MUHAMMAD NAIMAN JALIL

Customer Information Driven After Sales Service Management

Lessons from Spare Parts Logistics

Customer Information Driven After Sales Service Management: Lessons from Spare Parts Logistics

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Chapter 1

Introduction

What are the benefits of using customer related information to drive after sales service management? In a very broad sense, this question summarizes the main focus of this thesis. After sales service is defined as customer support following the purchase of a product or service. It is usually formalized by a warranty or service agreement between the service provider and the customer. By providing after sales services, the company facilitates the customer's attainment of the initially perceived value of the product (during purchase).

A rapidly changing business environment, increased use of technology, higher market competition, and higher potential profits in after sales service has changed the way companies view after sales services. It is no longer treated as a cost center, but instead, has become a major profit source with profitability ranging up to 45% of corporate revenues for many business environments (McCluskey et al., 2002). This transition is parallel to the growth of service contracts or service level agreements in the after sales service business, where a company offers an array of service contracts with varying service guarantees to its geographically dispersed customer base.

In this thesis, we study after sales service management and highlight the benefits of utilizing customer information to drive the operations management of after sales service. We argue that utilizing detailed customer information to provide responsive and timely service to each customer according to their service agreement, is beneficial to the service provider as well as the customers. The recommended approach results in increased profitability for the company while also allowing the company to better match its available resources for after sales service to the varying service needs of the heterogeneous customer base. In the remainder of this chapter, we first discuss the business trends in after sales service. After highlighting the best business practices to support after sales service in such a business environment, we study information management trends in after sales service. Next, we discuss the scope and contributions of this thesis. We then discuss the research methods used in this thesis and conclude this chapter with an outline of the rest of thesis.

1.1 Business Trends in After Sales Service

The after sales service business has grown in volume becoming a major profit center within many business environments. Multiple studies reveal that after sales services are growing both in volume and revenue share. Aberdeen group estimated that after sales service business worths more than $1,500 billion US dollars worldwide (Vigoroso, 2003). In 2005, McKinsey reported that aftermarket part supply business is around $400 billion US dollars (Gallagher et al., 2005). In 2006, the SAS institute estimated that approximately 8% of the gross national product of the United States is tied up in aftermarket spare parts and repair services (SAS, 2006). Blumberg estimated that the compound annual growth rate of after sales services is 14.9% in the United States and 15.8% worldwide (Amini et al., 2005). The Forrester group forecasted that services would eventually overtake products as a base revenue source for manufacturers as early as 2012 (BearingPoint, 2004). AMR research estimated that service revenues account for 24% of corporate revenues and 45% of corporate profits (McCluskey et al., 2002; Cohen, 2005). A survey by BearingPoint revealed that 38% of the surveyed companies considered their after sales service business a profit center. A breakdown by industrial sectors revealed that capital equipment, automotive, and hi-tech sectors lead in this aspect by having almost 40% to 50% of the respondents considering after sales service as a profit center.

In terms of financial contribution to the service revenues, a break down of activities by the Aberdeen group indicates that the sale of service contracts contributes the most , i.e. 31%, both servicing of contracted equipment and servicing of un-contracted equipment contribute 22% each (Dutta and Long, 2008). In terms of the motivation for value addition via servicing, a survey of North American machine manufacturers by the

FiveTwelve Group Ltd. reveals that machine manufacturers focused on after sales service to defend their market share against low cost manufacturers and potential market contraction. On the other hand, Kilpi (2008) reports that many aircraft original equipment manufacturers (OEMs) sell their products cheaper in order to attain lucrative after sales service business from the airline industry.

A key driver in the profitability of after sales service is the realization of the total cost of ownership (TCO). Öner et al. (2007) highlight that for capital goods acquisition costs typically account for only 33% of the total costs (see Figure 1.1). For other systems, the figures may change but a similar trend can be observed. The buyers / users look explicitly at the TCO when they buy new systems. These systems are technologically complex, which means that their maintenance is also a complex task. It is not economically feasible for many users to perform the maintenance themselves, especially, if they own a few of these systems. On the other hand, the service providers attempt to address these limitations by selling a range of service contracts (with varying availability guarantees) to meet the needs of a heterogeneous customer base.

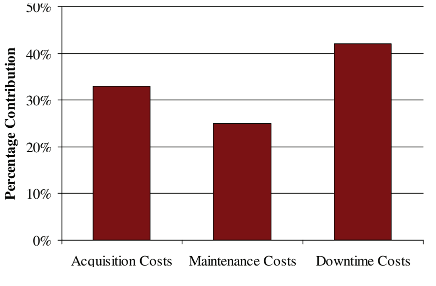

Figure 1.1: Total Cost of Ownership for Capital Goods - Source: Öner et al. (2007)

Whether the motivations for value addition via servicing are driven by profit, competition, or market contraction; academic researchers and practitioners agree on the business practices in after sales service to facilitate the value addition in servicing. These practices are highlighted in Table 1.1. Knowing the customer needs, segmenting the service offerings accordingly, and delivering the service according to the customer needs are considered the most important success factors in profit driven after sales service. Other important success factors are efficient use of technology, service performance measurement, and appropriate pricing schemes.

The aspects discussed in Table 1.1 expose a fundamental difference between the companies whose primary activities are limited to product sales and the companies who are actively involved in servicing their installed base. The companies that limit themselves to selling machines are often judged by how well and long the machine that they offer meets its functional purpose. Service focused companies are valuable to the customer when their activities enable the customer to achieve higher value from the available resources. Due to this, service focused companies need a precise and in-depth understanding of the customer's behaviors, attitudes, methods, processes, structures, and activities.

Table 1.1: Best Business Practices for After Sales Service

Source	**Business Practices**					
	Know the customer needs and deliver.	Segment service offerings.	Utilize technology efficiently.	Optimize for profits.	Get pricing right.	Measure the service.
Karofsky (2007)	✓	✓	✓	✓		
Cohen et al. (2006)	✓	✓	✓	✓		✓
Gallagher et al. (2005)	✓	✓		✓	✓	
Hayes (2005)	✓	✓	✓			✓
Oliva and Kallenberg (2003)	✓	✓	✓		✓	✓
Cohen (2009)	✓	✓	✓	✓		✓
Armistead and Clark (1991)	✓	✓			✓	
Cohen (2005)	✓	✓	✓	✓		✓
Auramo and Ala-Risku (2005)	✓	✓	✓			
Cohen et al. (2000)	✓	✓	✓	✓	✓	✓

Various researchers also highlight and caution that the business environment of after sales service is different from classical production or retail supply chains (Snitkin, 2004; Cohen, 2009; Cohen et al., 2006; Oliva and Kallenberg, 2003). Table 1.2 summarizes the differences between an after sales service business and a typical manufacturing supply chain. Slow moving or sporadic demand, rapid response requirements, a heterogeneous customer base, and slow inventory turnovers are commonly observed in after sales service. Simultaneously, the information management requirements to support after sales service operations are also different. In the next section, we discuss the information management trends to support operations management in after sales service.

Table 1.2: Characteristics Comparison - Source: Cohen et al. (2006)

PARAMETER	MANUFACTURING SUPPLY CHAIN	AFTER SALES SERVICE SUPPLY CHAIN
Nature of demand	Predictable, can be forecast	Always unpredictable, sporadic
Required response	Standard, can be scheduled	ASAP (same day or next day)
Number of SKUs	Limited	15 to 20 times more
Product portfolio	Largely homogeneous	Always heterogeneous
Delivery Network	Depends on nature of product; multiple networks necessary	Single network, capable of delivering different service products
Inventory management aim	Maximize the velocity of resources	Pre-position resources
Reverse Logistics	Doesn't handle	Handle returns, repair, and disposal of failed components
Performance metric	Fill rate	Product availability (uptime)
Inventory turns	Six to 50 a year	one to four a year

1.2 Information Management Trends in After Sales Service

The use of information in planning and execution in supply chain management is considered an enabler of better performance in supply chains. Jacobs et al. (2007) and Benton and Shin (1998) record the developments in the IT industry from MRP to MRP II and ERP systems and how these developments coincide with advances in supply chain management. Similarly in after sales service, Porter and Millar (1985), Slater (1996), and Wilson et al. (1999) highlight how the information can give a company the competitive advantage by enabling it to meet the customer expectations in a better way. In Figure 1.2, we depict a typical management information system to support spare parts logistics in after sales service. On the supply side, the service provider needs to collect and manage information to support supplier selection, management, and collaborative engineering. The service provider also uses significant information to support various planning tasks such as service network design, inventory replenishment, transportation and warehouse management, reverse logistics, and manpower resource planning for field and hub locations. On the delivery side, the tasks involve service planning and service execution.

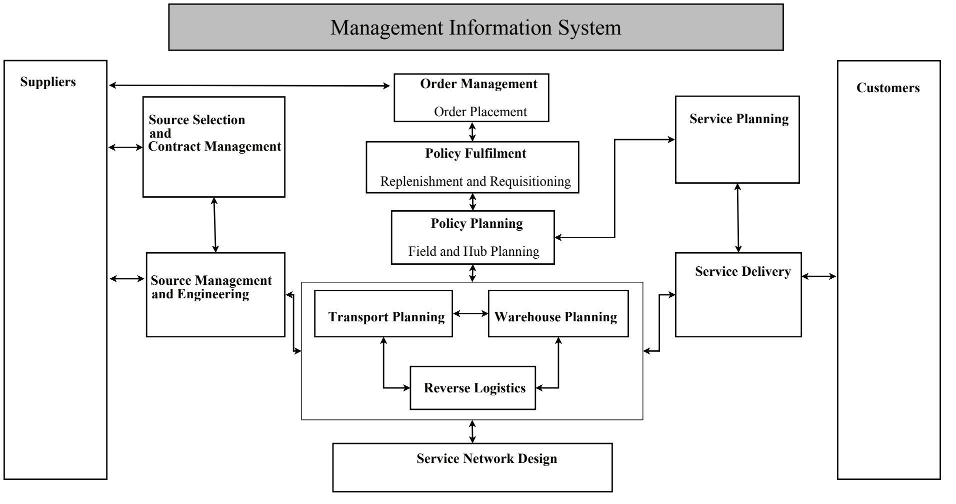

Figure 1.2: Management Information System for Spare Parts Logistics - Source: Draper and Suanet (2005)

In the literature, various researchers discuss the use of product, process and customer information to support various after sales service operations. Pinheiro et al. (2007) discuss the analysis of intelligent databases to observe failure trends in hard disks and improve maintenance services. Similarly, Lee et al. (2006) discuss the use of product life cycle information to transform the maintenance philosophy from *fail and fix* to *predict and prevent*. Blakeley et al. (2003) discuss the case of Schindler Corporation. The company developed a customized decision support system using real time data on field service engineers in combination with a geographical information system for tactical and operational decisions in service planning and delivery. Decisions such as field service engineer dispatching, routing and manpower planning are estimated by using the above information.

A comprehensive use of product, process and customer information in after sales service is highlighted by McFarlan and Stoddard (1986). Specifically, the authors discuss the case of the Otis Elevator Company, where the organization developed a decision support application called Otisline to support customer service. The initial focus of the application was to support production control, accounting, and inventory control. The company expanded the functionalities of the application so that it could support the entire after sales service execution in a coordinated manner. The application used product, process, and customer data for field service engineer dispatching, spare part shipments, inventory control, manpower planning, and after sales service marketing. The product, process, and customer data includes customer location data, contract data, network inventory data, field service engineering resources data, maintenance knowledge base, maintenance history data, and remotely collected machine's realtime operational data. From this discussion, one can argue that the customer information requirements are quite pertinent for the responsive and cost efficient delivery of service to the heterogeneous customer base in after sales service (Armistead and Clark, 1991).

In order to accommodate customer needs and to design customer focused after sales service, many companies actively maintain and utilize customer information in their after sales service operations (Oliva and Kallenberg, 2003; Auramo and Ala-Risku, 2005; Vigoroso, 2003; Cohen and Agrawal, 1999). In this respect, installed base data (IB), alternatively known as warranty management data, proves to be a valuable source of customer information. A survey by the Aberdeen group reveals that almost 57% of the best-in-class companies in after sales service utilize warranty management data for service planning and delivery (Gecker and Vigoroso, 2006). Another survey by BearingPoint (2004) reveals that almost 30% of the companies in the high-tech sector utilize installed base data to support spare parts inventory planning. IB data includes machine location data, contractual data, and machine type data. Together with request handling data, these data can also be used to identify the prior maintenance history of each install. In addition, IB data can also be used to derive transportation costs, penalty costs, and demand rates for each individual customer. In short, IB data can be used to address the challenging task of meeting strict customer service deadlines at minimum costs in after sales service.

In this thesis, we shall utilize the IB data as a source of customer information and incorporate this data in after sales service planning and execution. A practical obstacle that every company faces in gathering and using data is the issue of varying data quality (Wand and Wang, 1996; Korhonen et al., 1998; Fisher et al., 2000; Lee et al., 2002). IB data is no different. In this thesis, we also study the spare parts planning and execution methods for their robustness given the variations in IB data quality. In the next section, we discuss our research objectives in greater detail.

1.3 Scope, Research Contributions, and Research Methods

The execution of an after sales service job is a complex task requiring close interaction and coordination between different organizational functions or after sales service operations. These operations include maintenance service management, spare parts logistics management, service tool management, and reverse logistics management. Within each operation, a series of long term, mid term and short term decisions are made for effective functioning of the after sales service. The configuration of each of these operations is highly dependent on the service provider's after sales service strategy. In Chapter 2, we shall highlight these aspects in greater detail. Consistent with our earlier discussion, in this thesis, we focus on the after sales service operations that are designed with the strategic focus of executing the after sales service as a profit center.

1.3.1 Scope

One observes both business-to-business (B2B) and business-to-consumer (B2C) environments in after sales service. In a B2B environment, an OEM or service provider encounters its business customers who are using the product (e.g. capital good, or hi-tech product) as a part of a company's critical business infrastructure. After sales servicing of the consumer products is typically observed in a B2C environment. Armistead and Clark (1991) highlight the characteristics of servicing the B2B sector in terms of a stringent service response, complex service network, and on-site service delivery. For a B2C environment, such characteristics are not applicable, since the service requirements for consumer products are typically not as stringent as B2B market products.

In Section 1.1, we observed that the capital goods, hi-tech, and automotive sectors lead in profit driven after sales service management. In this thesis, we will focus on the service operations that match the after sales service strategy for such sectors. As we will learn from the discussion in Chapter 2, such service operations typically encounter on-site customer service, a mix of reactive and proactive maintenance policies, an array of service contract offerings, slow moving demand, and a geographically distributed customer base. Consistent with this observation, we shall focus on after sales service operations that match such characteristics.

As discussed earlier, after sales service management involves the interaction of various after sales service operations. To narrow the scope further, in this thesis, we focus on the spare parts logistics aspect of after sales service. Within spare parts logistics, we study the planning and execution stages of spare parts logistics; i.e. spare parts inventory planning, spare parts logistics execution and returns execution management. We study these logistics operations, since any attempt or intervention here directly effects the customer by impacting the after sales service execution (see Figure 2.2). Furthermore, we will mainly focus on a reactive type of maintenance policy, since it is the predominantly adopted maintenance policy for a short product life cycle and slow moving demand situation. Such characteristics can be commonly observed in the high-tech and capital goods sector. We should clarify that the results presented in this thesis are also applicable for the settings of condition based proactive maintenance.

1.3.2 Research Contributions

What are the benefits of using customer related information to drive after sales service management? From a theoretical perspective, this question relates to aspects of information acquisition, management, and usage to support value addition in after sales service. First of all, the question is how customer information should be utilized to induce value addition in after sales service management. One may argue that customer information may induce value addition via three mechanisms, i.e. by modifying the existing decision space, enabling a new decision space, or enabling more accurate decision making in the existing decision space. After identifying the potential mechanism for value addition, two factors are key for the realization of value addition. First, a supply chain analytic or optimization engine that can turn the raw data into useful information for decision making. Second, a quality data source that provides the appropriate level of detail.

In this thesis, we study both of these factors in a comprehensive manner. First, we study the existing analytics or optimization solutions from the after sales service management literature to observe their ability to account for the underlying business conditions in profit driven after sales service. In the absences of an appropriate solution available in literature, we attempt to devise such a solution for profit driven after sales service management. Secondly, we attempt to quantify the value addition enabled by using IB information to support after sales service management decisions. As mentioned in Section 1.2, none of the data sources in real life is perfect. Therefore, we also study the impact of varying IB data quality on the after sales service management decisions that are under-consideration. The contributions of our research are as follows:

1. We devise solution methods that enable us to meet the varying service needs of a heterogeneous customer base in after sales service. As mentioned in Section 1.3.1, we focus on spare parts logistics planning and execution. The provision of differentiated services to a heterogeneous customer base is conceptually similar to demand management or revenue management. The key idea in these subjects is to observe the demand of a segmented customer base and match the available resources to the segmented demand for service fulfillment. In this thesis, we follow similar ideas to devise solution methods for spare parts logistics.

2. We study the value of IB information for spare parts logistics by comparing the value addition induced by IB enriched decision making to the baseline situation. The baseline situation represents decision making without utilizing the IB data. We also study the potential impact of varying IB data quality. We should mention that the value of information is contextual and relies on the ability of the decision maker to use the information for potential gains. In this thesis, we assume the decision maker to be rational and we do not account for any behavioral aspects of the decision making situation.

These research contributions are the result of studying a variety of research problems. We shall discuss the details of the associated research problems in Sections 1.4 and 2.8. First, we discuss the research methods utilized in this thesis.

1.3.3 Research Methods

Many researchers have emphasized the importance of empirical input to enhance the practicality and relevance of supply chain management and operations management research. In line with the discussions by Boyer and Swink (2008); Fisher (2007); Meredith et al. (1989); Flynn et al. (1990); Bertrand and Fransoo (2002), the approach we take in this thesis is heavily influenced by the ground realities in spare parts logistics. We aim to combine practice and theory by using a two dimensional approach. We examine the after sales service academic literature simultaneously with the business trends in after sales service. We identify the gaps in academic and practice literature and emphasize that customer information driven after sales service management is better suited to fill these gaps. To enrich our understanding of the business environment of after sales service, we study after sales service management practices at IBM.

The business environment in which IBM provides after sales service is complex. IBM services its geographically dispersed customer base through a large scale service network with an intention to attain profits from its after sales service business. Its customer base is heterogeneous from service standpoint since IBM offers many service level agreements with varying but stringent service performance guarantees. Opportunities of consolidation, differentiation, and transshipment are present and often exploited. All these characteristics make IBM an inspiring case study to learn and understand the intricacies of operations management in after sales service. After sales service operations at IBM and more specifically IBM spare parts logistics is a also frequently cited case in academic literature as the state of the art in after sales service operations (Cohen et al., 1990; Hammond and Dutkiewicz, 1993; Cohen et al., 1997; Fleischmann et al., 2003; Tang, 2005; Draper and Suanet, 2005; Candas, 2007; Kutanoglu, 2008). A detailed study of the after sales services practice at IBM enriches our understanding of the business environment and emerging trends in after sales service. In addition, our study of the after sales service management system at IBM and our discussions with after sales service professionals at IBM allows us to better understand the issues emerging from the changing business environment of after sales service. Wherever possible, the dataset used in this thesis represents the real life product, customer and process data from IBM.

We should note that the results presented in this thesis are not limited to IBM situation for their application. Similar business conditions exists in other sectors, where companies view their after sales service operations as profit center and they need to provide quick service response to their geographically distributed heterogeneous customer base.

1.4 Organization of the Thesis

This thesis is organized as follows: In Chapter 2, we study after sales service in detail. We discuss the prevailing business conditions in the after sales service sector. Next, we discuss the execution of a typical after sales service function. We underscore the importance of close coordination and interaction among various after sales service operations to execute after sales service in a cost efficient and responsive manner. As mentioned earlier, these after sales service operations include maintenance service management, spare parts logistics management, and reverse logistics management. We further discuss the long term, mid term, and short term decisions within each of these operations and highlight the interrelation among these decisions. Finally, we discuss the after sales service management practice at IBM as an illustration of the state of the art in after sales service. We also note the limitations of the available academic and practice literature in after sales service to account for many of the underlying business conditions. We conclude Chapter 2 with a discussion of the research problems presented in the rest of the thesis.

In Chapter 3, we study the spare parts inventory planning system at IBM. In line with our research objectives, the focus here is to study the benefits of utilizing IB information to support spare parts inventory planning decisions. We perform a comparative study of an information enriched versus information aggregated case to establish the potential benefits of IB information enrichment in the spare parts inventory planning context. We further analyze the robustness of spare parts inventory planning analytics for common data quality errors in customer data. By studying the real life spare parts inventory planning situation at IBM, we establish the common business conditions that induce various types of data quality errors in IB data. We categorize the errors according to their structural and ontological characteristics. We further analyze the impact of these data quality errors on spare parts inventory planning and highlight the role of an error's structural and ontological characteristics. This chapter is based on the paper *Spare Parts Logistics and Installed Base Information* (Jalil et al., 2010b). We should note that this chapter is inspired by spare parts inventory planning situation at IBM. The data used for scenario analysis is real life spare parts inventory planning data from IBM. However, we should note that such inventory planning context (lateral transshipments and service levels) is not limited to IBM or computer industry. Therefore, the results presented in this chapter may also be applicable to other similar situation.

In Chapter 4, we study the spare parts logistics execution system at IBM. We observe the prevalence of first in - first out type of execution rules to support spare parts logistics execution in after sales service. We highlight the limitations of such decision rules to support varying service needs of a heterogeneous customer base. In this chapter, we first develop an advanced decision rule that uses the detailed customer information (i.e. installed base information) to support the execution management for spare parts. As mentioned earlier, we take inspiration from the subjects of demand management or revenue management for this problem. The idea is to match the available resources to the segmented customer demand. By performing a comparison with the existing execution rules at IBM (that do not use detailed customer information), we show the potential benefits of using detailed information for execution decisions in spare parts logistics. Similar to the previous chapter, the presented results are applicable to similar settings in other sectors also. This chapter is based on working paper *Revenue Management and Spare Parts Logistics Execution* (Jalil et al., 2010a).

In Chapter 5, we notice that the inaccuracies in spare parts demand information leads to return management issues in spare parts logistics. Again, we attempt to devise algorithms to support return management in the spare parts logistics context. We compare the information enriched methods with the existing methods, that do not use detailed information, and we show the potential improvements. By using the concepts from information enriched methods, we devise new heuristic solutions that do not use a similar level of data as information enriched methods, but perform similarly. We argue that it is the level of understanding provided by the information enriched methods that allows for such interventions. We should note that this chapter is not specifically based on IBM situation, although, the resulted in this chapter are also valid for IBM situation too.

Finally, we conclude with a reflection on the research contributions and lessons from this thesis in Chapter 6.

Chapter 2

After Sales Service

In this chapter, we highlight some of the typically observed business characteristics of after sales service. We identify various operational components that are needed to run an after sales service operation. Next, we review the academic and practice literature on the management of after sales service operations. We also discuss the impact of the business characteristics of after sales service on these operational components. Finally, we conclude this chapter with a discussion of after sales service practices at IBM as an illustrative case.

2.1 Business Context of After Sales Service

After sales service involves a continuous interaction between the service provider and the customer throughout the post-purchase product life cycle. At the time the product is sold to the customer, this interaction is formalized by a mutually agreed warranty or service contract. The exact terms of the warranty or service contract, the characteristics of the customer base, and the nature of the sold product influence the after sales service strategy of the service provider (Armistead and Clark, 1991; Cohen et al., 2006; Oliva and Kallenberg, 2003; Auramo and Ala-Risku, 2005). We should note that we restrict our discussion to the business characteristics that are relevant for the operations management aspect of profit driven after sales service.

2.1.1 Warranty - Service Contracts

Murthy and Blischke (2005) report that the earliest record of warranty dates back to the twenty-first century B.C. in the Babylonian and Assyrian tablets. Throughout history, the concept of product warranty can be found in Roman, Bavarian, Jewish, Hindu, Islamic and Egyptian trade laws. During the post-industrial revolution era, many legislations (such as the Uniform Sales Act (1914), Uniform Commercial Code (1952), and Magnuson-Moss Warranty-Federal Trade Commission Improvement Act (1975)) attempted to define the relationship between the consumer and the service provider for the product warranty. The service provider's and customer's rights and obligations for a given warranty contract have also evolved in these legislations. Simultaneously in academic literature, many theories attempt to explain the concept and role of the term "warranty". The Exploitative theory holds the view that the terms of a warranty contract are developed for the service provider's benefit. The Signal theory suggests that the product warranty provides an accurate signal of product reliability (Spence, 1977). More recently, the Investment theory suggests that the product warranty should be viewed both as an insurance policy and a repair contract. According to this theory, a consumer views a product warranty as an investment that reduces the risks of future opportunity losses due to machine failures (Priest, 1981).

The observation that a warranty contract is an insurance and repair contract has certain managerial consequences for the service provider. First, customers are interested in the continuous availability of the product. Due to this, two types of warranty policies are observed in practice: Replacement Policies, where a service provider agrees to repair or replace the failed items or parts of the product (usually free of charge); and Pro Rata Policies or Rebate Policies, where the service provider agrees to refund a specific amount if the product fails before a certain date after the purchase date (Blischke and Murthy, 1994). In after sales service, we generally encounter replacement type policies, therefore, throughout this thesis, the term warranty policy or service contract shall be used interchangeably for replacement policy.

