \\ h_f r_k + h_i \left(\sum_{i=0}^{S_k-1} \eta_{k-i} - r_k - T_{fi} - T_{nh} \right), & \mathbb{P}\left\{ \sum_{i=0}^{S_k-1} \eta_{k-i} > r_k + T_{fi} + T_{nh} \right\} \end{cases} \tag{5.10}$$

where r_k has a different definition from that in the time-based policy. It is defined as the time from the moment that the number of containers in the system changes from S_k to $S_k - 1$ (momentD_{k-S_k}) until the container is shipped to customer k (see Figure 5.2).

The expectation of the total cost for container k is shown in expression (5.10) and minimization of the system cost is done by the parameters S_k and r_k.

$$\begin{aligned} \mathbb{E}\left[C_k(r_k, S_k)\right] = \; & h_f r_k + c_b \int_0^{r_k+T_{fi}} (r_k + T_{fi} - \tau) f_{\sum_{i=0}^{S_{k-1}} \eta_{k-i}}(\tau)\, d\tau \\ & + h_i \int_{r_k+T_{fi}+T_{nh}}^{\infty} (\tau - r_k - T_{fi} - T_{nh}) f_{\sum_{i=0}^{S_{k-1}} \eta_{k-i}}(\tau)\, d\tau \end{aligned} \tag{5.11}$$

Lemma 9. *Given a continuous distribution of the inter-demand times η_k, optimal shipment moments $r_k(S_k)$, that minimize the expected cost for each container $\mathbb{E}[C_k(r_k, S_k)]$ either* *solve equation:*

$$\begin{array}{l}\mathbb{P}\left\{\sum_{i=0}^{S_k-1}\eta_{k-i}\leq r_k+T_{fi}-d_k\right\}\\+\frac{h_i}{(c_b+h_i)}\mathbb{P}\left\{r_k+T_{fi}-d_k\leq\sum_{i=0}^{S_k-1}\eta_{k-i}\leq r_k+T_{fi}+T_{nh}-d_k\right\}=\frac{h_i-h_f}{c_b+h_i}\end{array}\tag{5.12}$$

or equal to 0.

Proof. Proof of this lemma is similar to the proof of lemma 8. □

This lemma, however, requires knowing convolutions of the inter-demand times $\sum_{i=0}^{S_k-1}\eta_{k-i}$, which are not trivial in many cases. Still, for some distributions (such as normal or exponential), this convolutions are relatively easy. Let us find now optimal S_k and r_k for an Erlang demand process with identically distributed inter-demand times.

Erlang distributed inter-demand times

Let us assume that the inter-demand times are Erlang-distributed, i.i.d random variables with parameters λ and k, say $\eta_k\sim$ Erlang(k,λ). Since the inter-demand times are identically distributed, it is easy to conclude that for each arrival D_k the optimal parameters S_{kt} and r_{kt} will be identical. The convolutions $\sum_{i=0}^{S-1}\eta_i$ used in expression (5.11) will be then distributed according to Erlang(kS, λ) distribution. This means that we can write expression (5.11) as:

$$\mathbb{E}\left[C\left(r,S\right)\right]\;=\;h_f r+c_b\int_0^{r+T_{fi}}\left(r+T_{fi}-\tau\right)\frac{\lambda(\lambda\tau)^{kS-1}}{(kS-1)!}e^{-\lambda\tau}d\tau\tag{5.13}$$

Further integration gives us the following close-form expression:

$$\begin{aligned}\mathbb{E}\left[C\left(r,S\right)\right]\;=\;& h_f r+c_b\left(r+T_{fi}\right)\left(1-e^{-\lambda\left(r+T_{fi}\right)}\sum_{n=0}^{kS-1}\frac{\left(\lambda\left(r+T_{fi}\right)\right)^n}{n!}\right)\\&-c_b\frac{kS}{\lambda}\left(1-e^{-\lambda\left(r+T_{fi}\right)}\sum_{n=0}^{kS}\frac{\left(\lambda\left(r+T_{fi}\right)\right)^n}{n!}\right)\\&-h_i\left(r+T_{nh}+T_{nh}\right)e^{-\lambda\left(r+T_{fi}+T_{fi}\right)}\sum_{n=0}^{kS-1}\frac{\left(\lambda\left(r+T_{fi}+T_{nh}\right)\right)^n}{n!}\\&+h_i\frac{kS}{\lambda}e^{-\lambda\left(r+T_{fi}+T_{fi}\right)}\sum_{n=0}^{kS}\frac{\left(\lambda\left(r+T_{fi}+T_{fi}\right)\right)^n}{n!}\end{aligned}\tag{5.14}$$

It is easy to see that for a fixed number S, the optimal time $r(S)$ has to satisfy the following equation:

$$\begin{aligned}
\frac{\partial E[C(r,S)]}{\partial r} &= h_f + c_b \int_0^{r+T_{fi}} \frac{\lambda(\lambda\tau)^{kS-1}}{(kS-1)!} e^{-\lambda\tau} d\tau - h_i \int_{r+T_{fi}+T_{nh}}^{\infty} \frac{\lambda(\lambda\tau)^{kS-1}}{(kS-1)!} e^{-\lambda\tau} d\tau \\
&= h_f - h_i + c_b \left(1 - e^{-\lambda\left(r+T_{fi}\right)} \sum_{n=0}^{kS-1} \frac{\left(\lambda\left(r+T_{fi}\right)\right)^n}{n!}\right) \\
&\quad + h_i \left(1 - e^{-\lambda\left(r+T_{fi}+T_{fi}\right)} \sum_{n=0}^{kS-1} \frac{\left(\lambda\left(r+T_{fi}+T_{nh}\right)\right)^{n-1}}{n!}\right) = 0
\end{aligned} \tag{5.15}$$

Simplifying the last equation, we obtain an equation for the time, $r(S)$, that is quite similar to the equation in the previous section:

$$\begin{aligned}
&\left(1 - e^{-\lambda\left(r+T_{fi}\right)} \sum_{n=0}^{kS-1} \frac{\left(\lambda\left(r+T_{fi}\right)\right)^n}{n!}\right) \\
&+ \frac{h_i}{(c_b+h_i)} e^{-\lambda\left(r+T_{fi}\right)} \left(e^{-\lambda T_{nh}} \sum_{n=0}^{kS-1} \frac{\left(\lambda\left(r+T_{fi}+T_{nh}\right)\right)^n}{n!} - \sum_{n=0}^{kS-1} \frac{\left(\lambda\left(r+T_{fi}\right)\right)^n}{n!}\right) = \frac{h_i - h_f}{c_b+h_i}
\end{aligned} \tag{5.16}$$

and the optimal time $r(S)$ is either equal to 0 or solves this equation. Although, the function $\mathbb{E}\left[C\left(r\left(S\right), S\right)\right]$ and equation $\frac{\partial \mathbb{E}[C(r,S)]}{\partial r} = 0$ are not too complex for numerical computation, analytical derivation of the optimality conditions for S is not trivial. It is also not clear whether the function $\mathbb{E}\left[C\left(r\left(S\right), S\right)\right]$ is convex. On the other hand, S is a one-dimensional discrete variable and in the most of real- life situations it can not be extremely high (e.g., it can be limited by the number of available containers). Therefore, in many situations, optimization of S by enumeration will be still easy.

5.4.3 Calculation of safety stock for DS/CSS strategy

In DS/CSS strategy, safety stock is held at the factory and takes care of demand while the batch is being shipped to the intermodal terminal. The number of containers held as the safety stock is calculated based on a marginal cost analysis. We define $C(ss)$ as the cost of stocking ss containers in factory and dispatching the rest of production batch to intermodal terminals. If this value is increased by one unit, then extra holding cost should be paid at the factory, while it reduces the risk of shortage during shipment and decreases the holding cost at intermodal terminal since less containers are shipped to that terminal. Thus,

$$\begin{aligned} &C(ss+1) - C(ss) = \\ &\quad h_f \mathbb{E}(\tfrac{D_{ss+1}-D_{ss)}}{2}) - c_b \mathbb{E}(T_{fi} - D_{ss+1})^+ - h_i \mathbb{E}(D_{m-(ss+1)} - T_{fi} - T_{nh})^+ \geq 0 \\ &C(ss) - C(ss-1) = \\ &\quad h_f \mathbb{E}(\tfrac{D_{ss}-D_{ss-1}}{2}) - c_b \mathbb{E}(T_{fi} - D_{ss})^+ - h_i \mathbb{E}(D_{m-ss} - T_{fi} + T_{nh})^+ \leq 0 \end{aligned} \tag{5.17}$$