Second, the price that a customer is willing to pay for a certain warranty contract reflects the financial opportunity that the continuous machine availability provides to the customer (related to high downtime costs, see Figure 1.1). Due to these reasons, service providers offer a range of warranty contracts for a single product, where the warranty contracts differ in terms of the service provider's responsibilities in the event of machine failure. The standard base warranty is integral to the sale of the product and is factored into the product price. In addition, service providers also offer extended warranties which are often referred to as service contracts. At the time of product sale, the extended warranties or service contracts are offered as an option to the customer at additional cost. The difference from the base warranty is that service contracts typically follow the TCO concept and attempt to deliver a certain availability level by charging a yearly service contract fee.

2.1.2 Customer Base Heterogeneity

A service provider typically encounters a heterogeneous customer base in the provision of after sales service. Heterogeneity in the customer base stems from many causes. In the next few sections, we discuss these causes in further detail.

Warranty - Service Contracts

As discussed in Section 2.1.1, service providers offer an array of service contracts for a single product. The price premiums for these contracts are distinct. The service requirements imposed on the service provider by these contracts are also different. 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 response and (or) repair time commitments; and 2) Price and (or) cost structures. Vigoroso (2003) surveyed the response time requirements of the service contracts offered by various companies. As depicted in Figure 2.1, the response time requirements vary significantly. In many mission critical situations, the service provider is always present on-site. The same day category includes response times ranging from 2 hours to 24 hours. It can be observed from Figure 2.1 that the same day category constitutes 43% of the total contracts offered. One may also observe variations in response time requirements by industrial sector or product type. Cohen et al. (2006) highlight that consumer products such as TVs and PCs have lower response time requirements. On the other hand, business computing machines (such as main frames), construction equipment, and aircraft typically have very high response time requirements. In addition to varying service response time requirements, the service prices also vary per contract. In many instances, the failure to meet the service deadlines may result in penalties to the service providers. Such terms are negotiated during the contract formalization.

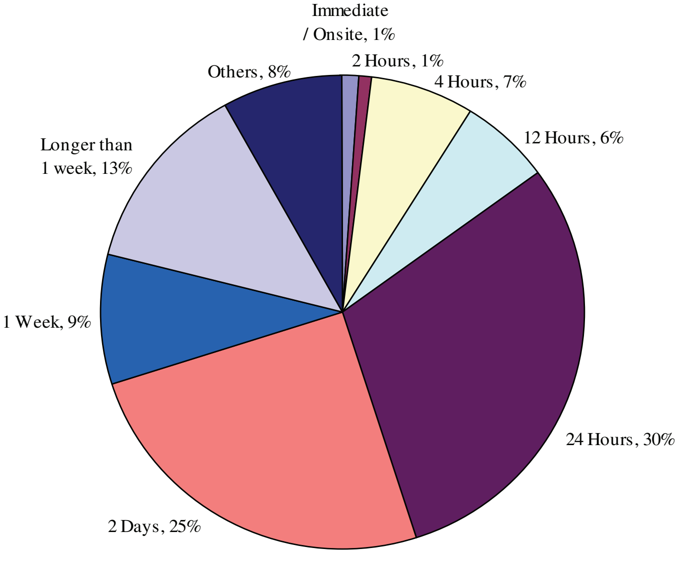

Figure 2.1: Response Time Requirements of Service Contracts (Source: Vigoroso (2003))

Geographical Distribution of Customers

More often than not, the customers are dispersed throughout a geographical region. If the warranty / service contract promises on-site maintenance services to the customer, then such dispersion results in distinct travel times and transportation costs for each customer. If the warranty or service contract induces quick response time requirements for after sales service, then the variation in transportation costs may be significant; since an expensive transportation mode is typically used for such maintenance service provision. For example, incoming demand with a 2 hour response time involves point to point transportation using an expensive transportation mode (such as a taxi). Cohen and Agrawal (1999) highlight that in practice, due to the variations in transportation costs, some companies differentiate among their customers based on geographical proximity. For example, Xerox guarantees the following service response times to its customers:

"Response times are determined by the distance of the customer's location from the nearest authorized Xerox service location (0 - 100 miles/0 - 161 km = next business day; 101 - 150 miles/162 - 241 km = second business day; 151+ miles/242+ km = third business day)" (Xerox, 2010a).

Spare Part Criticality

In many instances, a specific module or part is commonly used in many machine models. The criticality of the part / module in the overall machine's availability depends on many exogenous factors. For example, a redundancy may be built during the engineering design phase of a specific machine model by introducing two items in a parallel circuit. In another machine model, these items may be connected by a serial circuit, therefore resulting in less redundancy. In other words, the criticality of a specific demand request may stem from the engineering related features of a specific part and associated machine model. In the after sales service literature, the term process criticality is also encountered (Huiskonen, 2001). Process criticality relates to the consequence of the failure, i.e. downtime caused by the part failure in the specific machine (Kennedy et al., 2002; Huiskonen, 2001). Determining the exact costs of downtime is often difficult, however, several authors present various approaches to classify the consequence of failure. Gajpal et al. (1994) present an analytical hierarchy process (AHP) based approach to classify the criticality of a spare part demand. Huiskonen (2001) argues that the criticality of the failure should be time dependent. For example, the author highlights the following framework to classify the criticality of a failure. At the first level, the failure has to be corrected immediately. At the second level, the failure can be tolerated for a short period of time, during which the repair shall be preformed. Finally, at the third level, the failure is not critical and can be corrected over a longer period of time. The part's criticality for the overall machine's availability also introduces different response time requirements for each of these machine models.

2.1.3 Slow Moving or Sporadic Demand

Slow moving or sporadic demand patterns are often observed in spare parts logistics (Eaves and Kingsman, 2004; Snyder, 2002). Ever improving engineering technologies have contributed to products becoming more and more reliable. In some instances, the sporadic nature of demand is due to the fact that detailed historical demand data at each transaction level are simply not available. The slow moving or intermittent nature of demand presents additional challenges in after sales service, since the demand patterns are difficult to predict. Moreover, it alters the characteristics of inventory management in after sales service. For example, the primary decision in a high inventory turnover environment (such as retail) is to determine the appropriate number of items that can maximize the rate of inventory turns without stock-outs. In after sales service, where the inventory turnover rates are low, the objective of inventory management is to determine the optimum positioning of inventory units throughout the service network (Cohen et al., 2006). In addition, short product life cycles, and rapidly changing product technologies increase the risk of obsolescence of spare parts inventories in after sales service management. Cohen et al. (1997) report that obsolescence costs constitute upto 17.7% of the total operating costs in spare pats logistics.

2.1.4 Types of Maintenance Policies

When should maintenance be performed? Traditionally, two types of maintenance policies are discussed in the academic and practice literature: Reactive Maintenance Policies and Proactive Maintenance Policies. Reactive maintenance may be described as a fire-fighting approach to maintenance service. Equipment is allowed to run until failure. Then the failed equipment is repaired or replaced (Swanson, 2001). On the other hand, proactive maintenance is a strategy to perform maintenance actions before the actual failure occurs. Various classifications of proactive maintenance include usage based maintenance, condition based maintenance, and opportunity based maintenance (Stapelberg, 2009; Murthy and Blischke, 2005). One can argue that proactive maintenance policies are suitable for situations where the understanding of product reliability curves has matured via the gathering and analysis of extensive product life cycle data. Short life cycle products typically do not provide significant opportunities to gather and understand the life cycle data pertaining to product reliability. In such situations, one observes the prevalence of reactive maintenance policies (e.g. in the high-tech sector). In most practical situations, the practice is to utilize a combination of maintenance policies. For example, Xerox provides after sales support to its customers of copier machines by combining a reactive and condition based proactive maintenance policy. A usage based monitoring system is built into the machines. Types of maintenance requirements that are better understood from reliability aspects are performed on the basis of machine usage and condition. In addition to the usage/condition based maintenance, a reactive maintenance support system is also available to support the Xerox customer calls for the random failures (see details at Xerox (2010b)).

2.1.5 Methods of Service Provision

We now discuss the methods utilized in after sales service to support the customer request. In practice, the maintenance service is provided to the customer in three different manners.

1. Field replacement units.
2. Service provision at a designated service facility.
3. Service provision at the customer location.

The term field replacement units is used for instances in which the failed part can be easily replaced by the customer itself and the services of a service engineer (SE) are not required. Most of the failure instances are not so simple to repair. Therefore, the maintenance service is either provided at a designated service facility or at the customer location. For convenience, we term maintenance provision at the customer location as field maintenance service. To a certain extent, it is observed that capital goods are typically serviced at a customer location while consumer goods are serviced at a specified service facility (Armistead and Clark, 1991). As discussed in Section 2.1.1, capital goods are typically used as part of a customer's commercial infrastructure, therefore, the agreed service deadlines are more stringent than those for the commercial products. Moreover, due to their immovable nature, it is typically convenient and cost-effective to service the capital goods at the customer location. We should note that in some cases, the installed base is not fixed to any particular physical location. Examples of such situations are the airline or goods transportation sector, where the airplanes or trucks are continuously moving throughout their operational life cycle. In such cases, the service provider has to provide the maintenance at the current physical location of the airline or truck or at the nearest service facility. It should be noted that due to the limited scope of this thesis, such maintenance provision is not accounted for in the forthcoming chapters. However, some of the discussions in this thesis are still applicable in such settings.

2.2 After Sales Service Operations

To perform an after sales service operation, the primary requirements include a service engineer (SE), spare parts, and service tools. Formally, the management of these resources is termed as maintenance services management, spare parts logistics management, spare parts return management, and service tool management. In this chapter, we organize and discuss the management of these after sales service operations. First, we briefly describe a typical scheme for after sales service execution at the customer location as depicted in Figure 2.2. We should note that a similar execution scheme has been discussed by Cohen et al. (1997) and Candas (2007).

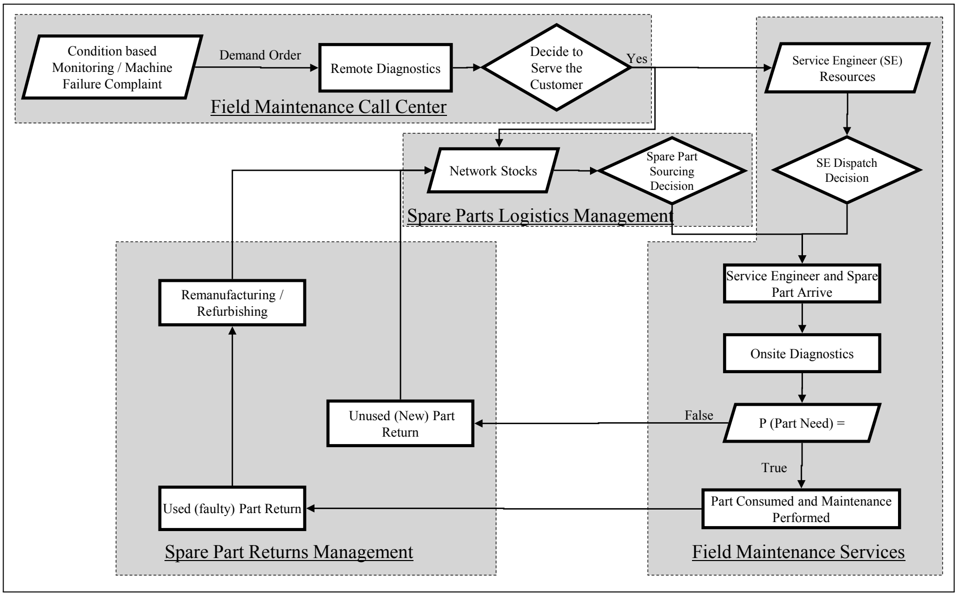

Figure 2.2: A Typical After Sales Service Operation

In this scheme, maintenance services management typically consists of field maintenance call center and field maintenance services. Field maintenance call center is a frontend operation that receives the customer call for maintenance and coordinates its execution with field maintenance services (i.e service engineering staff), and spare parts logistics. Whenever a machine fails at the customer location, the customer or machine sends a demand order that could represent machine failure information sent by the customer through telephone, email, internet or a potential failure signal sent by a failure prediction system within the machine. To determine the validity of the demand order, remote diagnostics are performed by maintenance services management (either by the field maintenance call center or by the field maintenance services). Although the remote diagnostics provide more information about the validity of the machine failure instance, the failure diagnosis could still be wrong unless it is confirmed by an on-site diagnosis. Based on the remote diagnostics outcome, a decision to provide the maintenance service is made. Consequent to this decision are two secondary decisions: Which service engineer (SE) should be dispatched to the customer location and when? And, from which stock location should the spare part be sourced?

The dispatching decision is made by the field maintenance services. The assigned service engineer travels to the customer location from his/her current location (i.e. either his/her idle location or the preceding customer location). The exact arrival time of the service engineer at the customer location is therefore dependent on the assignment of a specific service engineer by the field maintenance services. For the second decision, the field maintenance services department issues a part request to the spare parts logistics department. The latter subsequently determines the appropriate source stock location for the spare part shipment. To minimize the service engineer's idle time at the customer location, the spare part should arrive earlier or simultaneously with the service engineer's arrival at the customer location.

By performing on-site diagnostics of the machine, the validity of initial remote diagnostics is confirmed and demand is realized. Consequently, the spare part is consumed and maintenance is performed by the same service engineer. The on-site diagnostics may also reveal that the initial remote diagnostic inaccurately diagnosed the failure. In this case, spare parts logistics management and spare part return management, together, need to decide and execute another question: to which stock location, should the unused spare part be returned? This question highlights the importance of interaction between spare parts logistics management and spare part returns management. During the maintenance action, the used (faulty) spare part is recovered. Consequently, it is sent to the sorting / testing / refurbishing / remanufacturing / disposal facility. Considering the state of the used spare part, future demand, and cost structures, an appropriate disposition decision is made accordingly.

Figure 2.2 highlights the role of each of the operational components (i.e. maintenance services, spare parts logistics, and returns management) and their close interaction for the efficient and cost effective execution of an after sales service operation. It can be argued that the information and communication technologies are enablers in this respect. To manage these operations efficiently, a series of strategic, tactical and operational decisions are discussed in the academic literature. In Table 2.1, we organize and list the strategic, tactical and operational decisions for each of these after sales service operations.

Table 2.1: Strategic, Tactical, and Operational Decisions in After Sales Service

Phase	After Sales Service Maintenance Services	 Spare Parts Logistics	 Spare Part Returns
Strategic Decisions	Maintenance Territory Design (§2.3.1)	Spare Parts Network Design (§2.3.2) Spare Parts Distribution Management (§2.3.3)	Return Logistics Network Design (§2.3.4) Returns Distribution Management (§2.3.4)
Tactical Decisions	Permanent Manpower Planning (§2.4.1)	Spare Parts Inventory Planning (§2.4.2)	Returns Disposition Planning (§2.4.3)
Operational Decisions	Job Selection / Dispatching Rules (§2.5.1)	Spare Parts Execution Management (§2.5.2)	Disposition and Disassembly Execution (§2.5.3)

In the remainder of this chapter, we first describe these operational components (i.e. maintenance services management, spare parts logistics management and returns management) in Sections 2.2.1, 2.2.2, and 2.2.3. Next, we discuss various common key performance indicators (KPIs) that companies use to assess the performance of their after sales service operations. We proceed further by reviewing the academic literature on strategic, tactical and operational decisions for each of the after sales service operations.

2.2.1 Maintenance Services Management

In a broad sense, maintenance services management involves 'maintenance service provision to customers, either at the customer's location or at a specified service facility '.

For maintenance services management, providing maintenance service at a designated service facility or the customer's own location makes big difference (Tang, 2005). From a queueing theory perspective, field maintenance service is analogous to the situation where the server itself travels to the incoming job in the system. Upon job completion, the server travels to the next job or stays idle at the customer location. Thus, the waiting time in the queue for a subsequent incoming job is dependent on the preceding job. In comparison, maintenance service provision at a designated service facility takes the conventional queueing theory perspective, where each incoming job travels to the server for service provision.

Regardless of this distinction, maintenance service provision is not an easy task. It involves a variety of long term and short term decisions. Long term decisions include districting the service territory, and service station placements. Medium term tasks include resource acquisition and allocation. Short term tasks involve maintenance job selection and SE dispatching rules. Some of the important decisions are discussed in Sections 2.3.1, 2.4.1, and 2.5.1. It should be noted that some of these decisions are interrelated.

2.2.2 Spare Parts Logistics Management

The primary function of spare parts logistics management is to support maintenance services management for the after sales service function. At first, spare parts logistics may seem analogous to inventory management in any traditional supply chain management system. A careful look however reveals many subtle differences which render inventory management solutions from traditional supply chain management ineffectual. For example, slow moving demand, time based service levels, on-site service provisions, and customer base heterogeneity are some of the aspects that are not generally encountered in many traditional supply chain systems (Armistead and Clark, 1991; Cohen et al., 2006). Similar to maintenance services, spare parts logistics management involves many long term and short term tasks; such as logistics network design, stock location placements, inventory planning, logistics planning and spare parts logistics execution management. We shall discuss each of these tasks in Sections 2.3.2, 2.3.3, 2.4.2, and 2.5.2.

2.2.3 Spare Part Returns Management

Similar to the retail or manufacturing sectors, returns of new and used parts are encountered in after sales service. Product recovery options in retail, manufacturing or other sectors are typically classified as reuse, refurbish, remanufacture, harvest, and disposal. In after sales services, the part recovery options are limited to reuse, refurbishing, and disposal (De Brito and Dekker, 2003b; Fleischmann et al., 2003). In after sales services, used spare part returns originate during a maintenance or repair action, when the used (faulty) part is replaced with a new or working spare part. The used (faulty) part is often refurbished for future use or disposed. New spare part returns in after sales service primarily occur due to the incorrect failure diagnosis of the machine during a remote diagnosis action. New spare returns in after sales service can also originate due to the pessimistic ordering practices of service engineers. For example, the service engineers might order more than the required number of parts due to the uncertainties in failure diagnosis via remote diagnostics (Hammond and Dutkiewicz, 1993; De Brito and Dekker, 2003b). In practice, the frequency of new returns is quite high as Hammond and Dutkiewicz (1993) highlight that 58% of the first time fix exceptions during after sales service at IBM were caused by initial diagnostics errors. De Brito and Dekker (2003b) report the rate of new spare part returns to be around 5% of the overall spare part returns. Tan et al. (2003) study the spare parts logistics and reverse logistics practices at a computer manufacturer and report that the rate of good spare part returns is up to 27.4% of the entire spare part returns. Note the difference in the new and used spare part return logistics management. A designated facility (or facilities) that inspects, dismantles, harvests, refurbishes, or remanufactures the used spare parts is needed for the distribution management of used spare parts. New spare parts, however, can directly be returned to the inventory network (Tan et al., 2003; Thierry et al., 1995; De Brito and Dekker, 2003a). We will discuss the strategic, tactical and operational decision phases for efficient return management in after sales service in Sections 2.3.4, 2.4.3, and 2.5.3.

2.2.4 Performance Measurement in After Sales Service

In Figure 2.2, we observed that the execution of the after sales service function requires a close interaction and efficient functioning of various operational components. In academic and practice literature, many performance indicators or KPIs are discussed to assess the performance at the global and component levels of the after sales service function (Hammond and Dutkiewicz, 1993; Cohen and Agrawal, 1999; Vigoroso, 2003; Gecker and Vigoroso, 2006). In the next few paragraphs, we briefly discuss these KPIs. It should be noted that the importance of the KPIs varies according to the service provider's after sales service strategy. For example, many of the KPIs, that are important for the field maintenance situation, may have much less importance in other situations.

Overall Costs: Each operation's contribution to overall supply chain costs is perhaps the most widely used performance measurement instrument that any company uses to derive the performance of each of its operational components. Various subcategories in overall supply chain costs include transportation costs, warehousing costs, obsolescence costs, inventory costs and inventory turnover rates.

On-site Response and Fix Time: This category of performance measures record the response times of the after sales service function for any service call. On-site response time denotes the time taken by the service engineer to arrive at the customer location. An equivalent performance measure in maintenance at a designated facility is the customer's waiting time in the queue. Fix time denotes the time taken by the service engineer to complete the repair service since the initiation of the repair activity.

First Time Fix: This service measure records the validity of the repair job performed by the service engineer. If the maintenance service performed by the service engineer on his first arrival is inadequate to fully repair the machine, then a first time fix exception is recorded.

Service Engineer Idle Time: This performance measure is recorded to assess the operational efficiency of manpower planning in maintenance services management.

Fill Rate: A service measure related to the availability of spare parts in the inventory network. Whenever a stock location is unable to fulfil a demand realization from the available stock, a stock out occurs. A fill rate is estimated by calculating $1 - \textit{Stock out rate}$.

Parts Delivered on-Time: In the field maintenance service situation, if a spare part required for a specific customer's service call cannot be delivered within the contractually agreed service deadline from any network stock location, then an exception to the on-time part delivery is recorded. Monitoring these exceptions enables an estimation of the percentage of parts delivered on-time.

The management of each of the operational components in after sales service is not an easy task. In Table 2.1, we listed various strategic, tactical, and operational decisions for each service management component in after sales services. In the next few sections, we discuss these decisions in greater detail according to their strategic, tactical and operational nature.

2.3 Strategic Decisions for After Sales Service Management

At the strategic level, a company is concerned with the decisions that prescribe the company's after sales service strategy (Armistead and Clark, 1991). The attempt is to link the particular business context in which the company operates with the company's after sales service strategy. Typically these are long term decisions and are very expensive to alter on short notice.

2.3.1 Maintenance Service Territory Design

One of the most important decisions faced by the maintenance service manager is to divide the entire service area into sub-regions and assign the required service engineering resources such that an optimal balance between total costs and service levels can be achieved. Typically the entire service area is divided into service regions, which may be subdivided into service territories. One or more SEs, who are responsible for performing the maintenance activities on all machines within a territory, may be assigned to each service territory.

Clearly service territory design has a direct impact on the operational performance of the maintenance services. In an ideal world, a service territory would have a square shape, transportation routes would form a grid, and the customers would have a uniform geographical distribution with uniformly distributed machine failure rates Candas (2007). In most actual applications, service territory design is often constrained by the country / municipal / geographical (such as rivers or mountains) boundaries and irregular customer distributions (Simmons, 2001).

Reflecting on the distinct nature of field maintenance services and maintenance service at a dedicated facility, we argue that the transportation aspects (transportation costs and transportation time) are important for field maintenance services and should be explicitly considered for operational modeling of service territory design.

2.3.2 Spare Parts Logistics Network Design

In this task, the spare parts logistics manager has to decide on the positioning of the spare parts stocking facilities throughout the geographical network. Spare parts logistics network design problems can be considered as a special class of generic logistics network design problems. Similar to maintenance services management, the exact terms of warranty / service requirements and customer base characteristics in after sales service impact the design of the logistics network.

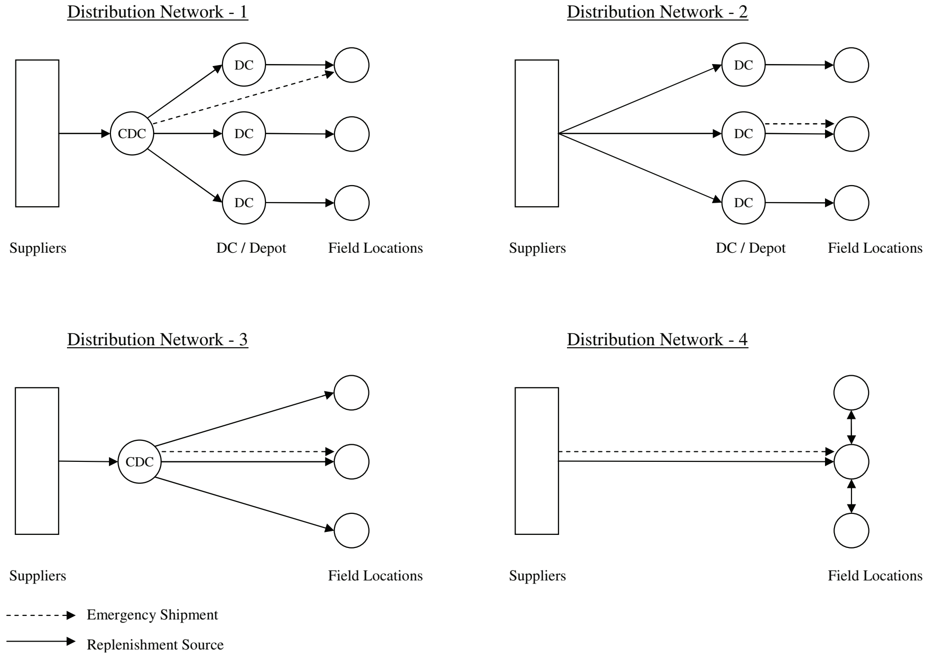

Figure 2.3: Spare Parts Logistics Network (Source: Cohen and Agrawal (1999))

Cohen et al. (1997); Cohen and Agrawal (1999); Cohen (2009) discuss the existing and emerging trends in spare parts logistics network design. Figure 2.3 depicts various types of logistics networks that are commonly observed in practice. A three echelon network consists of a central distribution center (CDC), one or many regional distribution centers (DCs) and multiple field stock locations (FSLs). A two echelon structure differs such that either the DC or CDC echelon is not present. The role of CDC or DC is to support the FSLs for replenishment or emergency shipments. The choice of having a CDC echelon or DC echelon is often dependent on the consideration of savings by inventory pooling at CDC vs. the ability of DCs to support FSLs in a responsive manner. It is also observed that, in some instances, a designated DC is exclusively used to fulfill emergency shipments. Cohen and Agrawal (1999) also discuss the emerging trends in logistics network design. The authors highlight that there is a gradual shift from multi-echelon structures to single echelon structures with direct shipments from supplier(s) to FSLs and lateral transshipments among FSLs. It is also observed that there are two approaches for spare parts stocking in the DC echelon vs. FSL echelon. The first approach is a forward parts deployment strategy with few DCs but more FSLs. The second approach is a delivery intensive centralized approach with a higher number of DCs and fewer FSLs. Tailored or hybrid networks are often observed in situations where the companies have mixed product lines, a geographically dispersed customer base with heterogeneous characteristics and variations in product/part cost.