5.5 Numerical Results (Case Study)

Below we present a real case which has been made together with the logistic service provider Vos Logistics in the Netherlands to illustrate our model. Vos Logistics is primarily a European trucking company, but provides intermodal transport as well. It faced more and more urgent transports with few opportunities for loaded return trips. Motivated by increasing road taxes, like the LKW-MAUT[†] in Germany, she was considering expanding her intermodal capabilities. The case is also described in Ochtman et al. (2004), but has been slightly adapted to allow the application of our models. The case is as follows: An FMCG-manufacturer runs a factory in Poznan (Poland) and distributes its products to two retail DCs in Germany, viz., one serving Dortmund and Koln and the other one covering demands from Rosselsheim (near Frankfurt), and Appenweier (near Strassbourg). At this moment, all orders are transported FTL by truck. The load unit is a 40 ft. container. An alternative intermodal route is a rail connection from a station in Gadki (15 km from Poznan) to two train terminals in Duisburg and Mannheim. The conceptual network representation for this case is depicted in Figure 5.3.

The transit time for all two direct truck routes is two days, including handling time for in- and outbound in the on-site DC. The intermodal connection makes use of the rail connection. Due to the long time needed for shunting, the transit time of the train transport to both terminals is 4 days. The shipping time from an intermodal terminal to a customer is one day via road transport. If a stock-out happens in one of the terminal, then the customer has to wait until the container arrives to the terminal. The components which are used to estimate the costs are linear per FTL container delivery and are detailed in Table 5.1. It is worth noting that direct truck transport is slightly cheaper than

[†]Germany‘s LKW-MAUT, implemented in January 2005, is a toll for goods vehicles based on the distance driven, the number of axles, weight and emission category of the vehicle.

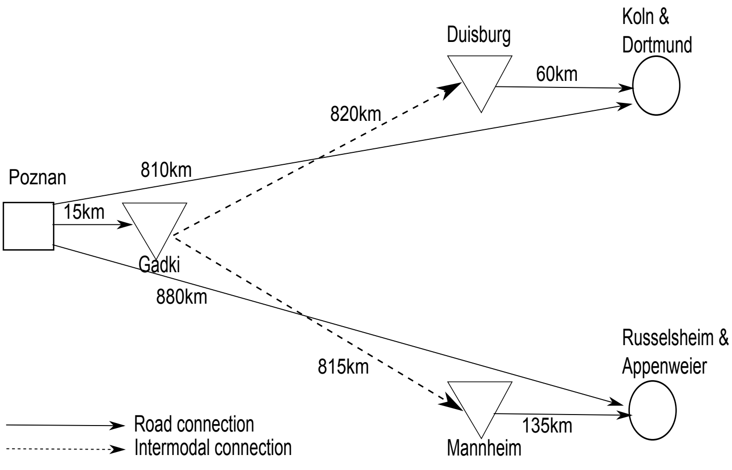

Figure 5.3: Conceptual network representation of the case.

intermodal transport. The model presented in section 3 is now applied separately for each intermodal terminal.

5.5.1 Simulation results

In order to be able to compare the developed policies with the other distribution strategies we implemented a simulation program using MATLAB 7.0. In this simulation the following criteria are considered: the expected total costs and the order fill rate. The order fill rate is the percentage of orders that can be fulfilled in less than two days. This two- day period is the direct shipping time from factory to the customer. In calculating total cost the fixed transportation cost component has been excluded, since it has no effect on the optimal value. Therefore we have no cost for direct transport and 20 units per container for intermodal transport. Assuming that the size of the production batch is 80 containers and demand at each terminal is exponentially distributed with rate $\lambda = 1.5$ per day, we reach the results shown in Table 5.2. Floating stock policies outperform the other strategies in total cost. Comparing the fill rates shows that the CS strategy and time based policies have the highest fill rate. The fill rate of the CS strategy is always 100% since in case of direct shipment all containers are delivered to customers in less than two days and moreover we assume a zero production lead time. The DS strategy has the lowest fill rate, since for the first four days, all demands that happen during this period have to wait

Table 5.1: Cost Components

Components:	Costs (Euro per container):
Storage and Holding	
Centralized holding cost at factory storage h_f	8 / day
Decentralized holding cost in terminal (first 3 days are free) h_i	18 / day
Backlogging cost at intermodal c_b	20 / day
Transportation	
For the direct road connection from factory to DC	880
For the intermodal connection from factory to DC	900

Table 5.2: Performance criterion for all policies

	CS	DS	CS/DSS	*FloatingStock*	
				Time based	Quantity based
Total Cost	79054.2	81958.9	82551.5	59337	73025
Fill Rate (%)	100	84	98	99.7	87

for the whole production batch to arrive at intermodal terminal. Extra analysis showed that if we exclude the constant transportation cost from total cost, more than 95% of the total cost is due to storage at factory and intermodal terminal, 3% is transportation cost and just 2% of the total cost results from backlogging. In Table 5.3, the optimal shipping times that results from the time-based policy are shown (rounded off to an integer number of days). It shows, for each day, how many containers should be shipped from factory to the each intermodal terminal. Since the arrival rates are assumed to be identical, number of containers that should be shipped to each terminal in each day is identical as well.

Sensitivity analysis

In this section, some sensitivity analysis is done on cost parameters. It is done for a case in which demand follows an Erlang distribution process. The cost parameters are changed and the results of different policies are shown in Tables 5.4 and 5.5. As it is obvious in Table 5.5, the floating stock and particularly the time based policy outperforms the other

Table 5.3: Optimal shipping time of containers to each terminal

Shipping Day	0	1	2	3	4	5	6	7	8	9	10	11	12
Number of containers	*4*	*4*	*3*	*4*	*3*	*3*	*4*	*3*	*2*	*2*	*2*	*3*	*3*

Table 5.4: Performance criterion for all policies $\lambda_D = 0.11$ and $\lambda_M = 0.13$ and $k = 3$

h_i	h_f	c_b	Performance	CS	DS	DS/CSS	*FloatingStock*			
							Time based	Quantity based	S_D	S_M
16	8	20	Total Cost	178720	278580	279350	240210	183040	1	1
			Fill Rate(%)	100	99.9	100	94.5	73.4		
24	8	20	Total Cost	178540	384190	382450	294490	190160	1	1
			Fill Rate(%)	100	99.9	100	96.6	70.8		
8	8	20	Total Cost	178120	176020	175600	185510	172210	1	1
			Fill Rate(%)	100	99.1	100	96.7	93.4		
16	2	20	Total Cost	97483	280800	278830	196410	139110	1	1
			Fill Rate(%)	100	99.1	100	90.1	85.0		
16	14	20	Total Cost	259010	280100	278770	281950	256380	1	1
			Fill Rate(%)	100	99.9	100	95.6	99.5		
16	8	50	Total Cost	178170	278430	279500	241560	179680	1	1
			Fill Rate(%)	100	99.1	100	95.7	95.7		
16	8	18	Total Cost	178580	279140	278850	239310	185420	1	1
			Fill Rate(%)	100	99.9	100	99.3	82.6		

strategies in minimizing total cost. But, as it is shown in Table 5.4, the floating stock strategy is not the best one when we are dealing with slow moving items. We did further analysis on the basic problem with cost parameters shown in Table 5.1 to find out under which arrival rates it is feasible to use floating stock. Since the time-based approach outperforms other ones for both criteria, we excluded the quantity- based policy in Figure 5.4. The results are depicted in Figure 5.4 and it is obvious that for a total arrival rate of more than 0.6 per day, it is profitable to implement a floating stock policy. The results in Table 5.4 and 5 are based on doing 100 independent simulation runs. 95%-Confidence intervals for the cost figures are some 300 to 500 cost units in size, which means that almost all differences between policies are significant.

5.6 Discussion and Conclusion

Floating stock is a concept where a new production batch is (partly) pushed into the supply chain, without determining the exact destination for each product beforehand. Using this concept may lead to lower storage costs and a shorter order lead time, without ruining demand fill rate. This is possible if the production batch is split up into some parts and being shipped to intermodal terminal in advance of demand realization at the right time. The contribution of this chapter to the literature is developing math-