In the academic literature, the early work on network design or facility location is discussed by Magnanti and Wong (1985), Drezner (1995) and Ghiani et al. (2004). This work focusses on finding regional equilibrium points to place stocking facilities of appropriate size, while considering demand rates, fixed and variable facility operating costs and transportation costs. Related work in this area also studies service constrained, stochastic, or reliability based problems. In addition, there are studies that discuss the effects of taxes, exchange rates, transfer prices, market prices, supplier reliability, and lead time uncertainty in single echelon or multi echelon contexts (Bundschuh et al., 2003; Vidal and Goetschalckx, 2000). For details of the earlier work, we refer the reader to the aforementioned reviews. The primary limitation of the earlier studies is that aspects of inventory management policies and multiple service deadlines are not considered. As discussed by Candas (2007), neglecting these aspects results in considerable losses. Such aspects are very relevant in a spare parts logistics context. In this respect, Candas (2007) accommodates the aspects of a one-for-one inventory replenishment policy and time based service level constraints in a single echelon network design formulation. The author also provides a computationally efficient solution procedure that is based on Lagrangian relaxation. Recent reviews on facility location problems that accommodate these spare parts logistics characteristics are provided by Snyder (2006) and Candas

(2007). It should be noted that the aspects of (s, S) or (r, Q) inventory replenishment policies and multi echelon configuration are unaddressed in the literature.

2.3.3 Spare Parts Distribution Management

Spare parts distribution management relates to the selection and planning of appropriate transportation resources to support after sales service operations. (Recall the earlier discussion in Section 2.2.1 regarding maintenance service provision at a designated service facility or customer's premises.) Clearly, if the firm's strategy is to provide maintenance service at a designated facility, then the task of distribution management is irrelevant. On the other hand, capital goods, that are often serviced on-site under strict service deadlines, necessitate responsive and cost efficient distribution management to distribute the spare part from the FSL to the customer location.

There exists a rich body of academic literature on distribution management in supply chains. Distribution management in spare parts logistics differs from distribution management in other sectors. For example, there are significantly less opportunities to consolidate shipments in spare parts logistics due to the prevalence of slow moving demand and strict service levels. This is particularly valid for the downstream distribution between FSLs and customer locations (i.e. last mile distribution). For example, if the inter-arrival time between two consecutive demand realizations is much larger than the time based service deadlines of those demand realizations, then the opportunity to consolidate shipments for consecutive demand arrivals is not available. The absence of consolidation and the prevalence of individual spare part shipments implies that distribution management in spare parts logistics involves a point to point type of transportation planning, especially in the last mile distribution between FSLs and customer locations. The vehicle routing solutions from traditional supply chain distribution management are not applicable. Multiple transportation modes are often used in spare parts logistics. This includes slower transportation modes such as truck, train, and ocean cargo as well as fast transportation modes such as taxi, courier, and chartered air service (Cohen et al., 1997).

With respect to partnerships with the logistics service providers, Cohen and Agrawal (1999) report the existence of three business models for spare parts distribution management. In the first case, the entire network's distribution is managed by one supplier. The second business model relates to the situation, where specific functions are outsourced to different suppliers (e.g. same day transportation is managed by one supplier in the entire network). Third, in large companies, it is typically observed that a single function is outsourced to different companies in different regions. The first business model is often termed as 4^{th} party logistics (4PL). In this system, the tasks of network design and inventory management are performed by the service provider itself, while the distribution and warehousing functions are outsourced. The second and third business models are termed as 3^{rd} party logistics (3PL), where the distribution tasks are outsourced to many service providers. Coordination among the suppliers is a delicate task requiring the direct intervention of the service provider.

2.3.4 Spare Parts Return Network Design and Distribution Management

At the strategic level, an infrastructure consisting of transportation, warehousing, testing and remanufacturing facilities is required to manage reverse flows in after sales service. Reverse logistics network design and reverse distribution management for spare part returns share many similar features with network design and distribution management in forward spare parts logistics. Fleischmann et al. (2001) note that the network design models to manage return flows are conceptually similar to classical warehouse location models, which also form the basis for network design problems in forward spare parts logistics. The differences from the forward chain stem from the fact that network design in the reverse logistics context is akin to simultaneously accommodating forward and reverse flows, whereas forward chain network design problems are limited to accommodating the forward flows. Similar to the forward case, 3PL and 4PL solutions for warehousing, transportation and remanufacturing are often observed in return distribution management. In comparison to the forward flows, vehicle routing and consolidation aspects are much more prevalent for return flows, since reverse distribution planning and management is driven by cost efficiencies instead of time based deadlines. Therefore, consolidation is commonly observed in the upper echelons and last mile distribution flows. For details on network design and distribution management in the reverse logistics context, we refer the reader to the review by Sasikumar and Kannan (2008b).

2.4 Tactical Decisions for After Sales Service Management

In this phase, advanced planning is performed for the operational execution of after sales service. Note that the configuration of the after sales service supply chain was fixed during the strategic phase. Thus, in this phase the objective is to define and implement maintenance planning, inventory planning and return disposition policies that can optimize the day to day execution of the supply chain while providing maximum flexibility. The decisions made during this phase are applicable for medium term (i.e. 6 month to 18 months).

2.4.1 Maintenance Manpower Planning

The manpower planning problem typically focuses on the number of SEs that should be hired for each service territory. In order to minimize costs, a decision is made regarding the exact number of SEs that minimize manpower costs while ensuring that customer service occurs according to the contractual service deadlines. In literature, the manpower planning problem for field maintenance services is studied by Agnihothri (1985). The author highlights that a service territory size in which the workload can be managed with one SE provides certain operational advantages. For example, the SE is able to develop a personal relationship with the customer, which helps the SE understand each customer's requirements better. The past maintenance history of each machine is also known to the SE, therefore it reduces the future machine repair times. A major disadvantage of one SE territory is that the SE needs a variety of skills to handle all kinds of service calls. The requisite skill set includes the technical skills to perform maintenance on the electrical, electronic, and mechanical components of the machines. It also includes the necessary skills for administrative and call center management tasks. Due to this, the service provider has to invest in extra training of the SE. Similarly, during a high workload season, customers have to wait longer for after sales service provision. Moreover, the opportunities to provide 24/7 services are limited with only one SE per territory. In most practical situations, more than one SE is used to manage the maintenance service requirements of each service territory. Having more than one SE enables improved service response times. In such a situation, the maintenance job selection rules or SE dispatching rules have an impact on the overall operational performance of maintenance services. We will discuss various types of job selection and dispatching rules in Section 2.5.1.

2.4.2 Spare Parts Inventory Management

Inventory management is a well established field in the academic literature. The earliest discussions relate to the planning of inventories for a single inventory source situation. With the advent of global supply chain management, the focus in inventory management research is to provide solutions that globally optimize the supply chain. The theory of multi-echelon inventory management is relevant for such situations. Within multi-echelon inventory management theory, the solutions for serial, divergent, convergent and mixed networks are discussed in the literature. We highlighted the schematic of distribution networks in Section 2.3.2. The corresponding network schematic in inventory management is termed as a divergent network. Therefore, we specifically focus on inventory management solutions for divergent networks that attempt to accommodate after sales service characteristics. For a detailed discussion on inventory management in all settings, we refer the reader to Axsäter (2006).

Much of the spare parts inventory management literature follows the one-for-one policy proposed by Feeney and Sherbrooke (1966). The one-for-one policy is often used for low demand spare stocking situations. The classic METRIC model for a multi echelon inventory system was developed by Sherbrooke (1968) for the inventory planning of repairable items at the US air force. The model consists of two echelons, a lower one consisting of n identical stocking locations and an upper echelon consisting of one central depot or warehouse. The objective of the model is to optimize the procurement decisions in the period of initial supply. Muckstadt (1973) extended this model to handle multi items and multi indenture and termed it as MOD-METRIC. In the initial METRIC approach, it is assumed that for each product, the number of items in repair follows a Poisson distribution (in which the variance equals the mean). Slay (1984) relaxed this assumption by deriving an expression for the variance of the number of items in repair and fitting a negative binomial distribution on the first two moments of these items to obtain a better approximation. This model was termed VARI-METRIC. Sherbrooke (1986) discussed the improved approximations for VARI-METRIC. In the METRIC approach, the contracted service guarantees of after sales service can be handled at the system level (Rustenburg et al., 2001). The initial METRIC formulations do not handle batch ordering. Various researchers such as Deuermeyer and Schwarz (1981); Svoronos and Zipkin (1988); Moinzadeh and Lee (1986); Lee and Moinzadeh (1987b,a); Axsäter et al. (2002); Axsäter (2003); Axsäter and Marklund (2008) have presented approximations to handle batch ordering in METRIC formulation. It has been shown that the approximation solution provided by Axsäter and Marklund (2008) performs even better than the echelon and installation (r, Q) policies.

Despite these developments in the academic literature for spare parts inventory planning, the use of the above solutions in practice is limited. Many companies often use simple methods that estimate the inventory requirements by using demand over replenishment lead time as a basis. The focus of these methods is towards inventory availability instead of inventory planning optimization. Though such methods provide short term solutions by ensuring the availability of stocks; in the long term, the problem is compounded by low inventory turnover rates and high obsolescence rates. There are many limitations originating in practical situations that inhibit companies from using optimization methods. Data availability and quality are two such limitations. In addition, modeling assumptions also have a role to play. Most of the optimization models assume one uninterrupted and uncapacitated external supply source. In reality, this assumption is often violated. Typically, there are multiple suppliers for one spare part type. These suppliers are often limited by their production capacities and their commitments to other business partners. Moreover, the demand volume is linked to the size of the service provider's installed base. Any sudden changes in installed base size consequently affect the demand patterns. Pince and Dekker (2009) discuss the potential interventions to mitigate sudden demand changes for single stock location and continuous review inventory policy settings. The problem is unaddressed for periodic inventory policies and more complex network configurations.

2.4.3 Returns Disposition Planning

The returns disposition decision or product recovery decision relates to the potential future use of the incoming returned spare part. In the reverse logistics literature, a recent review has been provided by Sasikumar and Kannan (2008a, 2009). The disposition decision is typically defined as follows: depending on the state of the returned product, a decision needs to be made to either reuse, refurbish, remanufacture or harvest the returned product for future use. Note that the majority of the reverse logistics literature does not specifically focus on spare parts or after sales service. As highlighted in Section 2.2.3, return management in spare parts logistics slightly differs from other sectors. Similar to other sectors, new spare part returns (which are similar to commercial returns in retail) are often put back into the spare parts inventory after minor testing/packaging. Differences can be noted primarily for the end of life or end of use returns. The disposition decision for product returns includes the options of repair, refurbish, remanufacture or harvest. In the case of spare part returns, the disposition decision is typically restricted to repair, or disposal of the spare part (De Brito and Dekker, 2003b; Fleischmann et al., 2003). In addition to the used spare part returns, an additional source of spare parts inventory is the harvesting operations for the end of use or end of life product returns (Fleischmann et al., 2003). In Chapter 5, we discuss these aspects in greater detail.

2.5 Operational Decisions for After Sales Service Management

In this phase, decisions are made regarding individual customer orders. The time frame for decisions in this phase is in weeks or days. Note that the supply chain configuration is fixed and policies are also defined. The objective here is to handle the incoming customer requests in the best possible manner. The decisions made during this phase include allocating inventory to individual orders, setting order due dates, selecting a particular shipping mode for specific orders, scheduling transportation and replenishment ordering.

2.5.1 Maintenance Job Selection and Dispatching Rules

The job selection rules or dispatching rules outline the basis on which the next job (from a pool of available jobs) is selected for service. For the designated service facility situation, simple rules such as First In - First Out (FIFO or alternatively FCFS for First Come - First Serve), Last In - First Out (LIFO), random service, round robin and, priority disciplines are discussed in the academic literature (Nahmias, 2004). For the field maintenance service situation, many dispatching rules such as FIFO, nearest neighbor, earliest due date, negative slack, and nearest call with positive slack are discussed by Hill

(1992). In addition to this, travel time and travel distance based SE dispatching rules are discussed by Hill (1992); Tang et al. (2008). For details on dispatching rules in a field maintenance service setting, we refer to Tang (2005). The optimum job selection or SE dispatching rule enables an estimation of optimum manpower requirements for each service territory.

2.5.2 Spare Parts Logistics Execution Management

Supply chain execution management refers to the allocation policy for the consumption of network inventory in the event of a demand arrival. Other terms such as event driven execution can be found in the literature to describe the same procedure. Before explaining the execution policies, we should define the terms that are used in the relevant literature. In the academic literature related to lateral transshipments, the terms primary stock location and secondary stock location are often observed. Primary stock location for any customer is the stock location that is assigned as the serving stock location in the case that demand arrives from an under-consideration customer. Typically, this assignment is based on the nearest FSL for that customer. Any stock location that is not a primary stock location for a specific customer is termed as a secondary stock location for the specific customer. We should note that the terms of primary and secondary customer are also encountered in literature. Such terms are used in a converse manner to primary and secondary stock location. For a specific stock location, the set of primary customer locations includes all of the customers that have a specific stock location as the nearest stock location. In the academic literature related to allocation strategies for a heterogeneous customer base, the terms demand classes or demand criticality levels are used. Demand classes could simply be based on a customer's value (contract fee that customers pay for a specific contract; see the warranty / service contract discussion in Section 2.1.2). In other situations, demand classes could also be based on demand criticality (see spare part criticality discussion in Section 2.1.2). We should also note that in literature, terms such as rationing level or critical limit (or level) are also observed. In this case, rationing level or critical limit (or level) has a relation to the inventory level at inventory source location. Consider an example of the inventory system with two demand criticality classes. If the current inventory level is lower than the rationing level or critical limit (or level), then demand requests from lower demand criticality class may not be served from the on-hand inventory.

We now discuss execution management practices in spare parts logistics. We should highlight the interaction between inventory planning and execution management. The interaction is due to the fact that for any inventory planning setting, the nature of the execution rule or allocation policy is an exogenous input. The most widely used allocation policy in supply chain execution is a FIFO policy, where the stock units at any stock location are allocated to the customers on a FIFO basis. (Recall the distribution network structures 1, 2, and 3 in Figure 2.3.) In these distribution networks, any arriving customer, regardless of the type of service contract it possesses or the criticality of its demand, is served from the nearest FSL. If that FSL is out of stock, then the customer's demand is lost or backordered until the next replenishment arrival at that FSL. In the above inventory planning solutions, the execution rule is limited to FIFO. Advanced execution rules accommodating lateral transshipments or customer based heterogeneity are not considered.

In this section, we review the academic literature that attempts to accommodate more advanced allocation rules during execution management. Similar to the earlier sections, we will restrict our discussion to the relevant research that studies supply chain execution management in network settings. It should be noted that typically two approaches are utilized to accommodate advanced execution rules in the literature. The first approach is similar to the FIFO approach in inventory planning, where the advanced execution policy (other than FIFO) is fixed and used in subsequent inventory planning. In other words, the allocation rule is studied in conjunction with the inventory planning policy. Examples of such a situation are the cases in which lateral transshipments are accommodated (or not) in conjunction with rationing that is static (or dynamic). The second approach is different in that an attempt is made to delineate inventory planning and execution. A dynamic rationing rule is utilized in such situations for execution management. The inventory planning is based on the long term aggregation of the execution policy behavior. One may argue that the second approach is perhaps better suited to exploit short term demand fluctuations. In general, the allocation rules for execution management can be subdivided into four categories.

- No Lateral Transshipments with Rationing. Such situations exist in hierarchical distribution networks where there are no lateral transshipments among the downstream FSLs. In addition to the replenishment of the downstream locations, the upstream stock locations also support the direct emergency deliveries for high priority customers. In many cases, the decision to support emergency deliveries or replenishment orders at an upstream location is based on some rationing rule. In the literature, such studies are presented by Cohen et al. (1988), and Cohen et al. (1990), who study the multi-echelon divergent structure with a (s, S) inventory policy to support inventory planning for such an execution rule. In both of these papers, customer heterogeneity is limited to two demand classes. Similar work is presented by Wang et al. (2002), where the authors study a one-for-one replenishment policy, a two echelon inventory system (one upstream and n downstream locations), two demand classes, and demand lead time specific service levels. The two demand classes differ in delivery lead times. Axsäter et al. (2004) study a two echelon system with one upstream location and n downstream locations. The inventory system is such that there are different service levels for each downstream location. The upstream location faces direct customer demand (i.e. due to stock out at the downstream location) and replenishment orders. A static critical level is defined for each downstream location to decide whether the replenishment order from the downstream location to the upstream location should be fulfilled from stock or referred to the external supplier for emergency shipment. The resultant policy provides the inventory planning parameters and rationing parameters.

- Lateral Transshipments with No Rationing. This situation extends the traditional hierarchical distribution structure to accommodate lateral transshipments in the distribution network. Distribution network structure 4 in Figure 2.3 represents this specific case. In the event of demand arrival, a prioritized list of FSLs is used to satisfy the demand. Typically the priority list is based on the FSLs' costs of service to fulfill the demand request. Note that there is no differentiation between customers on a contract or demand criticality basis. Such solutions in the academic literature are discussed by Kutanoglu (2008), Kutanoglu and Mahajan (2009), where the authors study a two echelon system with n downstream locations, one upstream location and n demand classes. The authors study this system under global and local service constraints that are based on a time to service criteria. The focus is to determine the policy parameters for inventory planning in the above settings. Reijnen et al. (2009) also study a similar system with partial lateral transshipments that are based on the sending stock location's ability to fulfill demand within the service deadline.

- Lateral Transshipments with Static Rationing. This category is an extension of the full lateral transshipment situation. Similar to the full lateral transshipment situation, a priority list of FSLs is typically determined on a cost of service basis. In addition, the concept of static critical limit or threshold limit is utilized at each FSL that determines whether a specific FSL will participate in lateral transshipments or not. In other words, a demand order from a primary customer is always served, and a static critical level is utilized by the FSL to serve the secondary customers. If the stocks at a specific FSL are below its critical limit, then the demand order from the secondary customer is not served. The relevant literature for various inventory replenishment policies and system characteristics are discussed by Zhao et al. (2005, 2006), Tempelmeier (2006), and Enders et al. (2008). Zhao et al. (2005, 2006) proved the optimality of a transshipment policy for decentralized dealer networks, where the locations are independently owned and operated with the inventory planning and static critical limit parameters determined for each location.

- Lateral Transshipments with Flexible/Dynamic Rationing. This rule is similar to the static execution rule with the exception that critical levels are not fixed. The critical levels change throughout the horizon depending on some system characteristics. The relevant work in this domain is discussed by Axsäter (2003), Grahovac and Chakravarty (2001) Minner et al. (2003) and Van Wijk et al. (2009). Axsäter (2003) discuss a single echelon system with lateral transshipments. The execution policy is dynamic and given a set of alternative decisions, the decision rule attempts to minimize the expected costs under the assumption that no further transshipments will take place. Grahovac and Chakravarty (2001) discuss the situation of expensive items with a low demand rate, where the decision is to identify a candidate secondary stock location for lateral transshipment in an instance of stock out at the primary stock location. Minner et al. (2003) discuss a similar system with an execution rule that decides the execution decision (i.e. from which stock location the incoming demand should be served) by accommodating expected risk. Van Wijk et al. (2009) study lateral transshipments between two field stock locations, where the demand can be fulfilled from 1) the nearest stock location, 2) lateral transshipment, or 3) an emergency external source. The allocation policy is a threshold type policy that decides on the fulfillment decision based on system characteristics. In comparison to the earlier categories, in these papers, the authors disintegrate the derivation of the execution and planning policies. The planning policy is considered as given and the attempt is to derive an optimal dynamic execution rule.

We should note that the execution management literature addressing multiple demand classes is limited. A primary reason is the cost based perspective in the inventory management literature. Customer heterogeneities due to service contract agreements in after sales service are mostly unaddressed. The work by Wang et al. (2002), Kutanoglu (2008), Kutanoglu and Mahajan (2009), and Reijnen et al. (2009) addresses it to some extent by incorporating the varying service requirements of a heterogeneous customer base. However, the focus is limited to accommodate customer base heterogeneity in the planning decision with a fixed or static execution rule.

2.5.3 Disposition Execution

We now discuss the day to day decisions in spare part returns management. At the operational level, the required activities involve implementing the planned disposition rule for future use of the returned spare part. In this respect, a common practice in many companies is to rank disposition alternatives by unit margins and utilize the ranking to execute disposition decisions on a day to day basis. Advanced decision rules explicitly incorporating uncertainty in a single period and (or) multi period setting are discussed by Ferguson et al. (2008). In addition to disposition execution, the academic literature in reverse logistics also lists disassembly operation scheduling as an operational decision. Notice that the disassembly scheduling decision for the spare part returns situation is perhaps not as challenging as the disassembly of the core product. However, with multiple types of used spare parts entering the disassembly system for repairs, scheduling becomes an important task for the operational efficiency of a repair facility.

2.6 Information Management in After Sales Service

The use of information about the customer in the planning and execution of supply chain operations is considered an enabler for better performance towards that customer. This seems particularly valid for after sales service operations and is unanimously agreed and supported by after sales service practitioners and academic researchers (Vigoroso, 2003; Oliva and Kallenberg, 2003). In a broad sense, the technology to support information usage in after sales service can be categorized as: 1) Information Technologies (IT) and 2) Communication Technologies. In a benchmark study of information technology use in the after sales service sector, the Aberdeen group reported that 82% of the surveyed companies use ERP or customized in-house information systems to support after sales service operations. In addition, 59% of the companies utilize state of the art IT systems to capture customer information and machine maintenance history data (Gecker and Vigoroso, 2006). On the communication technologies front, Cohen et al. (1997) survey industry practices regarding the use of various communication technologies to support after sales service operations as depicted in Figure 2.4.

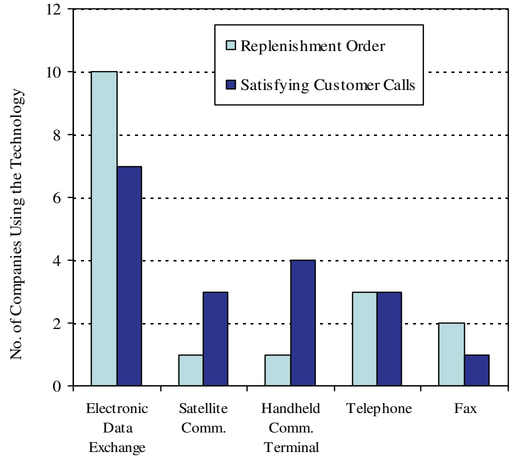

Figure 2.4: Usage of Communication Technologies (Total 11 data points. Source: Cohen et al. (1997))

We now review the information management practices in after sales service. We should note that information management is a broad subject and involves many specializations such as hardware technologies, software technologies, IT network management, and information architectures. We restrict ourselves to the information gathering and usage aspects that are relevant to the operations management in after sales service. We also discuss the practical issue of data quality that is associated with information management.

2.6.1 Role of Information Management in After Sales Service

The primary motivation for extensive data use in after sales service is to plan and execute customer focused service operations with cost minimization or profit maximization objectives. In Figure 2.5, we depict the survey results regarding IT solutions adoption by the after sales service sector.

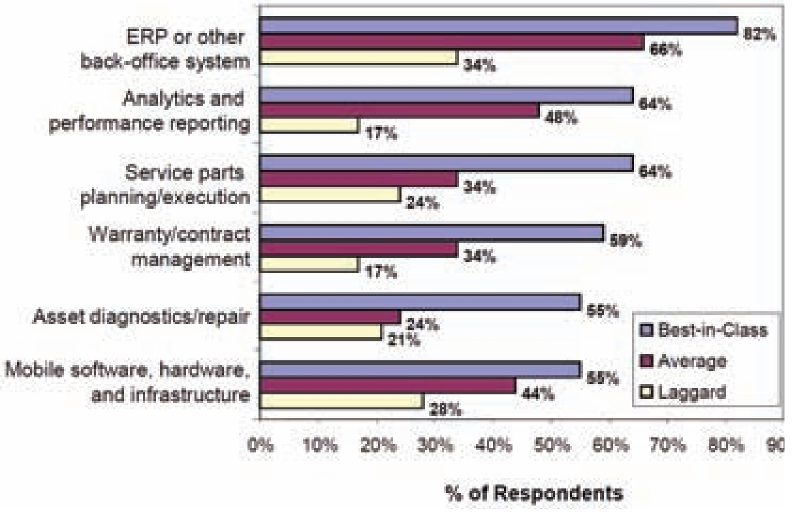

Figure 2.5: IT Adoption (Source: Gecker and Vigoroso (2006))

It is easy to note that the level of technology adoption in best-in-class companies is significantly higher than in the rest of the companies. It is not that these companies achieved the competitive edge solely due to technology adoption. Instead, the technology adoption generally matches the overall service strategy of the firm. According to the

Aberdeen group, the best in class companies also have a higher uptime of their serviceable assets and a higher degree of compliance with the service agreements as depicted in Table 2.2.