Table 5.5: Performance criterion for all policies λ_{Duis}=2.5, λ_{Mann}

h_i	h_f	c_b	Performance	CS	DS	DS/CSS	*FloatingStock*			
							Time based	Quantity based	S_D	S_M
16	8	20	Total Cost	22130	37597	29767	12453	19781	3	2
			Fill Rate(%)	100	95.6	100	92.5	84.8		
24	8	20	Total Cost	22090	55773	40057	14698	19484	3	2
			Fill Rate(%)	100	96	100	92.3	86.5		
8	8	20	Total Cost	22250	19684	20326	14563	18847	3	2
			Fill Rate(%)	100	96	100	100	81.2		
16	2	20	Total Cost	5543.7	37511	22637	5202	5484	3	2
			Fill Rate(%)	100	96	100	90.8	79.2		
16	14	20	Total Cost	38933	37550	36966	14133	25345	3	2
			Fill Rate(%)	100	96	100	99.4	80.3		
16	8	50	Total Cost	22210	37958	29614	10242	18334	3	2
			Fill Rate(%)	100	96.1	100	98.9	81.7		
16	8	18	Total Cost	22140	37647	29855	11481	19758	3	2
			Fill Rate(%)	100	95.9	100	96.6	81.4		

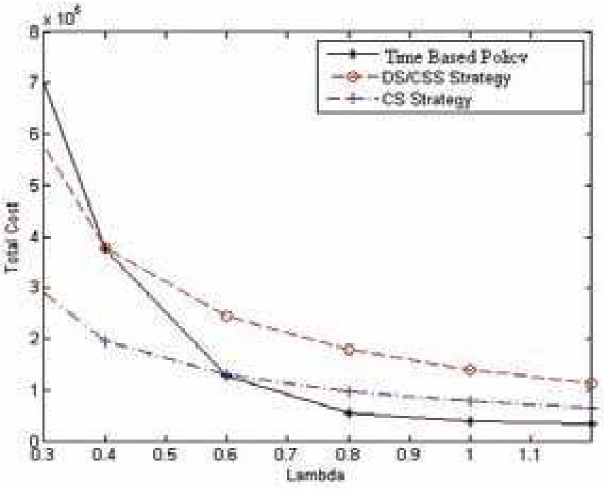

Figure 5.4: Total cost of different policies vs. λ

ematical approaches for floating stock strategy to determine the optimal shipping time of containers through intermodal route and showing that this strategy has advantages over other possible strategies. In the developed policies, the production batch is split up into some parts. In the time-based policy the shipping moments are optimized whereas in the quantity-based policy the optimal total number of containers in the pipeline and intermodal terminal is determined. The simulation results show that the floating stock strategy offers the best opportunity to benefit from low storage costs without affecting fill rate level. The popular just-in-time strategy often uses centralized storage and road transport. The computational results also show that the floating stock strategy can reduce costs and lead times, in spite of possibly higher transportation costs of an intermodal connection. The main conclusion that can be drawn is that when an intermodal transport is used even though it can be slower and more expensive, if we integrate it with inventory control then the results show that it leads to cost saving without affecting the service level. Therefore, when considering a move from factory to DC, storage and holding costs as well as transportation costs should be taken into account.

Chapter 6

Summary and Conclusion

In this study we focus on inventory decisions of a service part when it enters the final phase of service life cycle. The final phase starts as soon as the production of part stops and lasts till the last service or warranty obligation expires. The prime feature of this phase, differentiating it from other phases in service parts life cycle, is that further replenishment of parts is not guaranteed any more. This drives firms to plan parts acquisition before entering this phase. Firms can employ various measures to sustain customers demand satisfaction in this phase. One of the most popular tactics in practice, which is also the main focus of this study, is placing a final order at the beginning of this phase. The main issue, while placing the final order is that it should suffice for the entire final phase period but at the same time limit the risk of obsolescence at the end of this phase. Considering the risk of obsolescence is of vital importance since all parts left at the end of this phase are usually considered obsolete. With the advancement in technology and innovation parts enter the final phase earlier. For instance in case of consumer electronics, parts enter their final phase typically one year after production kick-off whereas service obligations run for three to five years after termination of production.

Even though this phase is known to be the longest in the life cycle of service parts, it has been ill researched. This study aims at addressing various aspects of service parts inventory management in the final phase.

In chapter 2, we study end-of-life inventory decisions of consumer electronics service parts. One of the main distinguishing features of consumer electronics products is their remarkable price erosion over time. The price of a a CE goods may typically erode 30% annually. This happens while the repair associated costs may stay steady over time.