Table 2.2: Service Commitment Fulfillments (Source: Aberdeen Group, Dec. 2007)

Aspect	Best in Class	All Others
Serviceable Asset Uptime	92%	82%
Service Agreement Compliance	92%	77%
Annual Growth in Service Revenue per Customer	19%	7%

Products, processes, customers and their interactions are vital sources of information in after sales service (Jalil et al., 2007; Van Nunen and Zuidwijk, 2004). In this section, we study IT management from each of these perspectives. The customer perspective relates to the activities that attempt to acquire, retain and manage relationships. Product data management in after sales service differs from retail or manufacturing sectors. The primary difference originates from the fact that in traditional retail or manufacturing sectors, product information does not extend beyond the point of sale. Process data management attempts to capture the information generated during various after sales service processes. In Table 2.3, we organize the various types of data that are captured and subsequently used during after sales service operations.

The maintenance knowledge base contains information regarding potential maintenance problems with each machine and the associated repair procedures. Initial information in the maintenance knowledge base comes from past maintenance experiences of similar products and the product design cycle. The maintenance knowledge base is used to understand and rectify the machine failures at hand, which, subsequently enriches the maintenance knowledge base through a continuous feedback cycle. In many situations, due to flexibilities introduced during the machine design phase, a spare part of one type can be substituted by another type. This data is further used during spare parts inventory planning and execution cycles.

As discussed earlier, process data management refers to the data generated during various after sales service operations. This data is also used for the subsequent planning and execution of after sales service operations. For example, the historical demand data is used for subsequent network design, maintenance manpower planning, and spare

Table 2.3: Product, Process, Customer - Three Sources of Information

	Product Data Management	Process Data Management	Customer Interaction
Maintenance Services	Maintenance knowledge base, Machine reliability data	Request handling data , Historical demand, Transportation times and costs, Manpower costs,	Installed base data , Customer relationship, management
Spare Parts Logistics	Part commonality data, Part substitutability information	Request handling data, Historical demand, Transportation times and costs, Spare part inventory, Inventory costs	Installed base data, Customer relationship management
Spare Parts Returns	Life cycle data, Maintenance knowledge base	Request handling data, Historical return rates, Disposition cost structures	Machine usage behavior data

parts inventory planning. Similarly, the cost accounting data generated during various processes is used to determine optimal tradeoffs for maintenance, service tool or spare parts logistics operations.

As a result of continuous customer interaction during after sales service operations, the service provider is able to learn and adapt its services to meet the requirements of a heterogeneous customer base. Installed base (IB) data and customer relationship management (CRM) data management practices formalize such aspects in after sales service. IB data contains the customer location information, machine model, parts configuration, and service agreements information for each customer. In the practice literature, one also encounters the terms of warranty or contract management data for IB data. Together with transportation cost rate information, IB data can be used to assess the transportation costs for each service. IB data can also be used together with request handling data to deduce the maintenance service profiles of each customer. Such information could be used to assess and design customer specific maintenance strategies.

By using sophisticated analytics and optimization models, the extensive product, process, and customer data can be transformed into useful information to design and execute customer focused service operations. The automated decision engine for network inventory planning is one such example (see for example the network neighborhood in Draper and Suanet (2005)). But as we observe in Figure 2.5, the extent to which companies use these analytics varies significantly. Dekker (1996) and Shapiro (2004) have reviewed and discussed the barriers to the use of maintenance optimization models in practice. Dekker (1996) cites the gap between industry and academia, data related issues, and a lack of decision support systems, as three major obstacles. In addition to these aspects, Shapiro (2004) has studied the impact of the behavioral context of the decision making situation in the effective use of supply chain analytics and optimization techniques. In the next section, we focus on the various information related issues that companies often encounter in practice.

2.6.2 Barriers to the Use of Analytics: The Information Aspect

In this section, we discuss the challenges the companies often encounter while implementing any after sales service analytic or optimization solutions from the literature. We specifically focus on the limitations imposed by information acquisition and management issues.

In a broad sense, the limited application of supply chain analytics from an information management perspective can be classified into two distinct reasons: 1) the cost of technology adoption and 2) data quality issues. In this section, we focus on the role of data quality issues as a barrier to the effective use of optimization models and analytics in after sales service management.

Data Quality Issues

It is universally accepted that the wide ranging application of supply chain principles in practice would not have happened without the developments in information and communication technologies. Owing to the developments in the IT era, organizations nowadays are enriched with all kinds of process, product and customer data. Simultaneously, the issue of information quality has also received significant attention in the Information Sciences (IS) literature. In this section, we first highlight the academic discussions in the field of IS to handle data quality issues. Subsequently, we explore the supply chain management and after sales service literature on the topic of data quality issues.

Data quality problems have received considerable attention in the IS literature. The notion of data quality in the IS literature finds its roots in total quality management

(TQM) concepts of quality, i.e. fitness for its purpose. In the IS literature, data quality is defined as a representation of various ontological characteristics of data (Wand and Wang, 1996; Mallach, 2000). Some of these ontological aspects of data quality read as follows: completeness indicates to what extent a data set contains all necessary values (Ballou and Pazer, 1985). Accuracy is defined as the degree of agreement between an observed value and an accepted reference value. Timeliness is an aspect that characterizes whether the current data set or data value is out of date for its intended use.

In the IS literature, many researchers have attempted to devise a framework to rank the impact of these various quality dimensions (Ballou and Pazer, 1985; Wang and Strong, 1996; Lee et al., 2002). These survey based studies are limited from an after sales service perspective due to the following reasons: first, the surveys were performed mainly on IT professionals who are not the end users of the data; second, the contextual implications of the decision making situation are not considered during the rank assessment.

Data quality issues have received much less attention in supply chain management or after sales service literature. Before we discuss the academic literature on data quality in after sales service, we intend to highlight the type of data quality issues that are encountered in practice. The sectoral studies by the Aberdeen group and Accenture reveal the following data quality issues in after sales service (Gecker and Vigoroso, 2006; Vigoroso, 2003; Dennis and Kambil, 2003).

- Lack of appropriate visibility into product information, inventory information, contract information and customer location information.
- Disparate and incompatible data sources and decision support systems.
- Inconsistent naming conventions.
- Lack of supply chain wide integration.

These aspects hinder the deployment or continuous use of optimization solutions. Either the solution is not deployed at all or even if the solution is deployed, the confidence in the optimization solution's performance is seriously undermined due to a "Garbage In-Garbage Out" perception. In general, there are two primary factors that account for data quality issues in after sales service, i.e. lack of appropriate technology adoption and human-machine interaction. Despite the developments in IT, the cost of firm-wide-technology adoption is still high. Many companies (large or small) are unable to reach a critical volume in after sales service business to make the technology adoption feasible. The high costs of sophisticated IT solutions force companies to compromise, thereby using no IT solution at all or settling for a less sophisticated solution. Often, companies attempt to extend the use of their MRP system from manufacturing to after sales service. MRP, or ERP systems, are tailored for high-volume, replenishment driven production environments (Cohen et al., 2006). Although such actions save costs, they result in a technology solution that is unable to capture the requisite details of the after sales service system. As a result, either the required data are simply not available (no IT solution in-place) or the data are available only at an aggregated level, which does not provide the necessary level of visibility. Data quality issues do not disappear with appropriate investments in IT solutions due to contextual aspects of data acquisition and management. For example, aspects of inconsistent naming conventions or incorrect or vague information originate due to human or systematic errors. We shall further discuss these aspects in Section 3.6.1.

Discussion of data quality in the after sales service related academic literature is scarce. In the area of network design or facility location, Ballou (1994, 2001) has discussed the effects of data quality variations (in location information and transportation cost / time information). In the broader context of supply chain management, Daganzo (1996); Rogers et al. (1991); Korhonen et al. (1998); Fisher et al. (2000); Cachon and Fisher (2000); Proudlove et al. (2007); Thonemann (2002) have discussed data quality issues in inventory planning, production planning, forecasting, and service planning. Since, the authors studied sectors other than after sales service, these studies do not accommodate some of the primary characteristics of after sales service (such as customer heterogeneity, varying service levels, slow moving demand rates, distribution network structure, and field service).

We now conclude our discussion on the academic and practice literature for after sales service. In the next section, we present a case study on after sales service practices at IBM. As mentioned earlier in Section 1.3.3, after sales service operations at IBM and more specifically IBM spare parts logistics is a frequently cited case in academic literature as the state of the art in after sales service operations (Cohen et al., 1990; Hammond and Dutkiewicz, 1993; Cohen et al., 1997; Fleischmann et al., 2003; Tang, 2005; Draper and Suanet, 2005; Candas, 2007; Kutanoglu, 2008). We should note our objective from this case study is to present an illustration of business context in which after sales service operate and to highlight how the solutions that exist in the academic literature are utilized in business practice for better understanding.

2.7 After Sales Service at IBM - An Illustrative Case

IBM after sales service is a frequently studied and cited case in academic literature as an example of the state of the art in after sales service operations (Cohen et al., 1990; Hammond and Dutkiewicz, 1993; Cohen et al., 1997; Fleischmann et al., 2003; Tang, 2005; Draper and Suanet, 2005; Candas, 2007; Kutanoglu, 2008). Among these studies, we would like to highlight Hammond and Dutkiewicz (1993). In this case study, the authors discuss the execution of a typical after sales service operation at IBM in detail. Other papers highlight spare parts inventory planning, network design, spare part returns management, and field maintenance planning solutions at IBM. In the subsequent sections, we discuss each of the after sales service operations and the associated optimization / analytics solutions to support these operations.

IBM encounters a heterogeneous customer base for after sales service planning and execution. Essentially, an IBM customer represents an installed machine at its premises for which it owns a valid service contract. These machines include IBM products as well as non-IBM products for which the customer holds a servicing contract from IBM. These machines can be subdivided into following groupings:

- Large Scale Systems: These are large scale computing machines sold primarily in the B2B sector. The customers are large organizations, governments and educational institutions, who use these machines as a part of their business infrastructure.
- Medium Scale Systems: These are slightly smaller versions of the computing machine (such as i Series). The primary target for these machine models is again the B2B sector. However, the computing needs of these organization (in terms of volume) do not match the users of the large scale system.
- Small Scale Systems: These are small scale machines such as personal computers, POS systems, multiplexes, and modems. These machines are sold in B2C and B2B sectors, however, in-terms of servicing, IBM only supports the B2B sector. For example, the sale of the personal computer business to Lenovo led IBM to

withdraw from the PC product sales in B2B and B2C markets. Simultaneously, IBM partnered with Lenovo to provide after sales service to Lenovo customers in the B2B market.

Significant differences exist in the after sales service management for large and medium scale systems vs. small scale systems. In line with the discussion in Section 2.1.5, the large and medium scale systems are serviced on-site, whereas small scale systems are serviced at a designated service facility. In addition to variations in machine models, IBM also sells various types of service contracts to service its installed base. For these contracts, the service commitments are organized in terms of committed response time and repair time. The response time commitments start from 0.2 hours from machine failure reporting. The repair time commitments include same day, next business day, and 2^{nd} business day commitments. Within the same day category, the lowest repair time commitment is 4 hours and ranges up to 24 hours with intermediate steps of 5, 6, 8, and 12 hours commitments (IBM, 2008).

In the remainder of this case study, we specifically focus on the B2B sector, i.e. after sales service management with field maintenance services. As noted in Section 1.3.1, the scope of this thesis is limited to spare parts logistics planning and execution in after sales service. Therefore, we limit the discussion to the spare parts logistics practices at IBM.

2.7.1 Spare Parts Logistics Practices

At IBM, the Service Parts Operations (IBM-SPO) operates in close coordination with the IBM Service Organization to satisfy the spare parts requirements for after sales service operation. The primary question that IBM-SPO encounters for spare parts planning is how to place the spare parts inventories throughout their service network. The IBM's service logistics network spreads across the globe. For efficient functioning, it has been subdivided into various regions termed as GEOs; where each GEO is responsible for the availability and delivery of spare parts within that geographical region. For the Europe, Middle East, & Africa (EMEA) GEO, IBM's network consists of almost 150 stock locations. The service network is organized to ensure that IBM has a sufficient presence in each region to provide timely service to its business customers. As mentioned earlier, these customers own the after sales service contract from IBM for IBM manufactured and non IBM manufactured products. The service contracts differ in terms of the time to provide complete repair service whenever a failure occurs.

Spare Parts Logistics Network

In this section, we discuss the characteristics of a spare parts logistics network. In the previous section, we mentioned that the concentration of stock locations in the logistics network is designed to ensure the ability to provide timely service to IBM customers at minimum cost. In the literature, this has been discussed by Candas (2007), who cite the network design problem at IBM as a motivation for their study. The specific study by Candas (2007) covers essential spare parts logistics characteristics, such as time based service levels, customer based heterogeneity, the role of a two echelon divergent network structure, and inventory policies. However, the aspects of a three (or more than three) echelon network structure, cross border constraints, taxes, and exchange rates are not addressed.

We now discuss the distribution structures for inventory management at IBM. Figure 2.6 depicts two types of network structures that exist in spare parts logistics at IBM.

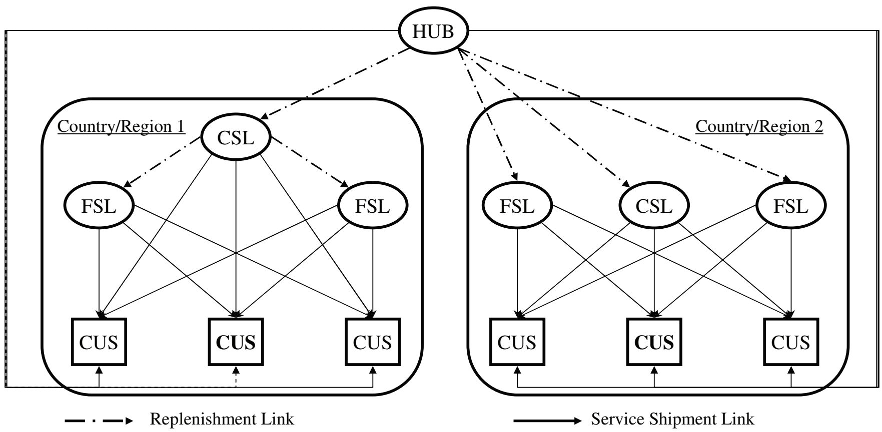

Figure 2.6: Spare Parts Network Configuration at IBM

Both of these network structures exist at various regions in IBM spare parts logistics. A common element between both of these structures is the aspect of lateral transshipments. The replenishment of spare parts differs, however, since region 1 and 2 represent the three and two echelon structures of Figure 2.3 (i.e. distribution network 1 and distribution network 3). As mentioned earlier, the network design solution mentioned in Candas (2007) does not cover the three (or more than three) echelon situation. We should also mention that the prevalence of multiple echelons in IBM's hierarchical inventory network setting in region 1 is not limited to three echelons. In line with the discussion by Cohen et al. (1990), we observed that the hierarchical replenishment network of the region 1 situation at IBM may contain up to five echelons in some regions.

Similar to Cohen and Agrawal (1999)'s observation in the benchmark study, we should also mention that there has been a gradual shift from the region 1 situation to the region 2 situation at IBM. The gradual shift to the two echelon structure has been accompanied by the deployment of an inventory planning solution for such a structure. The inventory planning solution for the multiple echelon structure (Cohen et al., 1990) is gradually being replaced. We describe the characteristics of these two inventory planning solutions in the next section.

Spare Parts Inventory Planning

We first discuss the characteristics of the planning solution for region 1's three echelon structure (Figure 2.6) at IBM. For spare parts planning, IBM has to decide on the exact amount of inventory units at each stock location of the three (or more than three) echelon network. For this purpose, IBM utilizes the solution discussed by Cohen et al. (1990). In this model, IBM attempts to find the exact inventory level for each stock location while considering inventory holding costs, regular and emergency transportation costs and service levels. In this model, demand is observed at the stock location level, therefore there is no possibility to account for the customer heterogeneities due to service contracts. Similarly, the service level constraints in this model are not time based service constraints. Instead, they follow a fill rate based rule. The aspect of lateral transshipments, which is practiced during after sales service execution, is not accounted for in this solution. Therefore, there is a disconnect between planning and execution. It is assumed that at each stock location the observed demand is independent of other stock locations and Poisson distributed. It should be noted that due to lateral transshipments, the independence assumption might be violated. However, one could argue that, due to the slow moving nature of demand, the effect of this violation will be limited.

We now discuss the planning solution for the two echelon network structure (i.e. country / region 2). Similar to Cohen et al. (1990), as an objective of spare parts planning, IBM has to decide on the exact amount of inventory units that should be held at each stock location. Due to a sufficient number of stock locations in each service region, it turns out that each customer can be served from many stock locations within the service deadline (i.e. overlapping service regions for different stock locations). Consequently, a possibility of lateral transshipment is available to IBM, if the nearest stock location is out of stock. The planning of spare parts inventories at IBM is performed by a Mixed Integer Programming based software tool, which has been developed and patented by IBM (Erke et al., 2003). The optimization model of this software tool is similar to the planning model presented by Kranenburg and Van Houtum (2009). Both of these models seek to minimize the holding and transportation costs via optimal placement of requisite spare parts inventory in the network. The constraints to this objective are service deadlines, lateral transshipments, and inventory balancing constraints. The formulated mathematical problem is a non-linear mixed integer programming problem. The non-linear constraints are linearized via approximation and the resultant mixed integer programming formulation is used to estimate the base stock levels for each stock location. We discuss the details of the planning situation and associated planning optimization model in Section 3.2.

As mentioned in the previous section, IBM is gradually replacing the three echelon distribution structure and planning solution with a two echelon structure and an associated planning model. It should be noted that the two echelon planning solution uses considerably more information (i.e. customer location level demand data, customer location data and contract data), therefore the decision to deploy a planning solution is dependent on the available customer and demand data. We discuss this aspect in greater detail in Section 3.2.

We now discuss some of the practical aspects that are not covered by either of the above planning models. Both of these models assume that external suppliers who replenish the HUB location are not capacitated. In practice, this is not true. For each spare part type, IBM partners with many suppliers. These suppliers are limited by their production capacities and their commitments to other OEMs. To counter this situation, IBM uses the above models to estimate the stocking requirements for all stock locations except for the HUB location. For the HUB location, IBM uses a time-phased inventory policy to determine replenishment order sizes and instances. According to this inventory policy, current inventory level, current inventory position and part requirements over replenishment lead time (lead time of supplier delivery) are reviewed to determine the size of the next order. The orders are placed once per week. The idea is simply to have the stock to match the incoming demand from IBM customers.

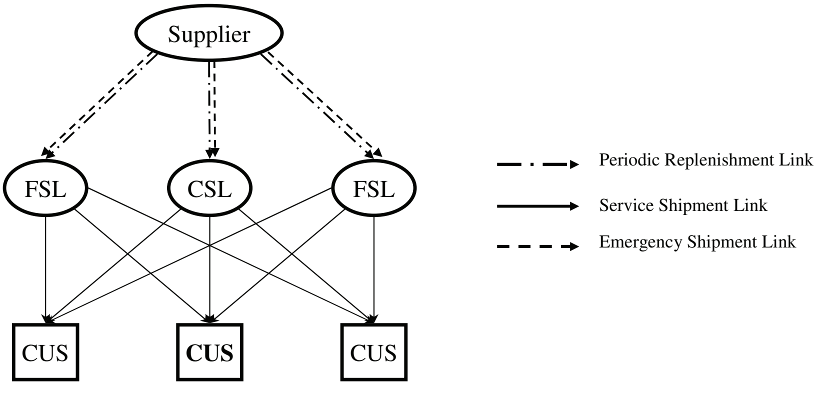

Figure 2.7: Spare Parts Network Configuration for Capacitated Supplier Situation

In some situations, suppliers are capacitated to the extent that the inventory system can be represented by the situation in Figure 2.7. In such a situation, a replenishment order based on the network demand over the replenishment lead time is periodically placed with the supplier. The supplier delivers the full or partial spare parts orders on a periodic basis. Arriving replenishment orders are used to fill up the network stock (downstream locations) up to the base stock levels. No or little remaining stock is kept at the HUB location, in such situations. The downstream location executes the customer orders with full or partial lateral transshipments. Any intermediate inventory requirements (between two replenishment arrivals), that cannot be fulfilled from network stock are sourced via emergency shipments. Note that the inventory network in Figure 2.7 can also be considered as a special case of the country / region 2 situation of Figure 2.6, where the review periods are long and replenishment ordering is performed at the same time for all field stock locations.

Spare Parts Logistics Execution

In the planning phase, the base stock levels for FSLs are determined. These stocks are periodically replenished from upstream locations (i.e. HUB and CSL for the region 1 and HUB for the region 2 situation) by using a slower and cheaper transportation mode that allows for consolidated shipments. In the execution phase, demand realization from any customer is satisfied by using the stocks from the stock locations. These requests are fulfilled by using a faster transportation mode such as a taxi. It should be noted that during the execution phase, lead-times for service request fulfillments are considerably shorter than the replenishment lead-times in the planning phase. To determine the appropriate stock location (i.e. HUB, CSL or FSL), for same day service request fulfillment in the execution phase, IBM utilizes a greedy heuristic termed the Spiral Router Heuristic (SRH). The next day service requests are directly shipped from HUB location or a predetermined next day servicing location. According to the SRH, each same day demand arrival from any customer type is satisfied from the nearest non-empty stock location. If there is no non-empty stock location that could serve the customer within the service deadline, then IBM has two choices. The service request can be fulfilled within the service deadline from an upstream location via an emergency shipment; or it can be fulfilled from the upstream location via a normal shipment. In the first situation, extra transportation costs are incurred due to an emergency shipment. In the latter case, a service deadline violation is incurred. Note that some situations might exist in which, despite using an emergency transportation mode, IBM is still unable to meet the service deadline. In such a situation, both emergency and penalty costs are incurred.

In addition to the SRH for execution management, IBM also utilizes static critical limits at all replenishing locations (i.e. HUB and CSL for region 1 and HUB for the region 2 situation). However, the critical limits do not ration stock units among a heterogeneous customer base. Instead, the idea is to ration stock between customer demand fulfillment and replenishment order fulfillment. If the stock level at any replenishing location is below the static critical limit, then all downstream replenishment orders are backordered until the next replenishment arrival at the replenishing location under consideration. The estimation of critical limits does not follow any optimization procedure. Instead, the idea is to combine the historical demand information with expert judgment and categorize the expected demand at the replenishing location according to its criticality. Based on the potential volume of higher criticality demand over the replenishing period, critical limits are set.

It is easy to note that execution management at IBM allows for lateral transshipments. However, the customer heterogeneities due to service contracts are accommodated in a limited manner by differentiating between next day and same day demand. Any incoming customer from the same day category, regardless of the contract type it possesses, would be served from the nearest non-empty stock location.

2.7.2 Information Management Practices

In this section, we discuss the information management practices in place at IBM to support after sales services. The strategic focus at IBM for information management is to support after sales service to its customers in a responsive manner. Van Oosterhout (2010) discusses the manner in which IBM translates this vision to the operational capabilities of information management in after sales service. The details regarding the required IT architectures and associated business processes are also discussed. In this section, we restrict our focus to study the type of information that is collected and used to support operations management in spare parts logistics at IBM. For other information management aspects at IBM, we refer the reader to Van Oosterhout (2010).

Throughout Section 2.7, we discussed the spare parts logistics management practices at IBM. We also discussed the OR tools and techniques that are used to support operations management at IBM. Many of these techniques are information intensive and require a significant amount of data as input. We should note that the data collected is usually not in the appropriate input form. Therefore, the data for input to the OR tools and techniques are derived from previously collected process, product and customer data. In this section, we first list the various types of process, product and customer data that is collected at IBM. Subsequently, we briefly discuss the manner in which the collected data is transformed into the required input form.

We first depict one of the main data tables used at IBM to collect and maintain the historical demand data. Table 2.4 lists the details of historical demand information that is collected and maintained at the spare part level. For each spare part, the collected information includes identifiers such as stock location and country code of the nearest stock location, machine type, demand emergency information, total instances of demand request and the demand volume for base warranty contracts and committed service contracts. In other words, total spare part demand can be classified according to demand's emergency classification, type of contract, machine model and its originating location.

Table 2.4: Historical Demand Data Collection Table

Item Code	Stock Location Code	Machine Type	Emergency Type Code	Period Start Date	Committed Services		Base Warranty	
					Demand Quantity	No. of Demands	Demand Quantity	No. of Demands

Similar to the historical demand data, IBM also maintains installed base data. Table 2.5 depicts the main data table used to maintain installed base information. Machine type information, nearest stock location, responsible maintenance organization, the machine's installation date, type of maintenance service contract, committed service indicator, customer location information, and spare part delivery time information is recorded for each customer. It should, however, be noted that this information is at the machine level. The part level information can be deduced by combining the IB data with the machine's engineering bill of material (BOM). The data table containing machine BOM information also contains the details of all the installed features on each specific machine serial number. The combination of these two data tables provides the complete list of the parts installed at each customer location. Further combination with the maintenance request handling data table provides the history of each installed part at the customer location.