This introduces the idea that there might be a break-even point in time from which on the price of a product is cheaper than the repair associated costs. Thus, having an alternative service policy such as swapping the defective product with a new one or offering a discount on the next generation of the product might be beneficial. Having considered this framework, the main contributions of this chapter can be listed as follows:

- We introduce the idea of adopting an alternative service policy for consumer electronics in the final phase of the service life cycle. A closed-form expression for the total expected cost function is derived.
- Various policies are developed aiming at capturing different planning aspects in the final phase. These include the possibility of disposing excessive parts and also dynamically updating the optimal inventory level or time to switch to the alternative policy.
- The numerical analysis verifies that such setting results in lowering cost and obsolescence risk in the final phase. Moreover, a policy with partially scrapping excessive parts outperforms all other policies.
- We also highlight the significance of considering a non-homogenous Poisson process to model demand behavior for service parts in the final phase. Our analysis shows that overlooking this aspect deteriorates the efficiency of a sound inventory system considerably.

Chapter 3 deals with the end of life inventory decisions for capital-intensive products when some products are returned to the OEM as phase-out items. Due to technology development, phase-out returns have become a common issue in many industries. Even though it might be considered as a planning burden we show that there is a huge opportunity in exploiting phase-out returns. In this setting, we assume the system faces three sources of parts acquisition namely final order quantity, repair of the defective items and phase-out returns. Phase-out returns can be considered as a source of parts cannibalization meaning that parts extracted from one phase-out item can be used to serve the demand of another customer for service. The main decisions in this problem are setting the optimal final order quantity and the timing of triggering a repair operation. Repairing an item while it is still not needed in the system adds extra carrying costs whereas late repair operations may lead to a poor service. Hence, balancing the two is important. Our contributions can be summarized as follows.

- We show that repair operation should be optimally controlled according to time and state-dependent threshold levels. The higher the level of serviceable inventory, the more reluctant the system is to repair items. Moreover, as it comes close to the end of the planning horizon, the system repairs less items.
- We highlight the value of phase-out information (i.e. schedule and quantity) and show that higher level of information results in more cost effective system. Moreover, planning the phase-out arrival, if possible, can lead to performance improvement.
- Our numerical analysis reveals that even though push and pull repair policies are known to perform well in the normal phase, their performance deteriorates as service part enter the final phase.

Chapter 4 deals with service obligations in the final phase. It is expected that service obligations are stretched to the final phase as parts production stops and parts enter the final phase. However, it becomes more critical to deal with service obligations in this phase since further replenishments of parts are not guaranteed in this phase. Therefore, it is absolutely crucial to consider service obligations while planning the final order quantity. To deal with this problem, in chapter 4, we consider the end-of-life inventory decision while the system faces an array of different customers. This customer differentiation may be due to different levels of demand criticality or various service contracts. The main decisions in such a setting are optimal final order quantity and the optimal action that should be taken facing each category of customers. Our contributions in this chapter can be summarized as follows:

- We show that in case of demand criticality based differentiation, the inventory should be optimally controlled according to time and state dependent rationing threshold levels.
- Moreover, in case of service contract based differentiation, other than rationing levels, we need to consider time and state dependent threshold levels for contract extension.

- Numerical analysis sheds light over the value of incorporating these decisions. They lead to a much more cost effective system while significantly reducing the risk of obsolescence at the end of the final phase.

Deviating from the final phase setting, chapter 5 proceeds by formulating a new concept called floating stock policy. The main idea is that by integrating both inventory and transportation systems and exploiting the advantages provided by intermodal transports we can make the system more cost efficient without any significant loss in order fill rates. Accordingly, by advanced deployment and carefully tuning demand with transport modes, we can reduce non-moving inventories, shorten lead times and improve the order fill rate. This strategy benefits from floating of stocks and the existence of intermodal terminals to postpone the selection of the destination so that a pooling effect can be obtained in comparison to direct road transport. The main contributions of this chapter are listed as follows

- We develop mathematical models for floating stock strategy to determine the optimal shipping time of containers through intermodal route and we investigate the advantages brought by floating stock policy as compared to other commonly used policies.

- In the developed policies, the production batch is split up into some parts. In the time-based policy the shipping moments are optimized whereas in the quantity-based policy the optimal total number of containers in the pipeline and intermodal terminal is determined.

- The numerical analysis shows that the floating stock strategy offers the best opportunity to benefit from low storage costs without negatively affecting the fill rate level.

As mentioned earlier, even though the end-of-life phase is known to be the longest phase in the service life cycle it has been understudied in the literature. Nowadays, rapid technology developments makes the end-of-life associated issues even more crucial. Thus, this provides some practically and theoretically relevant research opportunities.