Table 2.5: Installed Base Data Collection Table

Machine Type	Serial No.	Stock Location Code	Service Organization	Customer Identifier	Cust. Postal Code	Installation Date	Type of Maintenance Contract	Machine Status	Part Delivery Time	Committed Service Indicator

IBM also maintains transportation information as depicted in Table 2.6. This table contains the same day transportation distance and time information for all possible combinations of postal codes. We should note that the following information is maintained via close collaboration with the logistics service providing partner.

Table 2.6: Transportation Data Table

Ship From Country - Postal Code	Ship To Country - Postal Code	Travel Time	Travel Distance

We now discuss the manner in which the above information is used to support spare parts logistics management at IBM. We previously highlighted that the inventory planning solution at IBM accounts for the lateral transshipments and service levels of the heterogeneous customer base. The input requirements of the planning model are supported by using the collected process, product and customer data. To estimate demand information at each customer's postal code / contract type level, the historical demand information in Section 2.4 is utilized. The situation is complicated by the fact that demand is extremely slow moving. Therefore, it is difficult to forecast at the customer's postal code / service contract level by using extrapolation methods. To counter this, IBM uses an extrapolation method (such as a moving average) on aggregated demand at the country / GEO level and obtains the forecast information for the entire country / GEO. In order to obtain the demand forecast at the postal code / service contract level, the forecasted demand for the next period is subdivided according to the number of installs and contract types that are present at each postal code. We shall describe this procedure in detail in Section 3.2.1. In addition to the demand forecast, IB data is combined with transportation data to determine the postal codes of the stock locations that are able to serve each customer within the service deadline. Additionally, in partnership with its logistics service provider, IBM also determines the transportation cost information for each customer location and stock location link by using IB and transportation data.

The above discussion only provides a brief snapshot of information collection and utilization practices at IBM. In reality, the data collection and management activities are much more intensive. The spare parts logistics practices at IBM are in line with the practices followed by the best-in-class companies (see Figure 2.5) in the after sales service sector. The data management practices and the utilization of OR tools to support after sales service at IBM also represents the state of the art in the academic literature. However, we observe that many aspects, such as customer heterogeneity, partial lateral transshipments in planning and execution are not fully accommodated. In the next section, we identify these issues in a concise manner.

2.8 Relative Positioning and Research Problems

After reviewing the key characteristics of after sales service operations as presented in both the associated academic and practice literature, it is clear that there are significant opportunities for contributions in the area of after sales service management. More specifically, these opportunities exist, since there is a gap between available supply chain management analytics and key requirements for customer focused after sales service operations. In this section, we narrow the focus of this thesis to the core message. Consistent with the message in Chapter 1, we argue that to better align the after sales service operations to the key requirements for customer focused after sales service operations, an information intensive strategy should be utilized for operations management in after sales services. Two components are key to the success of this strategy: 1) an appropriate level of quality in customer related data and 2) a supply chain analytic solution that transforms the customer data into useful information for decision making. In our study of field maintenance provision as part of after sales service, the installed base data is an important source for customer location information, customer entitlement information, machine configuration information, and past maintenance history information. Therefore, throughout the thesis we use installed base data as a primary source of customer information. We attempt to study the potential benefits of using installed base data in spare parts logistics processes.

In this section, we identify and describe the research problems that are in line with the main message of this thesis. As outlined in Section 1.3.1, we focus on the spare parts logistics aspect of the after sales service. Specifically, we study the role of customer information enrichment in spare parts inventory planning and spare parts logistics execution. We also study the practical issue of data quality variation in the context of spare parts logistics. Again we focus on spare parts logistics planning and execution to study this issue. The idea is to study the impact of data quality with respect to the variations in installed base and demand data.

Table 2.7: Research Problems

Spare Parts Logistics			**Information Management**	
Inventory Planning	Logistics Execution	Returns Management	Information Enrichment	Information Quality
Chapter 3			Chapter 3	Chapter 3
	Chapter 4		Chapter 4	
	Chapter 5	Chapter 5		Chapter 5

In table 2.7, we organize the research problems discussed in the rest of the thesis according to their relation to the spare parts logistics decisions and the information management context. First in Chapter 3, we study the benefits of information enrichment in spare parts inventory planning. For this purpose, we study the planning model for the two echelon situation at IBM (see Sections 2.7.1 and 3.2 for details). We mentioned in Section 2.7.1, that the above planning model is able to accommodate the customer heterogeneity aspects discussed in Section 2.1.2 in the form of full and partial lateral transshipments and varying service levels. In our study, we analyze the impact of installed base data enrichment for spare parts inventory planning processes. We also study the effects of quality variations in the installed base data. In Chapter 4, we discuss how detailed customer data, such as installed base data, can be used to devise and improve execution management in spare parts logistics. We noted in Section 2.7.1 that the current execution method at IBM does not accommodate the aspects of customer base heterogeneity. Our attempt here is to devise a method that uses detailed customer data (i.e. installed base data) to enable service flexibility and customer differentiation in spare parts execution management. We also study the value of the installed base data in this context. Finally, in Chapter 5, we study the execution management in spare parts logistics and the role of inaccuracies in demand data during the execution management process. As a result of inaccuracies in demand realization during the execution process, a spare parts return management process needs to be initiated. In Chapter 5, we study the role of integrated vs. sequential management of forward execution and return management processes. We now discuss each of these research problems in further detail.

2.8.1 Inventory Planning and Information Enrichment

In Chapter 3, we turn our attention to spare parts inventory planning. We study a novel spare parts inventory planning approach that accounts for full and partial lateral transshipments, and customer heterogeneities. In the academic and practice literature, the planning approach of interest is discussed by (Erke et al., 2003) and Kranenburg and Van Houtum (2009). We study the benefits of installed base data enrichment in this inventory planning approach. A common tradition in the inventory planning literature is to utilize the stock location historical demand level data for planning purposes. By using installed base data, we devise scenarios where the customer location level demand forecast information is used for a spare parts planning situation (see Section 3.2 for details). A comparative analysis with the baseline situation shows the benefits of utilizing the detailed and disaggregated customer location information in a spare parts planning situation. Next, we turn our attention to the impact assessment of installed base data quality variations. In this regard, we review the academic literature on data quality. We first review the existing operations research (OR) literature on the impact of data quality in OR models. We observe that the notion of data quality in the OR literature is inept at encapsulating the various aspects of data quality in a real life spare parts inventory planning situation. Subsequently, we review the data quality in the information sciences (IS) literature and map the data quality aspects in the IS literature to the observed error types in spare parts inventory planning (see Section 3.6.1 for details). Next, we induce errors in installed base data according to the observed error types. Finally, we analyze to what extent the benefits of using installed base data are negated by the quality variations in installed base data.

2.8.2 Spare Parts Execution Management

This research problem is discussed in Chapter 4 of this thesis. In this research problem, we study spare parts logistics execution. We specifically study the potential benefits of introducing service flexibility in execution management. The flexibility in execution management is introduced in the following manner. We take the current situation of serving from nearest non-empty neighbor as a baseline (see Section 2.7.1). We replace this fixed execution rule by borrowing the concepts of differentiated and flexible service from revenue management. We extend our decision space by considering the secondary stock locations for service delivery. In other words, the devised approach is flexible in terms of the source location for service delivery. The inventory network situation considered for this approach is defined in figure 2.7 of Section 2.7.1. The devised approach uses the current system state (i.e. current network inventory situation) and customer base heterogeneity information as a basis for sourcing decisions. The devised approach is an information intensive solution for spare parts logistics execution. In Chapter 4, we demonstrate the potential benefits of information enrichment in execution management by comparing the long term performance of a flexible approach with the existing situation. The comparative numerical experiments, in Chapter 4, utilize real life installed base data and associated cost information.

2.8.3 Returns Management in Spare Parts Logistics

In Chapter 5, we extend our study of execution management. We study the situation, where a return process ensues as the result of inaccuracies during demand realization in execution management. We study this extension from two perspectives: 1) is there any potential benefit of deploying an integrated forward execution and return management process? And 2) what is the potential benefit of using installed base data for the return management process? In the first case, we study an information enriched integrated approach. In this respect, we consider bi-directional integration vs. uni-directional integration of forward sourcing and return decisions. In the bi-directional approach, we perform joint optimization of the forward sourcing and return management processes. In the one-directional approach, we optimize these decisions in a sequential manner. We first determine a forward sourcing decision. A return decision is subsequently made while accounting for the forward logistics decision. Regarding the use of installed base data to support the return process, we compare an information enriched approach to a heuristic approach. We provide more details regarding the problem characteristics and solution approaches in Chapter 5.

Chapter 3

Inventory Planning & Information Enrichment

3.1 Introduction

In a spare parts supply chain, the demand is realized during machine maintenance operations. Accordingly, the data about the realized demand and associated machine's location (i.e. installed base data) may be used for the subsequent planning. Installed base data includes machine location data, contractual data, and machine type data. These data can be used to address the challenging task of meeting strict customer deadlines at minimum costs in spare parts supply chains (Oliva and Kallenberg, 2003; Auramo and Ala-Risku, 2005; Vigoroso, 2003). However, what economic value is generated by the use of installed base data for the planning process still remains to be understood. A major obstacle that companies often face is the issue of varying data quality (Wand and Wang, 1996; Korhonen et al., 1998; Fisher et al., 2000; Lee et al., 2002). Many researchers have also cautioned regarding the potential impact of poor data quality on planning processes (Daganzo, 1987; Bender, 1985). However, the research is scarce for the impact assessment of data errors in a real-life spare parts planning situation.

In this chapter[1], we study IBM's spare parts logistics operations to observe the po-

[1] This chapter is based on the paper *Spare Parts Logistics and Installed Base Information* (Jalil et al., 2010b).

tential economic value of installed base data usage in real-life spare parts planning. We also analyze the extent to which the attained economic value degenerates by data quality variations in installed base data. As discussed in Section 2.7.1, IBM utilizes a mixed integer program of inventory - distribution optimization logic for spare parts inventory planning. In this chapter, we observe the gains of using installed base data for such an optimization program and assess the impact of installed base data quality variations on its performance. In other words, we test the planning model's robustness to installed base data errors for IBM's spare parts planning environment. In short, the main contributions of this chapter are as follows:

- In this chapter, we analyze the benefits of installed base data usage and the detriments of installed base data quality variation on the planning performance by considering scenarios relevant to the spare parts planning.
- By using an experimental setting, the chapter highlights the role of business environment of a spare parts supply chain that impacts the optimization model's robustness to installed base data errors for the spare parts planning.
- The study contributes to the existing body of literature by integrating the data error assessment methods in Operational Research (OR) literature and information quality concepts from Information Sciences (IS).

This chapter is organized as follows: First, we describe the important characteristics of spare parts logistics at IBM. We then formulate our research problem to analyze the impact of using machine specific data and its quality on the spare parts planning situation at IBM. In section 3.4, we discuss the relevant literature in Operational Research and Information Sciences. In section 3.5 and section 3.6, we perform the numerical study and discuss its results. We conclude with a discussion on our findings in section 3.7.

3.2 Spare Parts Inventory Planning

The planning of spare parts inventories at IBM is performed by a Mixed Integer Programming based software tool, which has been developed and patented by IBM (Erke et al., 2003). The optimization model of this software tool is similar to the planning model presented by Kranenburg and Van Houtum (2009). Both of these models seek to minimize the holding and transportation costs via optimal placement of spare parts inventory in the network. The constraints to this objective are service deadlines and lateral transshipments. The formulated mathematical problem is a non-linear mixed integer programming problem. Between IBM's patented technology and Kranenburg and Van Houtum (2009), the main difference is the developed solution method to solve the above problem efficiently. Kranenburg and Van Houtum (2009) uses an Erlang loss model based approximation to solve the model. The main idea of the IBM method is to linearize the non-linear constraints by developing an approximation. A very similar approximation method in literature is presented by Candas (2007). In this paper, the author presents a network design model for the spare parts inventory network, where a binary decision variable is used to close or open the warehouse facilities. In Kranenburg and Van Houtum (2009) and IBM's model, the binary decision variable is relaxed to integers to decide the exact amount of inventory units at that storage facility.

In this chapter, we present a simplified mathematical formulation that incorporates main characteristics of Erke et al. (2003). Consider an inventory network with n field stock locations and a central stock location. For each demand arrival, there are three possibilities. 1) A demand request is served from the nearest field stock location (i.e. primary stock location). 2) In case of stock out at a primary stock location, a demand request is fulfilled from the 2^{nd} nearest nonempty stock location, whose travel time is within a prespecified service deadline. 3) If there is no nonempty stock location within the service deadline distance, then the demand request is served from central stock location via an emergency shipment. Note that this network could be interpreted as an inventory network with partial lateral transshipments and time based service levels. The stock levels at each stock location are maintained by using a base stock inventory policy. The objective in spare parts inventory planning is to decide base stock level (denoted by S_i) for field stock locations and central stock location. We should note that each replenishment order arrives after some positive replenishment lead time. For details on inventory planning model, see Erke et al. (2003).

Before, we present simplified mathematical formulation, we aim to clarify some of the associated assumptions that we make for simplification. We assume that replenishment lead time is equal to the demand interval. Although a restrictive assumption, this considerably simplifies the mathematical formulation. Similar to Erke et al. (2003), we allow for splitting of demand order from customer j such that demand λ_j is fulfilled from many stock locations. Let y_{ij} represent the stock flow between a customer location j and stock location i then according to this assumption $\sum_i y_{ij} = \lambda_j \forall j$. At first, this assumption may seem unrealistic, however it is in accordance with the rationale of the model. The motivation is to find the regional equilibrium points and their associated weights to divide overall network demand forecast proportionally over the stock location network while accounting for lateral transshipments and time based service levels. Furthermore, we assume deterministic settings for incoming demand orders. We shall clarify the impact of this assumption in forthcoming paragraphs.

We now present the simplified mathematical formulation of the model. The notations of the mathematical formulation are as follows:

Notations

Sets

M = Set of stock locations (indexed by i)

N = Set of customer(s) (regions) (indexed by j)

Parameters

f_i^h = Holding costs per unit item per period at stock location i

f_{ij}^d = Unit transportation and handling costs between customer j and location i

λ_j = Demand rate of customer j per period

α = Required service level

$$\beta_{ij} = \begin{cases} 1 & \text{When travel time between } j \text{ and } i \text{ is within prespecified time} \\ 0 & \text{Otherwise} \end{cases}$$

Decision Variables

S_i = Stock level at location i

y_{ij} = Flow rate from sending stock location i to customers j

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Our objective is to place spare parts in the field stock location network such that the total inventory holding and transportation costs are minimized. Thus, the objective can be represented by the following function.

$$\sum_{i \in M} f_i^h S_i + \sum_{i \in M} \sum_{j \in N} f_{ij}^d y_{ij} \tag{3.1}$$

The first term in the objective function represents the inventory holding costs. Note that the presented expression is different from the standard holding cost expression in inventory planning textbooks. This is due to our simplifying assumption that replenishment lead time is equal to demand interval. The second term reflects the transportation and handling costs associated with the supply of stocks from stock location i to customer j. The outflow of the stock units from a stock location i to the customers should not exceed the available stock units at the stock location. The formulation of the constraint is as follows:

$$\sum_{j \in N} y_{ij} \leq S_i \qquad \forall\, i \in M \tag{3.2}$$

In addition, the demand of a customer j should always be satisfied. Since we assumed that splitting of demand order is allowed therefore, The associated demand constraint is as follows:

$$\sum_{i \in M} y_{ij} = \lambda_j \qquad \forall\, j \in N \tag{3.3}$$

The globalized time based service levels are incorporated in this scheme by formulating the following constraint.

$$\sum_{j \in N} \sum_{i \in M} \beta_{ij} y_{ij} \geq \alpha \sum_{j \in N} \lambda_j \tag{3.4}$$

Furthermore, the stock units at each stock location should be strictly integers and the stock flows between stock locations and customers should be non-negatives.

$$y_{ij} \geq 0, \qquad S_i \in \mathbb{Z}^+ \tag{3.5}$$

To identify the stocking requirements S_i at each stock location i, the objective function (i.e. eq. 3.1) should be minimized, while having eqs. 3.2, 3.3, 3.4, and 3.5 as constraints. The resultant decision vector would provide the stocking parameter S_i, which represents base stock level for each stock location.

We should also note that the above model does not consider uncertainty of demand, which is the source of non-linearity in Kranenburg and Van Houtum (2009) and IBM's patented model by Erke et al. (2003). We noted earlier, that Kranenburg and Van Houtum (2009) and Erke et al. (2003) handle demand uncertainty by developing approximations. As a result, in comparison to deterministic planning model, base stock levels estimated by the approximated model are inflated proportionally to the approximation parameters. In the presented simplified model, we assume deterministic setting as it reduces the computational complexity while retaining validity of presented results for the approximated version. We argue this due to following two reasons. First, we performed comparative experiments between the presented model and IBM's patented tool and results were found to be similar. This is due to the approximation coefficients chosen by IBM for application of planning tool, that essentially reduce the approximated model to deterministic setting.

Secondly, our objective in this chapter is not to present an inventory planning tool. Instead, our focus here is to analyze the benefits of using installed base information to support inventory planning versus no installed base information usage by observing reduced inventory planning costs due to installed base usage. As we shall notice in Section 3.2.1, that by using installed base data, we do not change the overall network demand forecast. We should note the amount of stocks that are needed to be placed in the stock network is bounded from below by network demand forecast and depends on equilibrium between holding and transportation costs, and time based service levels. If transportation costs are of lower magnitude in comparison to holding cost then optimization attempts to push base stock levels (integer values) towards network demand forecasts while accounting for time based service level. Therefore, any inflation in base stock level, due to approximation parameter, impacts installed base usage scenarios and no installed usage scenarios in a consistent manner. The consistent impact of approximation parameter also holds if holding costs rates are lower then transportation costs rates. Therefore, the results presented in this chapter (see Section 3.7) are also valid for stochastic settings.

IBM developed this planning tool to replace the existing hierarchal planning system (i.e. Cohen et al. (1990)). The existing system did not consider lateral transshipment and time based service levels, which are specifically considered in this approach. Currently, IBM is in the deployment phase of the developed tool. For the regions, where it has been already deployed, the deployment of this tool has resulted in considerable inventory savings. Note that the tool is designed to use the customer level data as an input. This includes customer demand rates, travel times, handling and transportation costs. At IBM spare parts logistics, the demand forecasting via extrapolation methods is impractical at the customer location level due to the slow moving nature of demand. Therefore, IBM uses installed base data to derive the customer demand forecasts, transportation costs, and travel times (see Section 3.2.1). The deployment decision is therefore highly dependent on the quality of the installed base data. We would further explain the interrelation of the deployment decision and installed base data quality in Section 3.2.2. We first describe the usage of installed base data at IBM.

3.2.1 Installed Base Data Usage at IBM

Machine location information in installed base data is used to derive transportation costs, travel times, and demand forecasts at customer's postal code level. First, we discuss the procedure used to derive the demand forecasts at IBM.

Demand Forecasting using Installed base

Similar to other spare parts logistics situations, IBM encounters slow moving demand for spare parts logistics management. As a first step, IBM accumulates the observed demand for the entire region and uses an extrapolation method (such as exponential smoothing) to derive the demand forecast for entire region. Let j be an installed machine at a customer location and $N = \{1, 2, 3, ..., J\}$ be the set of installs in the entire region with $j \in N$. Let λ_{jt} be the demand per period t from an install j. The accumulated demand per period is $\Lambda_t = \sum_{j \in N} \lambda_{jt}$. By using n-period exponential smoothing (ES) (i.e. $F_{t+1} = ES(\Lambda_t, \Lambda_{t-1}, \Lambda_{t-2}, ..., \Lambda_{t-n})$), IBM identifies the demand forecast F_{t+1} for the entire region. In the next step, the demand forecast per install for $t + 1$ period is derived by F_{t+1}/J. Finally, let k be the number of installs in each postal code (where $k \leq J$). Demand forecast per postal code for $t + 1$ period is calculated by $k \times$ demand forecast per install for period $t + 1$.

Transportation Costs and Travel Times using Installed base

To identify the transportation costs and travel times, installed base data is used to identify the customer location's postal code. By using routing optimization software, the travel distances and travel times from stock locations and customer's postal codes are identified. The travel distances are further used to identify the transportation costs associated with each stock location to customer's postal code link.

3.2.2 Deployment of Planning Solution at IBM

The decision to deploy the developed planning solution (see Section 3.2) is made on machine type and country basis. Within each machine type, there are several machine configurations identified as machine models. For example, a machine type of I-Series have 9 active machine models. In general, IBM intends to manage the spare parts logistics of approximately 166 machines models via the aforementioned developed planning solution. Similarly, the countries with active deployment or completed deployment are USA, Germany, Italy, France, Belgium, UK, Austria and The Netherlands. Within each of these countries approximately 25,000 spare parts types are being planned or to be planned by the developed planning approach.

As a first step for deployment of the developed planning solution, a machine type is selected whose installed base data is available for a specific country. On this basis, the procedure mentioned in Section 3.2.1 is used to deploy the planning solution. In the EMEA region, IBM uses the demand per postal code as a unit of analysis. In USA, the practice is to combine several postal/zip codes. Note that this implicitly highlights the issue of installed base data quality. Despite careful considerations, the quality level of installed base data varies due to a number of reasons. For example, the erroneous manual data entry of sales data results in missing data values or wrongly entered data values of installed base data. These errors are homogeneously distributed in all geographical regions. In some situations, the errors are concentrated in a specific geographical region due to a particular business environment. For example, in some regions IBM sells its machines through a third party sales organization. Due to the procedural mismatch in IT systems of two organizations, inaccurate installed base data is transmitted to IBM. Such types of instances are being classified as heterogeneously distributed errors. In Section 3.6.1, we list various observed errors in installed base data at IBM.

Within the scheme of planning solution deployment at IBM, our intervention at IBM comes via analyzing the value addition by using installed base data and the impacts of its varying data quality. The results of this study were communicated to IBM to encourage the use of installed base data for spare parts planning. In addition, the results of this study also aided enhanced understanding of the role of various data errors in spare parts planning performance at IBM. Thereby, the study aided the decision making process for the deployment of the planning solution.

At this point, we should also mention the complimentary nature of Kutanoglu and Mahajan (2009). The authors study a similar situation and analyze the developed model for its sensitivity to various model parameters (such as holding costs, transportation costs, replenishment rates). The priority sharing case in Kutanoglu and Mahajan (2009) is exactly similar to the situation considered in this chapter. On the other hand, we study the effect of using more detailed demand data (via installed base data) and its quality variations.

3.3 Problem Formulation

The availability of geographical information in IBM's installed base data provides an opportunity to use localized demand information at machine's postal code level for the spare parts planning situation described in Section 3.2.2. In such a situation, we attempt to answer the following questions:

- What additional value is generated by the use of accurate installed base data to derive the machine's postal code level demand forecasts in the spare parts planning optimization?
- What is the impact of installed base data errors on the outcome of the spare parts planning optimization?

The solution procedure to the first question relies on a comparative analysis of planning via stock location demand forecasts (No Customer Information Scenario) versus planning via machine location demand forecasts (Customer Information Scenario). In the first case, the demand observed at the stock location is used to derive the forecasts at stock location level. Albeit a common practice, the details of each individual customer (such as location information) are not accounted for during this procedure. In the second case, we specifically plan at the postal code level. In this case, we are incorporating more detailed information regarding the customer into the planning model. One may argue that the use of detailed customer information would lead to more accurate stock planning, thereby resulting in value gains. In the OR literature, a number of authors have discussed the use of planning optimization models with detailed or disaggregated data vs. aggregated data. However, no conclusive discussion is available in the OR literature for the intended optimization planning context.

The second question encapsulates the parallel research on data quality in OR and Information Sciences (IS). In the coming section, we review the existing literature on the impact assessment of data quality in the OR models. We observe that the notion of data quality in the OR literature is inept to encapsulate the various aspects of data quality in a real life spare parts planning situation. Subsequently, we review the data quality in IS literature and map the data quality aspects in the IS literature to the current case. We further analyze the impact of systematic and random data errors on the planning outcomes.

3.4 Literature Survey

Theoretically, the use of stock location data vs. installed machine's level data can be viewed as disaggregated data usage vs. data aggregation for usage in a planning model. In this section, we review the available literature on data aggregation vs. disaggregated data usage for OR planning models. Subsequently, we review the OR literature of data quality assessment and highlight its limitations to accommodate the real life data quality aspects. We then review the data quality notions in the IS literature. We also highlight the limitation of data quality assessment procedures in IS to accommodate the decision making context of spare parts planning.

3.4.1 Data Aggregation vs. Disaggregated Data Usage

The earlier discussion in the OR literature on inventory and distribution planning supports data aggregation due to computational complexity and data acquisition issues (Axsäter, 1981; Magee et al., 1985; Rogers et al., 1991; Ballou, 1994; Daganzo, 1996). The researchers attempted to outline the appropriate data aggregation level for transportation, inventory and distribution planning models. Some of these researchers also acknowledged that data aggregation is a source of potential input error for these planning models. The estimation of value loss due to data aggregation has been highlighted by Ballou (2001) as an unresolved issue for facility location and inventory-distribution optimization models.

Owing to the developments in the IT sector, organizations are now better equipped to acquire customer data. In a benchmark study, Cohen et al. (1997) discussed the criticality of advanced information systems for the design and management of timely service oriented spare parts logistics operations. A survey of spare parts management practices in 310 major companies by the Aberdeen group reported that 82% of the companies use ERP or in-house built information systems for spare parts management. In addition, 59% of the companies utilize state of the art IT systems to capture customer information and machine maintenance history data. The ability to use detailed customer information in spare parts planning was also stressed (Gecker and Vigoroso, 2006). Simultaneously, there are developments regarding the computational complexity of the intended class of optimization models. Candas (2007) and Kranenburg and Van Houtum (2009) have shown that the model could be efficiently solved within reasonable time by using advanced heuristic solution methods. However, the potential economic value that could be generated by using detailed data is unaddressed in the literature for the intended planning models.

3.4.2 Data Quality in Operational Research Literature

In the OR modeling literature on supply chain management, two different sources of input data errors are described that may impact the model output (i.e., results): 1) model approximation errors, and 2) data acquisition or sampling errors (Daganzo, 1996). Model approximation errors relate to the modeling assumptions and approximations made during the modeling process, and data acquisition errors relate to the data which is used as an input to the model. Since, we are interested in erroneous installed base data, our research questions justify a focus on the data acquisition errors. In a literature survey, Rogers et al. (1991) discussed the impact of data aggregation error in transportation planning, multicommodity distribution planning, production planning and scheduling problems. Daganzo (1996) studied the impact of data acquisition errors on inventory - distribution problems. The robustness of the Economic Order Quantity (EOQ) type formulation was analyzed with respect to demand data errors. Korhonen et al. (1998)

discussed the importance of data accuracy for demand management at the Nokia Corporation due to the short product life cycles, and the customer retention focus. Cachon and Fisher (2000) discuss the impact of sampling error on the value of shared information in a two stage supply chain with one supplier and multiple retailers. Toktay et al. (2003) analyze the robustness of various forecasting methods with respect to errors in product return parameters. Proudlove et al. (2007) discuss the impact of data quality variations in a health care OR system to manage and streamline in-patient flows. Leonard et al. (2005) study the data quality in a health care decision support system by using a scenario analysis methodology for the prioritization of the data quality improvement tasks. Olaya and Dyner (2005) study the potential application of OR modeling techniques to support policy decisions in the natural gas industry, when the relevant data is of poor quality. Thonemann (2002), by using a scenario analysis methodology, shows to what extent the benefits of using advanced demand data in a two-stage supply chain are mitigated due to erroneous demand data.

Another stream of literature, known as parametric and post-optimality analysis of linear, mixed integer and combinatorial programming problems is also relevant to our work. Primarily, the idea is to observe the behavior of the optimal decision for its stability/robustness given some variations in model parameters (such as costs). It is mentioned that the mixed integer and combinatorial and mixed integer problems are highly unstable to parametric changes (Wagelmans, 1990). In this stream, some of the earlier work is discussed by Geoffrion and Nauss (1977). We skip the discussion on earlier work and focus on more recent literature in this field. A comprehensive literature review has been provided by Greenberg (1998). Van Hoesel and Wagelmans (1999) have noted that, albeit post optimality is a well established field for linear programming problems, it is much less developed for mixed integer or combinatorial programming problems. Various researchers such as Wagelmans (1990); Acevedo and Pistikopoulos (1996); Jenkins (1990); Sotskov et al. (1995); Jia and Ierapetritou (2006) have discussed the post optimality analysis of parametric variations in mixed integer problems for network flow, shortest path, minimum spanning trees and perfect matching. The focus is mainly to study the perturbation in coefficients, its effects on the stability of the optimal decision via structural analysis, and the development the computationally efficient methods to recalculate the optimal decision given the perturbation. Note that in our problem, the quality variation in installed base data not only results in perturbation of transportation costs and demand coefficients, but also changes the set of customer locations, and the set of decision variables. The aforementioned results in the post-optimality literature are inadequate to support the extent of changes in our problem.

We note in the above papers that the widely used methodology for error assessment is either a structural analysis of the model or a scenario analysis of the planning model. We also observe that the impact of data errors has not been analyzed for the in-consideration optimization model. Moreover, in all of the above papers, the definition of quality is limited to the accuracy or sampling error dimension of the data quality. But as we witness in our study, in reality, data quality is a much richer concept than just accuracy or sampling error. To explore the various dimensions of data quality, we review the IS literature on data quality.

3.4.3 Data Quality in Information Science Literature

The notion of data quality in the IS literature is somewhat different from the OR literature and finds its roots in TQM concepts of quality, i.e., fitness for its purpose. In the IS literature, data quality is defined as a representation of various ontological characteristics of data (Wand and Wang, 1996; Mallach, 2000). Some of these ontological aspects of data quality read as follows: Completeness indicates to what extent a data set contains all necessary values: *all values for a certain variable are recorded* (Ballou and Pazer, 1985). Accuracy is defined as the degree of agreement between an observed value and an accepted reference value. Timeliness is an aspect that characterizes whether the current data set or data value is out of date for its intended use.

In the IS literature, many researchers have attempted to devise a framework to rank the impact of these various quality dimensions (Ballou and Pazer, 1985; Wang and Strong, 1996; Lee et al., 2002). These survey based studies are limited from an OR application perspective due to the following reasons: First, the surveys were performed mainly on IT professionals who are not the end users of the data. Secondly, the contextual implications of the decision making situation (such as spare parts planning at IBM and the associated geographical nature of errors in IBM's installed base data; see Section **?**) are not considered during the rank assessment.

To enrich the decision making context (i.e., spare parts planning environment) in our study, we utilize a scenario analysis based methodology. First, we analyze the economic value of using installed base data to support spare parts planning. Subsequently, we identify various dimensions of data error in installed base data. In terms of additional costs incurred due to the erroneous installed base data, we analyze the impacts for the spare parts planning by performing scenario analysis.

3.5 Value of Installed Base Data

In this section, we outline the analysis procedure and experimental design to answer the research questions (see Section 3.3). To answer the first question, we assess the value of using installed base data by scenario analysis. The details are provided in the next section.

3.5.1 Analysis Procedure

Figure 3.1 sequentially depicts the procedure followed for the scenario analysis. In the first step, we perform an optimization run by using the optimization model depicted in Section 3.2 with no customer data incorporation (No Installed Base Information Scenario). The no installed base information scenario can be formulated as follows. Since the customer locations are unknown, therefore our assumption here is to place all the surrounding customers at the nearest stock location. Referring to the notations in Section 3.2, the set of customer locations N is now equivalent to the set M. The historical demand observations at each stock location are used to derive the demand forecasts for each stock location via exponential smoothing. Similarly, the transportation costs and demand flow rates (i.e. f_{ij}^{d} and y_{ij}) represent the instance of sending stock location to receiving stock location. We use the planning model in Section 3.2 with the above adaptations and acquire no customer information scenario's stock plan (i.e. S_i^{BASE}).

In the second step, we introduce the installed base data (i.e. customer information enriched scenario). We use the procedure in Section 3.2.1 to acquire the set of customer locations N, demand rates λ_j, and transportation costs f_{ij}^{d}. We perform the optimization run on the planning model presented in Section 3.2 and acquire the costs for the information-enriched scenario. In the third step, no customer information scenario's stock plan is fixed in the (installed base) information enriched scenario by introducing

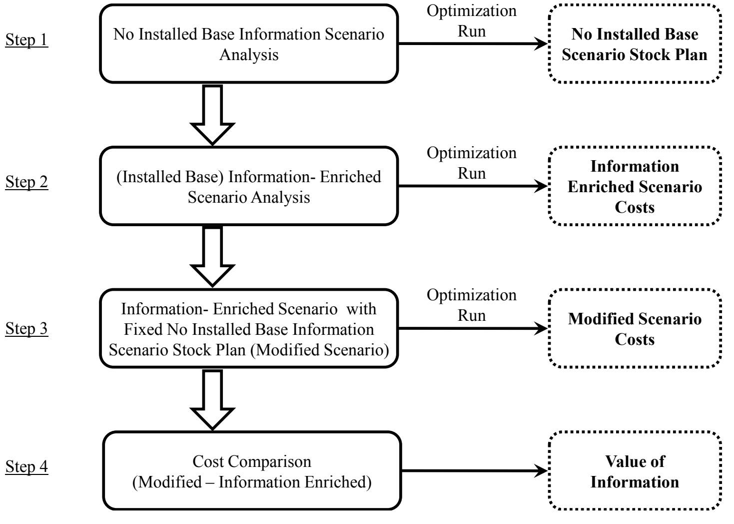


Figure 3.1: Analysis Procedure

the following additional constraints to the optimization model presented in Section 3.2.

$$S_i = S_i^{BASE} \qquad \text{if } i = \text{Field Stock Locations}$$
$$S_i \geq S_i^{BASE} \qquad \text{if } i = \text{Central Stock Location}$$

The primary idea is to calculate the planning costs while enforcing no customer information scenario's stock plan. In many cases, the no customer information scenario's stock plan is not optimal any more, since more customer information is now introduced into the planning model. We even run the risk of violating the globalized service level constraint (i.e. Equation 3.4). Therefore any additional stock that is needed in the service network to maintain the service level should come from the central stock location via emergency shipments. We perform the optimization of the modified scenario and acquire the planning costs. In the fourth step, we compare the costs of the modified scenario and the (installed base) information enriched scenario. The cost difference between the modified scenario and the (installed base) information enriched scenario indicates the value of that information.

Table 3.1 depicts the experimental design for the customer (installed base) informa-

Table 3.1: Experimental Design for Information Enrichment

Size of Installed Base	Installed Base (Customer) Information Used	Size of Set N	Size of Set M	Analyzed Demand Rates (units per week)
Small Installed Base Scenario	No Installed Base Information	9	9	0.5 , 1.0 , 5.0, 10.0
	With Installed Base Information	140	9	
Large Installed Base Scenario	No Installed Base Information	25	25	0.5 , 1.0 , 5.0, 10.0
	With Installed Base Information	23,885	25	

tion enrichment case. There exists a wide variety in the installed base sizes for various IBM products. For example, a specific machine could have a few hundred customers in the whole EMEA region, whereas a large installed base could have a size of twenty thousand. The impact of changes in installed base size was envisaged and accounted for during our analysis by formulating small installed base and large installed base scenarios. In fact the analysis depicted in this chapter is performed on an actual product installed base at IBM. Due to confidentiality reasons, we do not show the exact location information of these installs, derived transportation costs and travel time information. Only the transportation cost rates are provided in Appendix - 3A. The value of the installed base data was also analyzed for its sensitivity to demand rates for various installed base sizes. The demand rates and other cost parameters such as holding cost rates and service levels are selected according to the observed values of such parameters at IBM.

3.5.2 Results of Incorporation of Installed Base Data

Scenario 1 - Small Installed Base

By using the procedure outlined in Section 3.5.1, we analyze the value of installed base data usage. Figure 3.2 depicts the results of a small installed base scenario at varying cumulative network demand rates. Due to the slow moving nature of demand, these are the typically observed demand rates at IBM. The installed base size for this test bed scenario is 140 units. The demand rates are in units per week for the complete installed base region. The test bed parameters are listed in Appendix - 3A.

The vertical axis shows the planning costs (i.e., resultant value of the objective function; it includes transportation and inventory holding costs) of the various scenarios. The customer information enrichment shows cost improvements (relative percentage changes range from 1% to 16%) as it merges the detailed geographical information about the customer location in the planning process. The gains are considerable for lower demand rates. We argue that in case of lower demand rates, the exact magnitude and positioning of stock units in the network is more critical. The use of customer

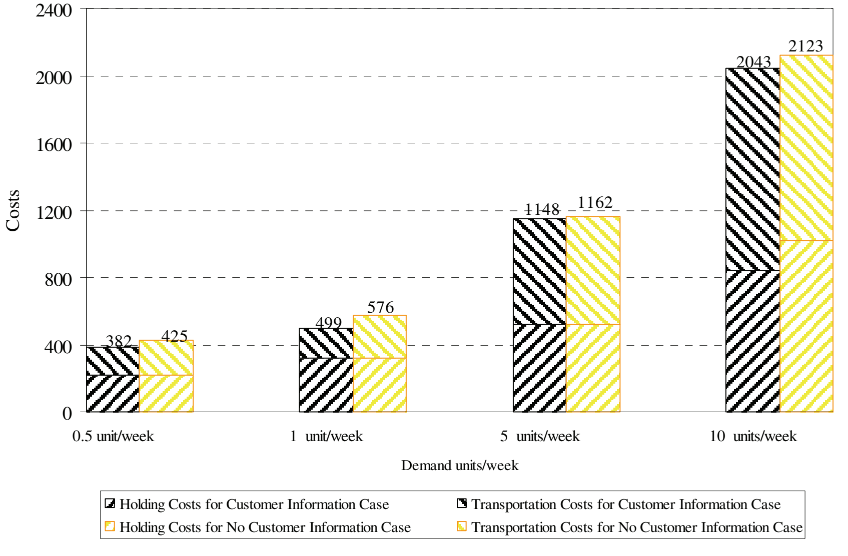


Figure 3.2: Comparison between No Customer Information and Customer Information Scenario (Information Enrichment)

information facilitates the improved stock positioning in the network and subsequently provides cost improvements by reducing the transportation needs. In addition, the installed base also provides detailed information regarding the neighborhood region for each customer. For higher demand rates, this customer information led to slightly lower stock requirements. This is due to the fact that fewer stock units are needed to meet the global service level constraint during the optimization. Due to this, it results in lower inventory holding costs for this scenario.

Scenario 2 - Large Installed Base

In this section, we present the value of installed base data for a large installed base scenario. The size of the installed base is 23,885 machines. For various typically observed cumulative network demand rates (units/week) at IBM, we present the gains of using installed base information in Figure 3.3. In this comparative analysis, we observe

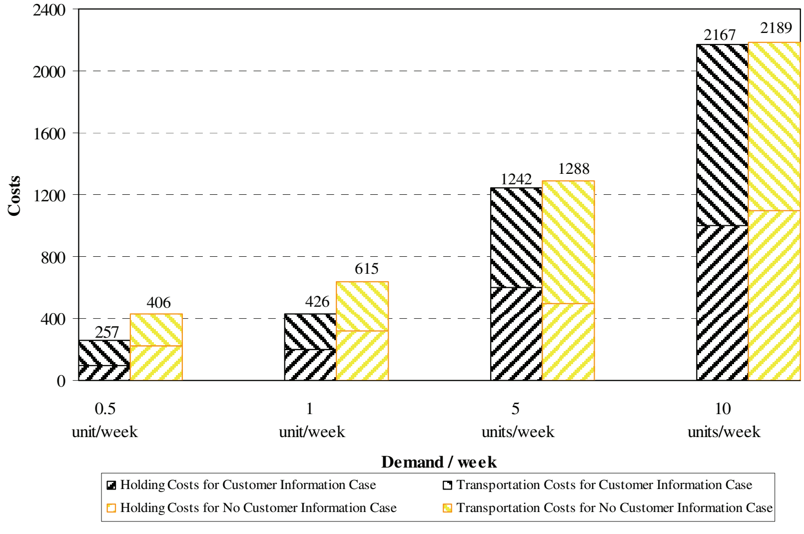


Figure 3.3: Comparison between No Customer Information and Customer Information Scenario (Information Enrichment)

even higher gains (1% to 58%) of using installed base information for various demand rates. The cost savings primarily occurred due to the combination of lower stock requirements and reduction of transportation costs in the (installed base) information enriched scenarios. We should note that our results do not support the argument that installed base information enrichment will always result in lower transportation costs or lower inventory costs. Instead, the benefits of installed base information enrichment are in terms of total costs only. The cost savings are greater at lower demand rates. The results confirm our earlier argument that the benefits of using installed base information are particularly relevant for lower demand rates.

3.6 Data Quality and its Analysis

The resultant data quality in a specific database system is the by-product of its design, implementation and usage. It is due to the human-machine interface that most of the erroneous data are generated. This implicitly highlights the need to account for the contextual aspects of the decision situation at hand (e.g. business environment of spare parts planning) during the impact assessment of erroneous data.

3.6.1 Installed Base Data Quality Variation and its Analysis

There are many systematic reasons that influence the nature of erroneous data. These reasons relate to the business environment of spare parts logistic and are identified via discussions with the planning experts at IBM. In this section, we list some of the reasons that account for frequent data errors in installed base data.

Homogeneously Distributed Error - Missing Value Error and Wrong Value Error

Due to human mistakes during data collection and data entry process, we observe completeness and accuracy errors in installed base data. For example, if a specific install is not listed in the installed base data, then the completeness aspect of the data quality is observed (i.e., missing value error). On the other hand, if the install is listed, but location information is incorrectly recorded (i.e., wrong value error) then it would be categorized as an error pertaining to the accuracy aspect. In general, these mistakes typically occur at random due to human behavior during data collection and entry process; therefore, the error is distributed homogeneously throughout the customer base.

Heterogeneously Distributed Error - Head Quarter Error (i.e. HQ Error)

A common cause for erroneous installed base data could relate to a customer who owns a large percentage of the installed base. In this error scenario, the spare parts logistics provider has listed the customer's company head quarter as machine installation location for all machines. In reality, the machines are installed at many sub-offices of the company. Note that in such a situation, the total size of the installed base remains the same, but a certain number of installs from the complete region are listed at a single location.

Heterogeneously Distributed Error - Primary Stock Location Error (i.e. PSL Error)
In many instances, installed base data contains partial information (e.g. incomplete street or city address) regarding the location of the specific installed machine. In such a case, the planning procedure usually attempts to assign the installed machine to the primary (nearest) stock location.

Heterogeneously Distributed Error - Data Communication Error
In many regions, the OEM sells its machines in partnership with local IT vendors. Due to a mismatch between the data collection procedures and the IT systems used, the customer location information is not transferred to the spare parts logistics provider (i.e., Data Communication Error).

Experimental Design

We observe that the errors caused by various business phenomena may have different characteristics. In Table 3.2, we classify the various completeness and accuracy errors according to the case context of geographical error distribution. The procedure adopted

Table 3.2: Classification of Error Causes according to their Geographical Distribution

		Case Context – Geographical Distribution	
		Homogeneously Distributed Error	Heterogeneously Distributed Error
Data Quality Characteristics	Accuracy	– Wrong Value Error	– HQ Error – PSL Error
	Completeness	– Missing Value Error	– Data Comm. Error

to analyze these various error scenarios is similar to the procedure outlined in the information enrichment case (see Section 3.5). In this case, we take the customer (installed base) information enriched scenario as a baseline and perform optimization runs to acquire baseline scenario planning costs. Subsequently, we induce errors in the dataset by omitting certain installs according to the specific business phenomenon. For example, the accuracy error of missing value type represents the situation when certain installs are not listed in the installed base data. This error occurs homogeneously throughout the customer base. For this purpose, we categorize the country level baseline installed base into many smaller regions. Within each region, a certain frequency of installs are deleted at random. This ensures that within each region the errors occur at random, however, the total frequency of errors in each region is similar. We devise various error frequency levels according to each error scenario. Note that due to the error induction, the set N, λ_j, and y_{ij} are different from the baseline situation. For each error frequency, we perform an optimization run on the planning model and acquire the stock plan. The cost deviations are acquired by fixing the error prone stock plans in the baseline scenario by using the constraints outlined in Section 3.5.1.

In the following sections, we analyze the above completeness and accuracy errors by organizing them according to their geographical distribution. Table 3.3 outlines the experimental design for the impact analysis of installed base data quality. As mentioned

Table 3.3: Experimental Design - Data Quality Analysis

Scenario		Installed Base Size	Analyzed Error Frequency	Demand Rate
Homogeneous Error Distribution	Completeness Error / Missing Value	Small = 140 Installs	10%, 20%, 30%	1 Unit / week
		Small = 140 Installs	10%, 20%, 30%	10 Unit / week
		Large = 23,885 Installs	10%, 20%, 30%	1 Units / week
		Large = 23,885 Installs	10%, 20%, 30%	10 Units / week
	Accuracy Error / Wrong Value	Small = 140 Installs	10%, 20%, 30%	1 Unit / week
		Small = 140 Installs	10%, 20%, 30%	10 Unit / week
		Large = 23,885 Installs	10%, 20%, 30%	1 Units / week
		Large = 23,885 Installs	10%, 20%, 30%	10 Units / week
Heterogeneous Error Distribution	HQ Error	Small = 140 Installs	10%, 20%, 30%	1 Unit / week
		Small = 140 Installs	10%, 20%, 30%	10 Units / week
	PSL Error	Small = 140 Installs	10%, 20%, 30%	1 Unit / week
		Small = 140 Installs	10%, 20%, 30%	10 Unit / week
	Data Comm. Error	Small = 140 Installs	10%, 20%, 30%	1 Unit / week
		Small = 140 Installs	10%, 20%, 30%	10 Unit / week

in Table 3.3, these error scenarios were analyzed for various demand rates and installed base sizes. The choice of the error frequencies is made to understand the impact of data errors on the robustness of the planning method at various error concentrations. These chosen error frequencies cover the actual error concentrations in IBM's installed base data. In fact, our attempt here is to go further and analyze the optimization model's behavior even at exaggerated levels of error frequencies. As mentioned earlier in Section 3.5.1, the installed base data used for these analysis belongs to the various IBM products. Other parameters (such as demand rates for the entire region and holding costs) in these scenarios are formulated to represent the observed characteristics of the planning system at IBM. For example, the observation of errors in large installed base sizes is only plausible for homogeneous errors. The choice of the associated demand rates is also in agreement with the typically observed demand rates for small and large installed base sizes.

3.6.2 Results of Data Quality Assessment

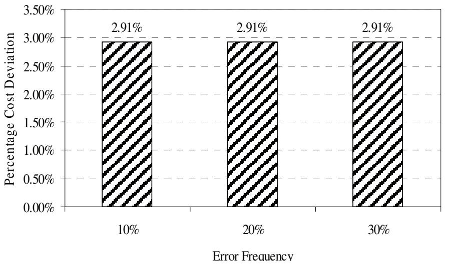
In this section, we analyze the impact of the various information quality aspects outlined in Section 3.6.1. In the first step, we analyze the effect of various error frequencies in the homogeneously distributed error case. Subsequently, we examine the heterogeneously distributed error case by devising the scenarios to depict the underlying business phenomena as outlined in the previous section.

Homogeneously Distributed Error

For the homogeneously distributed error in the installed base data, we formulate the associated scenarios for the accuracy and completeness error in small and large installed base sizes.

Scenario 3: Homogeneously Distributed Completeness Error

Figure 3.4 depicts the results of the completeness aspect of the homogeneously distributed error (i.e., Missing Value Error) for a small installed base case at demand rates of 1 unit/week (Fig. 3.4a) and 10 units/week (Fig. 3.4b). The test bed parameters are listed in Appendix - 3A. We observe that, despite having highly erroneous installed base data, the results show trivial losses due to data quality degradations. The losses can be explained from the fact that, due to homogeneously induced error, the demand sizes at each individual postal code homogeneously change throughout the network.



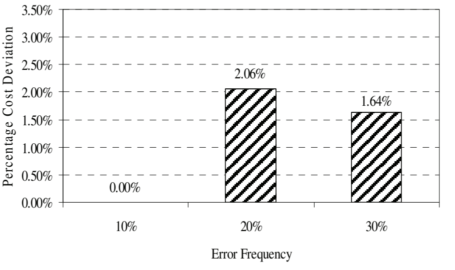


Figure 3.4: Percentage Cost Deviation from Baseline for Completeness Aspect (Fig. 3.4a (left) Demand rate = 1 unit/week, Fig. 3.4b (right) Demand rate = 10 units/week)

As a result, the overall geographical distribution of the installed base is preserved to a large extent. In erroneous scenarios, the requisite quantity of stocks in the entire network is similar to the baseline case. The only variation in costs results due to slight geographical shifts in stock positioning decisions. This incurs cost variations in terms of additional transportation costs. For lower demand rates, these variations are unable to offset the gains of using installed base information. In case of a higher demand rate (i.e. 10 units/week), we observed in Section 3.5.2 that the gains of using installed base data are small. Therefore, the small losses in the caae of a higher demand rate (Figure 5b) are able to negate the gains of using installed base data.

The above argument regarding the preservation of the geographical distribution for homogeneously induced error is particularly valid in large installed base scenarios. These scenarios were analyzed according to the listed variations in the experimental design (Table 3.3). It should be noted that no losses were observed for large installed base scenarios at all error frequencies and demand rates. We argue that in the case of a large installed base, we tend to normalize any asymmetric effects of errors in the geographical distribution of installs.