In the three chapters related to the end-of-life inventory decisions, our models aim at optimizing final order quantities with respect to cost for one specific spare part. However, in practice the decision of placing final order quantities should be made for multiple parts used in one specific product, thus extending the problem to a multiple part setting seems a plausible twist to our formulation. In such a setting, as we point out in the end of chapter 4, perhaps characterizing the optimal policy structure requires coping with a multi-dimensional dynamic program and hence dealing with the curse of dimensionality. Therefore, developing easy to implement heuristic policies might be a suitable direction to proceed.

As it is observed in chapter 2, any misinterpretation of demand behavior may remarkably deteriorate the improvements of a sound and sophisticated inventory system. Thus a painstaking attention should be devoted to demand forecasting in the final phase. Switching from traditional black box forecasting methods to the more comprehensive and intelligent approaches such as installed base forecasting might be a valuable investment. The prime reason is that we expect sufficient data regarding the size of available installed base in the market, failure rate, discard rate, etc. become available before entering the final phase and thus an installed base forecasting approach can benefit from this information availability to the fullest.

There are several other operational decisions of interest that can be coupled with end-of-life inventory decisions. For instance simultaneously optimizing the final order quantity and the partial scrapping decision. In chapter 2, the partial scrapping decision is decoupled from the final order decision. However, using a finite horizon Markov decision process similar to chapters 3 and 4 might streamline modeling such a setting and accordingly we can gain more insights on the value of considering such decision in the model. Another aspect of interest might be coupling the final order decision with the next generation product development. In such a setting, the system should aim at optimizing the final order quantity together with the initial order quantity for the next generation product and the timing of the launch of the new product such that the operational costs and the risk of obsolescence are minimized.

Nederlandse Samenvatting (Summary in Dutch)

In deze studie concentreren we ons op voorraadbeslissingen aangaande een reserveonderdeel wanneer de laatste fase van de servicelevenscyclus ingaat. Deze laatste fase begint zodra de productie van het onderdeel stopt en duurt totdat de laatste service- of garantieverplichting afloopt. De belangrijkste eigenschap van deze fase, die haar onderscheidt van andere fases in de levenscyclus van reserveonderdelen, is dat de aanvulling van onderdelen niet langer gegarandeerd is. Dit motiveert bedrijven om de acquisitie van onderdelen te plannen vr deze fase begint. Bedrijven kunnen verschillende middelen inzetten om aan de klantvraag te blijven voldoen in deze fase. Een van de meest populaire strategieen in de praktijk is het plaatsen van een laatste bestelling aan het begin van deze fase. Op deze strategie zullen we ons in deze studie dan ook voornamelijk concentreren. Het belangrijkste probleem bij het plaatsen van een laatste bestelling is dat de te bestellen hoeveelheid moet worden bepaald zodat zij voldoende is voor de volledige periode en zodat zij de kans op obsolescence aan het einde van de fase minimaliseert.

In hoofdstuk 2 bestuderen we *end-of-life*-voorraadbeslissingen voor reserveonderdelen van consumentenelektronica. Een van de belangrijke onderscheidende eigenschappen van consumentenelektronica is hun aanzienlijke prijserosie over de jaren. De prijs van consumentenelektronica zakt in het algemeen met dertig procent per jaar, terwijl de kosten van reparatie stabiel blijven. Hieruit volgt het idee dat er wellicht een break-evenpoint in de tijd bestaat vanaf wanneer de prijs van het product lager is dan de reparatiekosten. Daarmee wordt het mogelijk voordelig om een alternatieve serviceoptie te hebben, zoals het verwisselen van defecte producten met nieuwe producten, of het aanbieden van een korting op de volgende generatie van het product. Dit in overweging nemende ontwikkelen we modellen waarin de mogelijkheid van een alternatieve serviceoptie is meegenomen. We laten zien hoe deze setting resulteert in kostenefficientie.