Scenario 4: Homogeneously Distributed Accuracy Error

In this scenario, we simulate the homogeneously distributed accuracy dimension due to data entry errors. In this case, the erroneous install listing represents the installed machine which is listed at the wrong address in the installed base data. The test bed parameters are depicted in Appendix - 3A. Figure 3.5 depicts the results of this

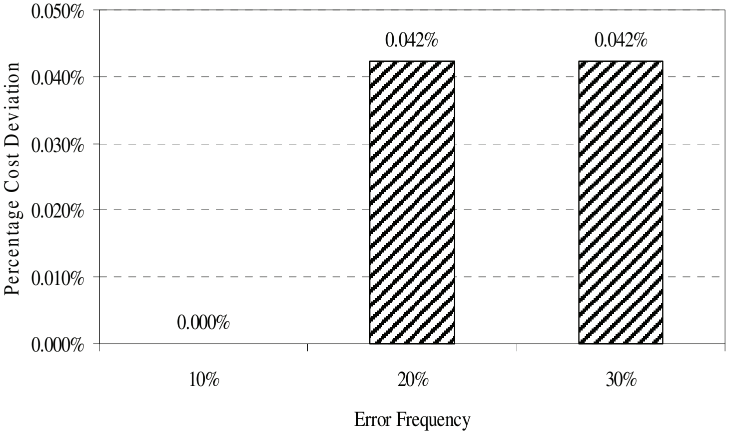


Figure 3.5: Percentage Cost Deviation from Baseline for Accuracy Aspect

experiment for a small installed base at a demand rate of 1 unit/week. We observe the negligible impact of erroneous installed base data. The explanation for the low impact is similar to the previous case of completeness error. The cost deviations are incurred due to the additional transportation costs. For 10 units/week demand rate scenarios of small and large installed base sizes, and 1 unit/week demand rate for a large installed base, we do not observe any impact of the error scenarios in our analysis.

We observed in the previous scenarios for the homogeneous error that despite having a very high frequency of errors in the installed base, the losses are somewhat insignificant compared to the gains of using the installed base. This is particularly valid for lower demand rates, where additional information considerably improves the stock positioning decision. In the next section, we analyze heterogeneously distributed errors in installed base data to observe their impact on spare parts planning.

Heterogeneously Distributed Error

In this section, we analyze the impact of heterogeneously erroneous data due to various business situations listed in Section 3.6.1. We formulate these scenarios by using the customer (installed base) information enriched situation as a baseline and induce errors in the dataset by following the underlying behavior of the business phenomena.

Scenario 5: Heterogeneously Distributed Accuracy Error - HQ Error

Due to the specific business situation (as outlined in Section 3.6.1), a concentration of installs is listed at a single location; whereas in reality, these installs are geographically dispersed at various locations. We formulate this behavior at varying levels of error intensity and subsequently observe the system behavior at different demand levels. The test bed parameters are again listed in Appendix - 3A. Figure 3.6 shows the planning system behavior for this scenario.

Due to the slow moving nature of spare parts demand, 1 unit per week (for the complete network) is the typically observed demand for such an installed base size. The 10% error case relates to a customer who owns 10% of the total installs. The spare parts logistics provider has listed all the specific customer's installs at the company's head quarter location. In reality, the machines are dispersed homogeneously throughout the geographical network at the sub-locations. We observe cost variations from 2.92% to

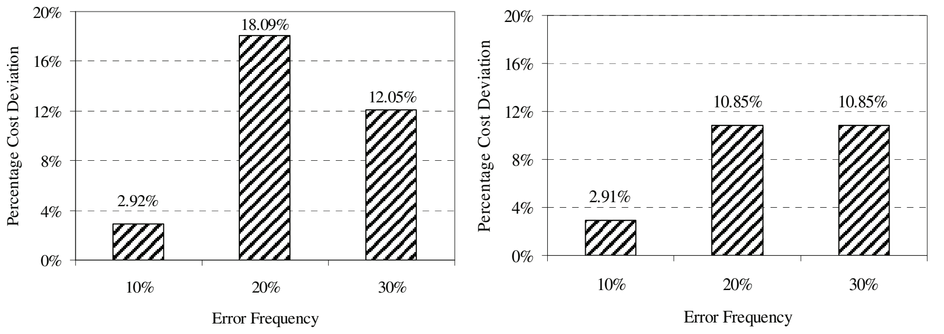


Figure 3.6: Percentage Cost Deviation from Baseline (HQ Error) (Fig. 3.6a (left) Demand rate = 1 unit/week, Fig. 3.6b (right) Demand rate = 10 units/week)

18.09% approximately for various error cases at 1 unit/week demand (Figure 3.6a). For the higher demand category (i.e., 10 units/week, Figure 3.6b), the cost deviations are 2.91% to 10.85%. Note that in both of these scenarios; the costs of poor data quality offset the benefits of using installed base data for some error frequencies (see Section 3.5.2).

For the lower demand rate scenario, the losses are observed due to the following situation. During the optimization, the stock outflows originating from a single stock location to all nearby customer locations are accumulated. The corresponding stocking decision for the stock location is the lowest integer value that is higher than the accumulated outflows from that stock location. Due to the HQ error, we place a higher demand requirement at a single postal code. Therefore, the optimization accumulates all these flows to the nearby stock location and satisfies the service level constrains at a lower stock placement level. As a result, the overall stock placement in the network is lower than the baseline case due to the accumulated flows at a single stock location. There is a higher build-up of stock at a single location. Therefore, the transportation costs to serve the actual installed base (i.e., baseline installed base) are also higher.

In the higher demand case, as a result of optimization, we tend to place higher stock units at the HQ error inducing customer's postal code. This results in extra holding and transportation costs due to erroneous placement of stocks at a specific location.

Scenario 6: Heterogeneously Distributed Accuracy Error - PSL Scenario

In this scenario, the installs with incomplete location data are assigned to the nearest stock location's postal code. We analyze this scenario by using the test bed parameters listed in Appendix - 3A. Figure 3.7 depicts the results for this scenario. For a demand rate of 1 unit/week we observe cost variations of 0.00% to 1.64%. In this case, the total

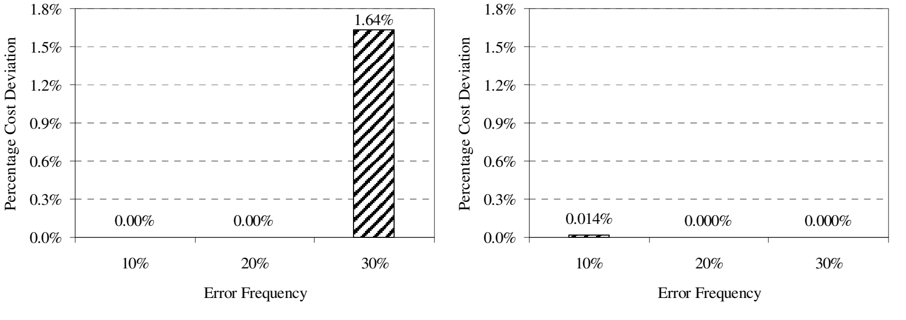


Figure 3.7: Percentage Cost Deviation from Baseline (PSL Error) (Fig. 3.7a (left) Demand rate = 1 unit/week, Fig. 3.7b (right) Demand rate = 10 units/week)

stock placement in the entire network is the same for the baseline and the erroneous scenario. The minor cost deviations relate to the increased transportation costs due to inaccurate stock positioning in the erroneous scenarios. Similar is the situation for the higher demand rate, where additional transportation costs result for some error frequencies due to the inaccurate positioning of stock.

Scenario 7: Heterogeneously Distributed Completeness Error - Data Comm. Error

In many situations, OEM sells its products through a partnership with the local vendor. Due to IT infrastructural or procedural shortfalls, the sales information is not fully communicated to the OEM. This results in an erroneous installed base for a specific sub-region. In this section, we analyze this situation and observe the cost variations for such scenario at various demand rates. Figure 3.8a depicts the relative cost deviations

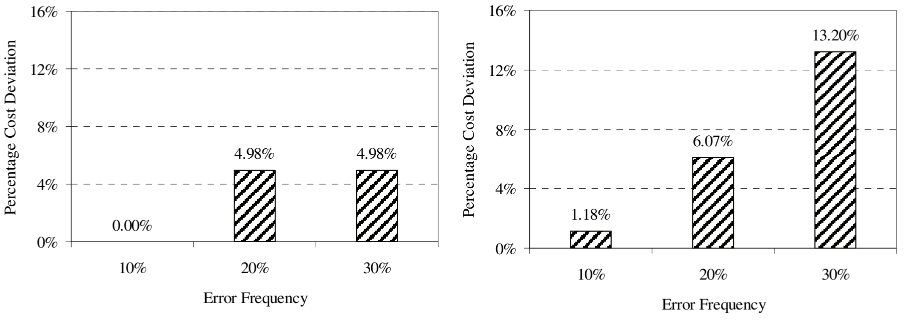


Figure 3.8: Percentage Cost Deviation from Baseline (Data Comm. Error) (Fig. 3.8a (left) Demand rate = 1 unit/week, Fig. 3.8b (right) Demand rate = 10 units/week)

of 0.00% to 4.98% for 1 unit/week demand rate. The inaccurate placement of stocks in erroneous scenarios leads to an increase in transportation costs. Figure 3.8b depicts the results for the higher demand rate. In this case, the combination of inaccurate stock quantities and inaccurate stock positioning contributes to the losses. Also note for this scenario, that the losses due to inaccuracies in installed base are much higher than the observed gains of using installed base data.

We observe in the above heterogeneous error scenarios that there are additional costs incurred due to the variations in installed base data quality. Depending on the error structure induced by each of the error scenarios, the results vary. In many cases, the losses due to inaccuracies negate the benefits of using installed base data.

3.7 Discussion and Conclusions

In this chapter, we analyzed the gains of using installed base data in spare parts planning. We also identified the various types of data errors that are present in installed base data, and analyzed the impact of these errors on spare parts planning performance. Table 3.4 summarizes the results of the numerical study. The positives represent situations where the overall value enhancement due to the information enrichment is not negated by the data quality errors. The negatives represent the situations where data quality errors have negated the value enhancement of information enrichment. We observe that the gains of using installed base data are significant. This is particularly relevant for low demand rates (a predominant characteristic in spare parts logistics). We classify the

Table 3.4: Summary - Effects of Information Enrichment

Installed Base Size	Demand Rate	Information Enrichment with No Error	Information Enrichment with Error				
			Homogeneous Error		Heterogeneous Error		
			Missing Value Error	Wrong Value Error	HQ Error	PSL Error	Data Comm. Error
Large	Low	+	+	+	N/A	N/A	N/A
	High	+	+	+	N/A	N/A	N/A
Small	Low	+	+	+	–	+	+
	High	+	–	+	–	+	–

various types of data errors in installed base data as homogeneous and heterogeneous with respect to the geographical distribution of machines. We observe in homogeneous error scenarios that the large frequencies of errors in installed base data typically do not result in significant impact. Therefore, the benefit attained by information usage is preserved. This is related to the robustness of the planning method. We observe that the planning method positions inventories in the network based on the geographical distribution of demand. If the overall geographical distribution of demand is preserved, the planning method shows little sensitivity to the geographical displacement of customer locations. In the homogeneous error case, despite having large errors percentages; the regional demand's contribution to optimization remains the same. Because, by having errors homogeneously distributed, we tend to homogeneously inflate the demand for the rest of the installs by proportionally distributing demand over the installed base. Due to this, we do not observe significant cost deviations in homogeneous error cases. This observation is in line with Fildes et al. (2008), who suggest that the effectiveness of a forecasting method is linked to the organizational context in which the planning model will be applied. Observe that we assume that the size of the installed base is accurate in all scenarios. This allows us to compare the scenarios using cost analysis.

In general, we observe higher cost deviations in heterogeneous error cases. The geographical synergy effect of forecasting via an installed base spreading and planning method does not provide robustness against heterogeneous errors. Since, by having the heterogeneously distributed error, we tend to disturb the proportionality of the original geographical distribution of demand. For the heterogeneous error scenarios, we observed that the gains of installed base data usage deteriorated. To summarize, we list the following implications and conclusions from our analysis.

- There are potentially significant gains in using detailed customer's geographical information (i.e., installed base data) for the planning of network inventory in a multiple stock locations and geographically dispersed customers setting.

- It is beneficial to use installed base data for spare parts planning. However, one should identify, understand and align the business environment of data acquisition and usage to acquire maximum gain.

- Data quality has been researched from various standpoints. In OR research, it has been mainly analyzed from the sampling error aspect, whereas, in many OR application situations, the realistic situation extends to various other quality dimensions. Therefore, it is useful to extend the data quality research in OR to include the data quality dimensions as described by IS research. However, one should account for the planning context. For example, we observe that an accuracy error is present in both homogeneously and heterogeneously distributed error cases. Only in the heterogeneous case, the impact is significant.

- We also argue that spare parts planning managers should attempt to understand the business phenomena that induce certain data errors. This supports the prioritization of data quality improvement investments.

- We also observe that the relative gains are greater for smaller demand rates, since the stock positioning decision is more important due to less available redundancies in that case. Therefore, there is a strong case for using the customer's geographical information for slow moving demand situations.

3.8 Limitations and Generalization

Finally, we will comment on the replicability and generalizability of the results presented in this chapter. The results presented in this chapter belong to a mixed integer program of inventory distribution type with lateral transshipments, regular and emergency transportation costs, and time based service levels (see Section 3.2). The procedures to use installed base data to derive demand forecasts, travel times and transportation costs are mentioned in Section 3.2.1. We outline the analysis procedure for information enrichment and information quality analysis in Section 3.5.1 and Section 3.6.1. The parametric values used in numerical experiment are provided in Appendix - 3A. For data quality experiments, we outline how the errors are induced in installed base data (see Section 3.6.1 for example). The only missing parameters are the ones associated with installed base data. We are unable to provide the actual locations and transportation cost information from product installs to stock locations due to confidentiality reasons (since the analysis is performed on the installed base of IBM's product). However, we attempt to provide sufficient characteristics of product installed base and stock location network for clear understanding of the reader.

We understand that the results provided in this chapter depend on the planning situation, characteristics of the product installed base and stock location network. For any system with slow moving demand, significant variation between emergency and regular transportation costs and overlapping stock locations, the results presented in this chapter would hold. The geographical overlapping of serving locations, emergency shipments and time based constraints play an important role in our findings. The same results may not completely hold if we study a model that does not allow these characteristics. Beside spare parts placement in spare parts supply chains, many facility location and network design problems are similar in nature. The results of this study may also be applicable in these settings.

Appendix - 3A

Test Bed Parameters

Table 3.5: Test Bed Parameters

Scenario No.	Normal Transportation Cost from Field Locations (€)	Emergency Transportation Cost from Central Location (€)	Holding Cost for Field Locations	Holding Cost Rate for Central Location	Unit Cost (€)	Service Level
1	Fixed: 57, Var.: 0.12/km	1250	0.25	0.05	400	0.9
2	Fixed: 57, Var.: 0.12/km	1250	0.25	0.05	400	0.9
3	Fixed: 57, Var.: 0.12/km	1250	0.25	0.05	400	0.9
4	Fixed: 57, Var.: 0.12/km	1250	0.25	0.05	400	0.9
5	Fixed: 57, Var.: 0.12/km	1250	0.25	0.05	400	0.9
6	Fixed: 57, Var.: 0.12/km	1250	0.25	0.05	400	0.9
7	Fixed: 57, Var.: 0.12/km	1250	0.25	0.05	400	0.9

Chapter 4

Spare Parts Execution Management

4.1 Introduction

In this chapter[1], we highlight the benefits of using installed base data in spare parts execution management. In Section 2.7.1, we discussed the current execution management practices at IBM spare parts logistics. Consistent with the discussion in Section 2.8, we develop a customer value based execution technique that uses installed base data for spare parts execution management. The technique developed accommodates the customer base heterogeneities by introducing sourcing flexibility in the execution decision space. We then perform a comparative numerical analysis with the current execution scheme at IBM (i.e. the baseline situation) to highlight the benefits of using installed base information. To summarize, the contributions of this chapters are as follows:

- We study a real life spare parts logistics execution system at IBM that is based on first in - first out rule. We highlight the limitations of such execution rule to support customer based heterogeneities in spare parts logistics execution.
- We present a multi-period MDP formulation that represents the important charac-

[1] This chapter is based on working paper *Revenue Management and Spare Parts Logistics Execution* (Jalil et al., 2010a).

teristics of the spare parts logistics execution; namely customer heterogeneity, and short term sourcing flexibility. Previous literature for jointly addressing these two aspects is scarce.

- We discuss the structural properties of the model, and develop an efficient greedy heuristic solution for the spare parts logistics execution.
- We compare the proposed heuristic solution with the traditional execution practice of first in - first out. We show that accommodating customer based heterogeneities in spare parts logistics execution yields significant gains.

The chapter is organized in the following manner. First, we discuss the associated academic literature in the area of inventory rationing and quantity based revenue management. Next, we formulate the problem in a formal manner. By performing a structural analysis of the associated Markov Decision Process (MDP) formulation, we develop computationally efficient heuristics for execution management. Finally, we perform numerical experiments to depict the benefits of using installed base data for execution management and conclude the chapter.

4.2 Literature Review

Exploiting the heterogeneities in a customer base for improved planning and execution is not a new concept. Significant literature exists in the field of inventory rationing and revenue management (RM) that incorporates these concepts. The relevant inventory rationing literature has been discussed in Section 2.5.2. In this chapter, we restrict our discussion to the most relevant work in inventory rationing.

4.2.1 Inventory Rationing

In this section, we discuss inventory rationing literature that relates to multi location logistics networks. For broader scope of single and multi location logistics networks, we refer the reader to Kleijn and Dekker (2000) and Teunter and Haneveld (2008). The relevant work in inventory rationing for multi location logistics networks is discussed by Grahovac and Chakravarty (2001), Axsäter (2003), and Minner et al. (2003). Grahovac and Chakravarty (2001) discuss a lateral transshipment solution for the two-echelon inventory network with one upstream location, n downstream locations and a one-for-one inventory policy. The possibility of lateral transshipment is only considered when the stock at the sending stock location is above a static critical level and stock at the receiving stock location is below a static critical level. Minner et al. (2003) studied a similar inventory network situation with an (s, Q) inventory policy with the objective of minimizing the expected risk of a future stock out. Axsäter (2003) presents a decision rule to decide on the possibility of lateral transshipment with an assumption that no future lateral transshipments would take place. The network configuration considered is similar to that of Grahovac and Chakravarty (2001) with an (r, Q) inventory replenishment policy. We, on the other hand, make no such assumption regarding future lateral transshipments. Moreover, the inventory replenishment policy considered in our approach is different from the above papers (see Section 4.3 for details). The approach that we present in this chapter follows RM concepts. In the next section, we discuss the relevant RM literature.

4.2.2 Quantity Based Revenue Management

There is a rich body of literature in the field of RM. The main theme in this stream of literature is to optimally utilize the capacitated resource in the presence of heterogeneous demand. Talluri and Van Ryzin (2004) organize the RM literature as quantity based RM and price based RM. In our problem, the price charged to a specific customer is exogenous, therefore the category of quantity based RM is more relevant.

In this domain, the majority of the work extends from the Littlewood (2005) two class model. Various researchers, such as Belobaba (1989), Van Slyke and Young (2000), Subramanian et al. (1999), and Lee and Hersh (1993) have proposed static or dynamic formulations for single-leg airline RM while accommodating overbookings, no-shows, or cancellations. The n-class model with a Markov Decision Process (MDP) formulation was proposed by Lautenbacher and Stidham (1999). By using the work of Stidham (1978), the authors prove the concavity of the associated value function and optimality of a nested booking limit policy. In most practical situations, airline customers travel from origin A to destination B via a series of connecting flights. The associated RM problem for such a situation is termed as network RM problem. The extensions for multi-leg airline RM (also known as network RM) problems have been proposed by Curry (1990), Bertsimas and Popescu (2003), and Boer et al. (2002). Bertsimas and Popescu (2003) discuss and classify airline networks RM problem as origin - destination (OD) problem and itinerary based problem based on their network structure. OD problem relates to the network structure where each inventory source is presented to the customer in the form of origin and destination of all flight legs. Such network organization may result in a situation that a customer who is seeking an itinerary composed of a series of flight legs may be accepted on some flight legs, while rejected on others. To overcome this problem, Bertsimas and Popescu (2003) present an itinerary based inventory source network organization for airline Network RM. In spare parts logistics, the network consideration is such that the spare parts logistics network consists of many alternative inventory sources available at a single echelon. We will discuss the differences and similarities in these two network configurations further in Sections 4.3.2 and 4.4.2.

Due to the curse of dimensionality, it is not computationally feasible to deploy the MDP formulation in most practical settings (Powell, 2007). The RM literature discusses various approximation oriented techniques for efficient computations. The most widely discussed approaches approximate the marginal values (i.e. bid prices) through deterministic or probabilistic approximations. Various techniques, such as Deterministic Linear Programming (DLP)(Chen et al., 1998, 1999; Cooper, 2002), Probabilistic Non-Linear Programming (PNLP)(Boer et al., 2002; Williamson, 1992), Randomized Linear programming (RLP)(Talluri and Van Ryzin, 1999; Boer et al., 2002), and Dynamic Programming Decomposition (DPD)(Bertsimas and Popescu, 2003) are studied in the literature. Many of these techniques originate from variations of the knapsack problem and they solve the single-leg or multi-leg airline RM problem with varying levels of efficiency and accuracy. Williamson (1992) and Talluri and Van Ryzin (1998) have shown that the booking limits produced by the DLP has better asymptotic properties for large seat capacities and sales volumes. Therefore, the approximation of booking limits by DLP provides better results for these settings. We skip the details of these techniques and refer to Talluri and Van Ryzin (2004) for a comprehensive overview.

To summarize, the quantity based RM literature discusses dynamic, critical levels for serving a heterogeneous customer base, where the inventory source is either a single location or a sequential network. In this chapter, we present a dynamic control mechanism for a horizontal network of inventory source locations. Such a network configuration is typically observed in spare parts logistics situations.

4.3 Problem Formulation

In this section, we introduce our notation and provide a more formal problem description. Next, we present an MDP formulation for the current problem setting.

4.3.1 Problem Description and Notation

In accordance with figure 2.7 in Section 2.7.1, we consider a two tier inventory network with one supplier in the top tier and n FSLs of finite capacity in the bottom tier. Figure 4.1 depicts a schematic diagram of the inventory system with three FSLs and a supplier. At regular intervals (agreed upon between the supplier and service provider), the part shipments from the supplier arrive. The service provider uses these parts to replenish its FSL locations. The stocked spare parts at FSLs are further utilized to fulfil incoming demand requests. Between two regular shipment arrivals from the supplier, the service provider can also request an emergency part shipment from the supplier, albeit at an emergency shipment rate. In the current execution scheme, these emergency shipments are only ordered when the FSL network is out of stock (see Section 2.7.1 for details). We however attempt to relax this assumption in our approach.

All of the customers are dispersed at various geographical locations. The demand follows an independent Poisson process requesting one part at a time. Note that the part may represent a kit of spare parts fit for satisfying (generic) customer requests. A demand arrival can be fulfilled from any of the FSLs at regular transportation costs. The regular transportation costs are linearly increasing in distance with a fixed cost component. Upon demand fulfillment, each customer is charged a price as per their contractual agreement. The notation for the above setting is as follows:

Notations

Sets

N = Set of customers (indexed by j)

M = Set of source locations (indexed by i, with $i = 0$ for supplier and $i \in \{1, 2, 3, \ldots\}$ for FSLs)

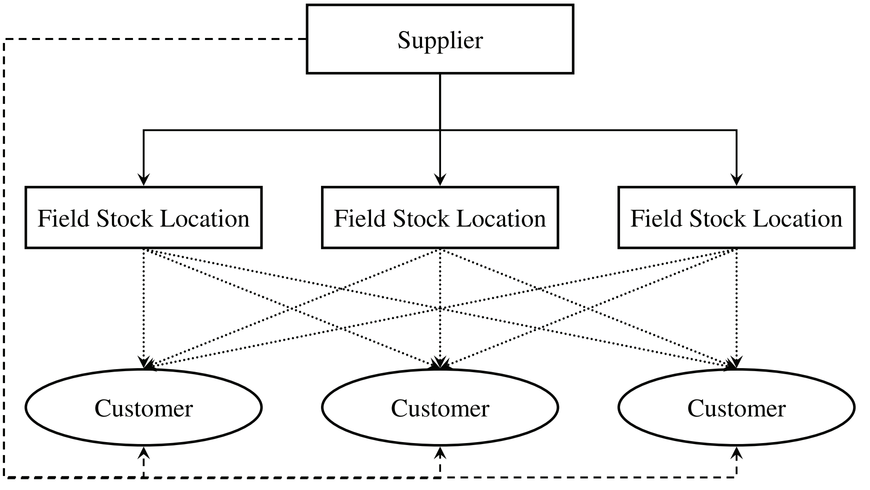


Figure 4.1: A Two Tier Inventory System

$t \in \{1, 2, ..., T\}$, Time intervals

Parameters

g_j = Service price charged to customer j
f_j^p = Penalty costs for customer j
f_{ij}^d = Transportation costs for service to customer j from location i
λ_j = Demand rate from customer j
x_i = Amount of inventory at a field stock location (FSL) i
$\vec{x} = \{x_1, x_2, ..., x_i\}$, Vector representing inventories at all field stock locations (FSLs)
$\vec{e}_i$ = A standard vector with zeros in all rows except the ith row, which takes the value 1
$R_{ij} = g_j - f_{ij}^d + f_j^p$

The notation j and i represent the indices for customers and inventory source locations, respectively. The length of each time interval is represented by t and the total horizon length is T, which corresponds to the duration between two consecutive regular replenishment arrivals from the supplier. In other words, all field stock locations receive replenishments at the start of horizon. It should be noted that time instants

$t = \{1, 2, \ldots, T\}$ represent the beginning of each period t. The end of the last period is denoted by $T + 1$. The variable x_i denotes current inventory level at each field stock location at each time instance $t = \{1, 2, \ldots, T\}$. It is easy to note that x_i changes over time and does not represent base stock level of each field stock location i (even at $t = 1$). The parameter g_j represents the price charged to the customer against the provision of a unit of service. In the subsequent text, the term *high paying customer* refers to a customer who pays a relatively high service price due to the premium contractual agreement with the service provider. The *low paying customer* is a customer who does not hold any premium service contract and pays a lower service price. The transportation costs from any FSL i to a customer j are represented by f_{ij}^d (superscript d identifies the transportation aspect). The penalty cost parameter f_j^p represents the costs associated with the service denial from the FSL network (superscript p identifies the penalty aspect). It represents the emergency transportation costs incurred by the service provider. It could also represent the opportunity losses incurred by the service provider due to service deadline violation. The parameter R_{ij} reflects the value associated with each service fulfillment. It accounts for the price the customer pays, incurred transportation costs, and saved penalty cost for each service request fulfillment. Next we discuss some of the modeling assumptions that reflect the business context of the spare parts logistics system.