Hoofdstuk 3 behandelt *end-of-life*-voorraadbeslissingen voor kapitaalintensieve producten wanneer sommige producten teruggebracht worden naar de oorspronkelijke producent van het product, als zogenoemde phase-out items. In deze setting nemen we aan dat er drie bronnen voor onderdelen zijn: een laatste bestelling, reparatie van defecte items en teruggebrachte phase-out items. Teruggebrachte phase-out items kunnen worden beschouwd als een bron voor partskannibalisatie, wat betekent dat onderdelen onttrokken uit een phase-out item gebruikt kunnen worden om aan de vraag van een andere klant naar service te voldoen. De belangrijkste beslissingen in dit probleem zijn het bepalen van de optimale laatste bestelgrootte en de timing van reparaties. We laten zien dat de reparatieactiviteiten optimaal gestuurd zouden moeten worden door middel van tijds- en toestandsafhankelijke drempelwaardes. Bovendien benadrukken we de waarde van phase-out informatie (i.e. planning en hoeveelheid) en laten we zien dat meer informatie resulteert in een kosteneffectiever systeem. Hoofdstuk 4 behandelt serviceverplichtingen in de laatste fase. Om dit probleem aan te pakken beschouwen we de *end-of-life*-voorraadbeslissing wanneer het systeem geconfronteerd wordt met een aantal verschillende klanten. Het verschil tussen klanten kan bestaan uit verschillende niveaus van vraagimportantie of uit verschillende servicecontracten. De belangrijkste beslissingen in een dergelijke setting zijn de optimale laatste bestelhoeveelheid en de optimale wijze van omgaan met iedere klantcategorie. We laten zien dat in het geval van klanten die verschillen in vraagimportantie, de voorraad optimaal zou moeten worden gecontroleerd aan de hand van tijds- en toestandsafhankelijke rantsoeneringsniveaus. Wanneer klanten verschillen door verschillende servicecontracten, moeten we naast rantsoeneringsniveaus gebruik maken van tijds- en toestandsafhankelijke drempelwaardes voor contractverlenging.

In afwijking van de laatste-fase setting, gaat hoofdstuk 5 verder met het formuleren van een nieuw concept, namelijk pijplijnvoorraadstrategie. Het kernidee is dat we door het integreren van voorraad- en transportsystemen en door het benutten van de voordelen die intermodale transporten bieden, het systeem kostenefficienter kunnen maken zonder enig significant verlies van ordervervullingsgraad. Op die manier kunnen we met vraaganticiperende positionering en met het zorgvuldig afstemmen van vraag en transportmodaliteiten de nietbewegende voorraad reduceren, de levertijden verkorten en de ordervervullingsgraad verbeteren. Deze strategie put voordeel uit pijplijnvoorraad en het bestaan van intermodale terminals door de selectie van de bestemming uit te stellen, zodat een voordeel kan onstaan door het samenvoegen van vraag in vergelijking met direct transport over de weg. We ontwikkelen wiskundige modellen voor de pijplijnvoorraadstrategie om de optimale verschepingstijden van containers door de intermodale route te bepalen. We onderzoeken de voordelen die de pijplijnvoorraadstrategie brengt in vergelijking met andere vaak gebruikte strategieen. In de ontwikkelde strategieen wordt de productiebatch gesplitst. In de tijdsgebaseerde strategie worden de verschepingstijden geoptimaliseerd, terwijl in de hoeveelheidsgebaseerde strategie het optimale aantal containers in de pijplijn en de intermodale terminal bepaald worden.

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END-OF-LIFE INVENTORY DECISIONS OF SERVICE PARTS

With the spurt of technology and innovation the life cycles of products have become shorter and products enter their final phases more quickly than before. Consequently, service parts also enter their end-of-life phases earlier. Final phase of a typical service part starts as soon as the part production is ceased and ends when the last service or warranty contract expires. However, a firm obligation to satisfy demands for spare parts during service periods, which normally goes beyond the termination time of part production, drives inventory managers to plan for service parts acquisition before the start of the end-of-life phase. One popular tactic in practice is placing a final order. The prime challenge of a firm while deciding a final order quantity is to minimize inventory-carrying costs together with the risk of obsolescence at the end of the planning period.

In this study, end-of-life inventory decisions for an array of products including both consumer electronics and capital-intensive products are investigated. For consumer electronics we show that considering an alternative service policy, such as swapping the defective product with a new one, besides a regular repair policy improves cost efficiency.

Moreover, for capital-intensive products we study systems with phase-out returns and systems with customer differentiation in the end-of-life phase. Our analysis reveals that taming the uncertainty associated with phase-out arrivals engenders a remarkable efficiency improvement. Moreover, including rationing decisions in the end-of-life phase enhances the performance of the system by a significant reduction in cost and risk of obsolescence.

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