ASSUMPTION 1. *Demand orders from each customer follows an independent Poisson process.*

The Poisson assumption is common in many RM applications and spare parts logistics. In a spare parts logistics situation, demand realization is the result of a machine failure. It is plausible to assume that machine failures at various customer locations occur independently. We also assume that each machine failure requires no more than one spare part unit (of a specific type) for machine maintenance. It should be noted that due to Poisson assumption, an implicit transition from a continuous-time demand process to a demand process at discrete time points is being assumed where demand arrives at the start of time period t. We further assume that utmost one demand order arrives during each time interval t.

ASSUMPTION 2. *If* $g_m > g_n$ *where* m *&* $n \in N$, *then* $f_m^p \geq f_n^p$.

This assumption extends from the nature of the service agreements in spare parts logistics. If the service deadline is missed for a high paying customer, then the penalty costs (due to opportunity losses) are higher.

With these assumptions, our objective is to maximize the profits when deciding to serve a realized demand from any of the FSLs or the supplier. We intend to maximize the profits over a finite horizon, while considering service prices, transportation costs, and penalty costs. Upon arrival of customer j at time t, we need to observe the following trade-offs to make the above decision: (a) the profit of serving customer j at time t from FSL i *versus* the profit of serving a subsequent customer j' from FSL i at some time in the future, and (b) the profit of serving customer j at time t from FSL i *versus* the profit of serving customer j at time t from another FSL i'. By observing these tradeoffs, we choose the optimal i for serving each customer j.

4.3.2 MDP Formulation

We now present the MDP model for the problem described in Section 4.3.1.

$$V_t(\vec{x}) = V_{t+1}(\vec{x}) + \sum_{j \in N} \lambda_j \left[\max_{i \in M} \left\{ R_{ij} - \triangle_i V_{t+1}(\vec{x}) \right\} \right] - \sum_{j \in N} \lambda_j f_j^p$$

$$V_{T+1}(\vec{x}) = 0, \qquad V_t(\vec{0}) = 0,$$

$$\text{where} \qquad \triangle_i V_{t+1}(\vec{x}) = V_{t+1}(\vec{x}) - V_{t+1}(\vec{x} - \vec{e}_i).$$

The above formulation is a decomposition of the standard Bellman equation. Commonly used in RM literature, it decomposes the problem into the demand realization steps of a single unit. We further assume that $V_{T+1}(\vec{x}) = 0$ and $V_t(\vec{0}) = 0$. It is easy to note from the above formulation that the optimal policy originates from the inner maximization of the value function. Starting from the boundary conditions $V_{T+1}(\vec{x})$ and $V_t(\vec{0})$, we proceed with backward recursion in time t and inventory $\vec{x}$ to compute the optimal FSL i for serving customer j at each t. Note the similarities of the above formulation with Lautenbacher and Stidham (1999). The difference is in terms of multiple inventory source locations $\vec{x}$ and penalty costs f_j^p. The above formulation is also similar to Bertsimas and

Popescu (2003) except for the structure of underlying inventory source network and penalty costs.

4.4 Structural Analysis and Heuristic Solution

We first discuss the structural properties of the MDP formulation.

4.4.1 Structural Analysis

In Section 4.2.2, we highlighted that OD problem in airline RM relates to the network structure where each inventory source is presented to the customer in the form of origin to destination of the flight leg. Consider two itineraries based travel plans A-B-D and A-C-D with flight legs A,B,C, & D. Each flight leg A, B, C, & D are accounted distinctly as an inventory source in OD configuration. Such network organization may result in a situation that a customer who is seeking an itinerary composed of a series of flight legs may be accepted on some flight legs, while rejected on others. Moreover, a customer is usually interested in some specific flight legs only that fit its itinerary travel plan.

An alternate way to model airline RM problem is via itinerary based inventory network configuration. The underlying network structure of itinerary based network RM problem is such that seat inventories of consecutive flight legs are represented as a single inventory unit according to each itinerary. In this case, each itinerary A-B-D and A-C-D are distinct inventory units. It may occur that intermediate legs B & C are are also shared by other itineraries. In addition, an airline may offer itineraries A-B-D, A-B, and B-D to its customers. In such a case, accepting a customer for A-B itinerary involves risking a no sale on D flight leg. In spare parts logistics execution each customer can be served from any of FSLs in the logistics network. A similar situation may exist in airline RM problem where the itineraries do not share any flights legs with other itineraries and each customer is path indifferent (i.e. willing to travel via any itinerary). We should however note that due to practical reasons, such network configuration is highly unlikely in airline RM.

The multi-dimensional MDP formulation for spare parts logistics execution retains many structural properties of the multi-dimensional MDP formulation presented by Bertsimas and Popescu (2003). It can be shown that the value of additional inventory units is non-negative (i.e. $V_t(\vec{x} + \vec{e_i}) \geq V_t(\vec{x})$). In addition, the marginal value of each inventory unit is concave in additional inventory units (i.e. $\triangle_i V_t(\vec{x}) \geq \triangle_i V_t(\vec{x} + \vec{e_i})$) and remaining time (i.e. $\triangle_i V_{t+1}(\vec{x}) \leq \triangle_i V_t(\vec{x})$). From these results, one can deduce that if a specific customer is chosen to be served given a specific $\vec{x}$ and t, it would always be served for: 1) all greater amounts of $\vec{x}$, given t remains constant, and 2) all remaining time periods t, given $\vec{x}$ remains constant.

We should also note that nested protection levels cannot be devised for spare parts logistics execution, since, $\triangle_i V_t(\vec{x})$ does not behave in a consistent manner over the set M. Suppose we order the set M according to decreasing values of R_{ij}, then the behavior of $\triangle_i V_t(\vec{x})$ over the ordered set M is non-monotonic. This behavior varies according to the variations in t and each x_i. This is due to the fact that MDP formulation for spare parts logistics execution does not exhibit a certain type of cross concavity property called decreasing differences that is proposed by Karaesmen and Van Ryzin (2004). For this reason, we resort to an online search algorithm that (upon demand arrival) attempts to maximize $(R_{ij} - \triangle_i V_{t+1}(\vec{x}))$. We should note that our exhaustive search algorithm is similar to certainty equivalent control proposed by Bertsimas and Popescu (2003). Note that the computational complexity of this online algorithm (that is based on exhaustive search over M) is also not very attractive. In Section 4.4.3, we provide a greedy search algorithm that reduces the computational complexity considerably while performing quite competitively to the exhaustive search. We shall discuss the details in Sections 4.4.3 and 4.5.3.

The MDP approach to calculate $\triangle_i V_t(\vec{x})$ strongly suffers from the curse of dimensionality due to the multidimensional nature of $\vec{x}$. In the next section, we first discuss the approximation of $V_t(\vec{x})$. Next, we present a heuristic based approach that could be easily implemented in any large scale spare part logistics application.

4.4.2 Approximation of Value Function

The term $\triangle_i V_t(\vec{x})$ represents the marginal value or bid price of an inventory unit at any FSL location i. The approximation solution for the marginal values $\triangle_i V_t(\vec{x})$ is a subject of interest to many researchers in RM as discussed in Section 4.2.2. The primary motivation is to avoid the recursive computations that are needed in the MDP. In this section, we discuss a linear programming based approximation solution for the marginal values. Note that the MDP formulation could be viewed as an online version of the knapsack problem. It is due to this reason that many approximations to efficiently compute marginal values attempt to utilize the associated knapsack problem (see Section 4.2.2). Similar to the RM literature, the primary idea is to utilize the expectation of demand to devise the knapsack formulation. In comparison to the single choice knapsack formulations utilized in RM literature, the horizontal nature of a spare parts logistics network yields a multiple choice knapsack formulation. The devised formulation enables an approximation of $V_t(\vec{x})$. We define a decision variable U_{ij} that represents the stock units reserved for customer j at stock location i. The reserved stock units for all customers at a specific FSL i should not exceed the total capacity of the FSL, which is represented by following supply constraint:

$$\sum_{j \in N} U_{ij} \leq x_i \qquad \forall\, i \in M \qquad \text{(Supply Constraint)}$$

In addition, the reserved stock units for any customer j should not exceed the total incoming demand from customer j. Here $(T-t)$ denotes the length of the remaining horizon.

$$\sum_{i \in M} U_{ij} \leq \lambda_j (T-t) \qquad \forall\, j \in N \qquad \text{(Demand Constraint)}$$

With these constraints, our objective is to maximize the total profits for the remaining horizon, while considering service prices g_j, transportation costs f^d_{ij}, and penalty costs f^p_j. We formulate our objective as follows:

$$\textit{Obj. fn.} = \sum_{j \in N} \sum_{i \in M} (g_j - f^d_{ij}) U_{ij} - \sum_{j \in N} (\lambda_j (T-t) - \sum_{i \in M} U_{ij}) f^p_j$$

The first term represents the profits attained by serving the customer from FSL i and the second term represents the penalty costs incurred for not serving the customer. By rearranging the above equation.

$$\textit{Obj. fn.} = \sum_{j\in N}\sum_{i\in M} R_{ij}U_{ij} - \sum_{j\in n} f_j^p \lambda_j (T-t)$$

Collecting the objective function and all of the constraints yields the following linear programming problem. We denote $V_t^{LP}(\vec{x})$ as the value of the inventory $\vec{x}$ at time t, that is computed by the LP formulation.

$$\begin{aligned}
V_t^{LP}(\vec{x}) = \max \quad & \sum_{j\in N}\sum_{i\in M} R_{ij}U_{ij} - \sum_{j\in N} f_j^p \lambda_j (T-t) & & \\
s.t. \quad & \sum_{j\in N} U_{ij} \le x_i & \forall\, i \in M & \qquad \text{(Supply Constraint)} \\
& \sum_{i\in M} U_{ij} \le \lambda_j (T-t) & \forall\, j \in N & \qquad \text{(Demand Constraint)} \\
& U_{ij} \ge 0 & &
\end{aligned}$$

The optimal objective function value reflects the maximum attainable profit for a given $\vec{x}$ and t. By using the mean demand for the remaining time periods, the above formulation does not accommodate the stochastic nature of the problem, therefore, one may argue in favor of a probabilistic version. However, the computational complexity of a stochastic programming formulation makes it unattractive for any large scale practical application. Note that the unit demand assumption implies that the LHS of each constraint only contains a summation of the decision variables U_{ij}. Consequently, the linear multiple choice knapsack problem relaxes to the linear assignment problem. The linear assignment problem is a well studied problem and can be efficiently solved (Kuhn, 2005; Koopmans and Beckmann, 1957).

One may argue that a more efficient way to compute marginal values is to utilize the shadow prices associated with the supply constraints of primal LP formulation or the decision variables of dual LP formulation. We should note that Bertsimas and Popescu (2003) argue for the use of dual formulation although it is unclear whether the use of dual formulation is to utilize decision variables values or objective function results. In our experiments, we observed that the applicable range of the shadow prices of primal LP formulation is typically smaller than the perturbation of x_i by a single unit. Therefore, the marginal values attained via shadow prices of primal LP formulation or via the decision variables of the dual formulation are invalid. In our experiments, we observed lower performance by utilizing the shadow prices of primal LP formulation or dual decision variable values. Therefore, we restrict ourselves to resolving the primal LP formulation by perturbation of single inventory unit. The greedy algorithm that we present in Section 4.4.3 reduces the computational complexity of resolving primal LP formulation significantly, while performing closely to exhaustive search over x_i perturbation in primal LP formulation. Now we turn our attention to devise a computationally efficient online heuristic for spare parts logistics.

4.4.3 Heuristic Solution

In this section, we first present a search algorithm that is based on approximate dynamic programming. It utilizes the $\triangle_i V_t^{LP}(\vec{x})$ in the inner maximization of the MDP to determine the serving decision at time t, given inventory $\vec{x}$ and customer j demand. We denote the following search algorithm as RMH+.

RMH+

Step 1. At given $\vec{x}$ and t. Observe the demand realization from customer j
Step 2. For customer j, compute R_{ij} for all FSLs in M
Step 3. Approximate $\triangle_i V_{t+1}^{LP}$ for all FSLs in M
Step 4. Select $l \in M$, such that $l = \arg\max_M \{R_{ij} - \triangle_i V_{t+1}^{LP}\} \geq 0$
Step 5.
. If $l = \emptyset$ then
. Serve from the supplier via an emergency shipment
. Else $l \neq \emptyset$ then
. Serve from FSL l
. End if
Step 6. End

It is easy to note that the computational efficiency of the above search algorithm relies on the computational times of the $|M| + 1$ linear programs that we need to solve via perturbation of x_i to compute the marginal value vector $\vec{\triangle} V_t^{LP}(\vec{x})$. Despite having a computationally efficient LP formulation of the assignment problem, any practical application of the above algorithm in a large scale spare parts logistics network is not particularly attractive. To improve the computational efficiency further, we propose the following local search heuristic. We denote the presented local heuristic as RMH.

RMH

Step 1. At given $\vec{x}$ and t. Observe the demand realization from customer j
Step 2. For customer j, compute R_{ij} for all FSLs in M
Step 3.
. Let $R_{i_1 j} = \max_M \{R_{ij}\}$
. Let $R_{i_2 j} = \max_{M \setminus i_1} \{R_{ij}\}$
Step 4. Approximate $\triangle_{i_1} V_{t+1}^{LP}(\vec{x})$ and $\triangle_{i_2} V_{t+1}^{LP}(\vec{x})$
Step 5.
If $R_{i_1 j} - \triangle_{i_1} V_{t+1}^{LP}(\vec{x}) \geq R_{i_2 j} - \triangle_{i_2} V_{t+1}^{LP}(\vec{x})$ then
. If $R_{i_1 j} \geq \triangle_{i_1} V_{t+1}^{LP}(\vec{x})$ then
. Serve customer j from FSL i_1
. Goto step 6
. Else
. Serve from the supplier via an emergency shipment
. Goto step 6
. End if
Else if
. Set M = Set $M \setminus i_1$
. Goto Step 3
End if
Step 6. End

In RMH, we perform local search in the vicinity of customer j to identify the candidate FSL for service. In Section 4.4.1, we identified that the behavior of $\triangle_i V_t(\vec{x})$ is non-monotonic over M. Therefore, RMH is a greedy heuristic, resulting at times in a sub-optimal solution. We start the local search from the nearest stock location in an orderly manner, since there is a higher likelihood that the local optimum in the vicinity of the customer is also a global optimum. On the other hand, the computational complexity is significantly reduced due to the local search. In Section 4.5.3, we discuss the computational efficiency aspects of the MDP approach, RMH+, and RMH.

4.5 Numerical Experiments

In this section, we analyze the performance of our proposed RMH against the MDP approach, RMH+ and existing Spiral Router heuristic (SRH) at IBM (described in Section 2.7.1). According to SRH, each incoming demand should be fulfilled from nearest non-empty stock location. From stock location perspective, SRH heuristic is of FIFO or FCFS nature where each incoming customer, regardless of the contract type it posses, gets a spare part. From customer perspective, the objective is find nearest neighbor stock location that is non-empty. We should note that SRH is conceptually similar to nearest neighbor heuristic proposed by Bertsimas and Van Ryzin (1991). The authors propose nearest neighbor heuristics for service engineer dispatching problem, where each incoming demand request is to be served by nearest available service engineer. Although, the formal proof of optimality is not provided, the authors show that nearest neighbor heuristic performs better than other execution heuristic for service engineer dispatching problem. There are two major differences between service engineering dispatching problem considered by Bertsimas and Van Ryzin (1991) and current problem settings of spare parts logistics execution. First, service engineer resources are reused to service future demand requests. In other words, a service engineer who is being considered for the incoming job may be sent from his current idle location or his current working location (i.e. customer location). Due to this, the current service engineer dispatching decision is dependent on preceding dispatching decision for given service engineer. In spare parts logistics, a part is always sent from either of the non-empty stock locations (fixed locations). Secondly, the analysis performed by Bertsimas and Van Ryzin (1991) does not account for customer base heterogeneity.

As mentioned in Section 4.1, our goal in this chapter is to develop a technique that accounts for various aspects of customer heterogeneities in spare parts logistics execution. The heterogeneities in the customer base exist due to distinct contractual agreements and customer locations. Due to the distant service contracts for a single spare part type, the customers pay different service prices for the maintenance service. Similarly, the penalty costs associated with service deadline violations are also different per service contract.

Lastly, two customers with the same machine and service contracts could be located at entirely different locations in the spare part supply chain network. The install locations also introduce heterogeneity due to varying levels of transportation costs. We observe the impacts of customer heterogeneities at various demand / capacity ratios. This allows us to observe the effects of customer heterogeneities in terms of under-stocking and over-stocking of the stock network. For notational convenience, we further denote the MDP approach as RMO, and the Spiral Router heuristic as SRH. First, we formulate the recursive equation to represent the profits of the SRH.

According to the SRH, each demand arrival from any customer type is satisfied from the nearest non-empty FSL. We formulate the following recursive equation to evaluate the expected profits $V_t^{SR}(\vec{x})$ at time t and inventory $\vec{x}$ for the SRH.

$$V_t^{SR}(\vec{x}) = \begin{cases} \sum_j \lambda_j \left[\max_k\{g_j - f_{kj}^d\} + V_{t+1}^{SR}(\vec{x} - \vec{e}_{k_{(i)}})\right] & if \quad \vec{x} > 0 \\ \sum_j \lambda_j \left[-f_j^p + V_{t+1}^{SR}(\vec{x})\right] & if \quad \vec{x} \leq 0 \end{cases}$$

4.5.1 Experimental Setup

We perform the numerical analysis by simulating the supply chain execution. The details of the simulation design are provided in Section 4.5.2 for a small scenario and in Section 4.5.3 for a large scale scenario. The various aspects of the numerical experiments are summarized in Table 4.1.

Table 4.1: Summary of Numerical Experiments

	Small Scenario		**Full Scale Scenario**	
	Solution Quality	Computational Efficiency	Solution Quality	Computational Efficiency
Heterogeneity	SRH, RMH / RMH+, RMO	N/A	SRH, RMH, RMH+	SRH, RMH, RMH+, RMO
Demand / Capacity Ratio	SRH, RMH / RMH+, RMO	N/A	SRH, RMH, RMH+	SRH, RMH, RMH+, RMO

The term small scenario refers to a small scale scenario used to observe the behavior of SRH, RMH, RMH+ and RMO with respect to customer base heterogeneities and the demand / capacity ratio. The small scenario consists of 3 FSLs and 5 customers. The details are provided in Section 4.5.2. The full scale scenario consists of 9 FSLs and 133 customers. It represents a typical spare parts execution situation at IBM (see Section 4.5.3). The term solution quality refers to the average profits and average customer service levels for each technique in simulation. Note that the small scenario is used to compare the solution quality of RMH / RMH+, and SRH against RMO. It should be noted that in the small scenario, the non-monotonic behavior of $R_{ij} - \triangle_i V_{t+1}(\vec{x})$ over i was not observed due to its limited size. Therefore, the results of RMH and RMH+ are equal. In addition, any computational efficiency estimations for the small scenario are also meaningless due to its smaller size. For the full scale scenario, a comparison is made for RMH, RMH+, and SRH based on solution quality. Due to the sheer volume of the requisite computations, RMO is not analyzed for the full scale scenario. The computational efficiency of RMH, RMH+, RMO, and SRH is discussed in Section 4.5.3.

4.5.2 Small Scenario

The small scenario consists of 3 stock locations and 5 customers. The total stock in the FSL network is 5 units with $x_1 = 2$, $x_2 = 2$, $x_3 = 1$. The customer arrival process for $T = 10$ periods is generated according to mean demand rates of each customer. The schematic of the small scenario is listed in Figure 4.2.

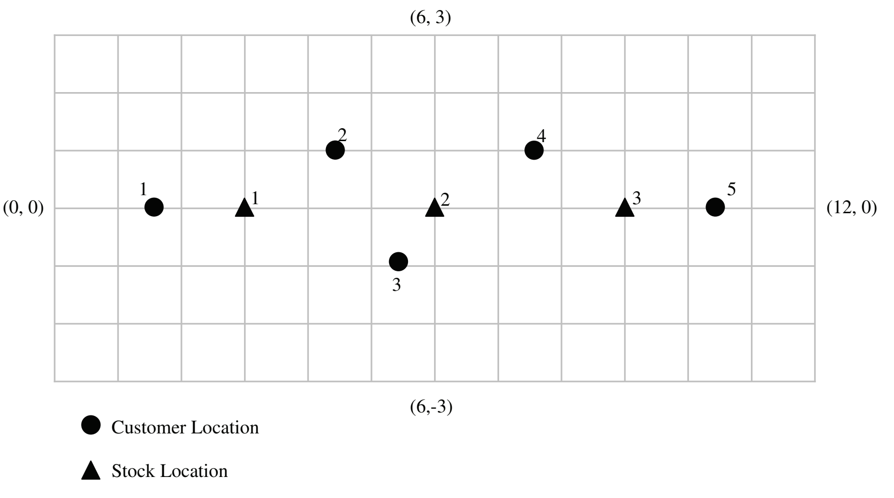


Figure 4.2: Small Scenario Schematic Diagram

The transportation costs are constant in all experiments and are depicted in Table 4.2. For the customer heterogeneity experiments, the demand rates for each customer are fixed at $\lambda_j = 0.12$. Customer heterogeneity is introduced by varying service prices and penalty cost. The varied parameters are listed in Table 4.3. For the Demand/Capacity ratio experiments, the various FSL Demand / FSL Capacity ratios (D/C ratios) are introduced via varying λ_j and are listed in Table 4.5.

Table 4.2: Experimental Setup - Transportation Costs($j = 5$, $FSLs = 3$, $T = 10$)

Customer No.	Stock Location 1	Stock Location 2	Stock Location 3
1	15	45	75
2	18.03	18.03	46.1
3	26.93	11.18	36.40
4	46.1	18.03	18.03
5	75	45	15

In each simulation run, the fulfilment decisions are made according to each fulfilment policy (i.e. RMO, RMH / RMH+, and SRH). Based on the fulfilment decisions, the profits for $T = 10$ periods are calculated in each simulation run. As mentioned earlier in Section 4.5.1, RMH and RMH+ provide equivalent results in the small scale scenario, therefore we depict the results as RMH / RMH+. The total number of simulation runs is 5000. The numerical experiments are performed to observe the effect of customer heterogeneity on RMO, RMH / RMH+, and SRH from the overall profit and customer service standpoint. In addition, the sensitivity of RMO, RMH / RMH+, and SRH to the D/C ratio is also analyzed from the profit and customer service standpoint.

Customer Heterogeneity

We observe the effects of customer heterogeneity in terms of the degree of variation in service prices and penalty costs among various customers. We introduce heterogeneities in the customer base by varying the service prices or penalty costs or both. Table 4.3 shows the chosen parameters for the analysis of service price and penalty cost heterogeneity and its results.

Experiment 1 serves as a baseline or non-heterogeneous case, since the service prices and penalty costs of all customers are equal. Experiments 2 - 5 represent service price

Table 4.3: Heterogeneity in Service Prices and/or Penalty Costs - Average Profits

Exp. No.	Service Prices					Penalty Costs					Average Profits			Loss from RMO	
	g_1	g_2	g_3	g_4	g_5	f_1^p	f_2^p	f_3^p	f_4^p	f_5^p	RMO	RMH/RMH+	SRH	RMH/RMH+	SRH
1	200	200	200	200	200	10	10	10	10	10	843	820	818	2.87%	2.98%
2	280	260	240	220	200	10	10	10	10	10	1041	1022	1005	1.82%	3.37%
3	360	320	280	240	200	10	10	10	10	10	1247	1239	1201	0.62%	3.70%
4	520	440	360	280	200	10	10	10	10	10	1678	1658	1581	1.18%	5.75%
5	840	680	520	360	200	10	10	10	10	10	2530	2519	2352	0.46%	7.05%
6	200	200	200	200	200	50	40	30	20	10	820	799	794	2.55%	3.15%
7	200	200	200	200	200	90	70	50	30	10	804	788	769	1.96%	4.29%
8	200	200	200	200	200	130	100	70	40	10	784	770	744	1.88%	5.11%
9	200	200	200	200	200	170	130	90	50	10	765	757	722	1.00%	5.59%
10	280	260	240	220	200	50	40	30	20	10	1023	1009	988	1.34%	3.39%
11	360	320	280	240	200	90	70	50	30	10	1217	1208	1149	0.71%	5.54%
12	520	440	360	280	200	130	100	70	40	10	1632	1626	1512	0.35%	7.35%
13	840	680	520	360	200	170	130	90	50	10	2486	2462	2262	0.97%	8.99%

heterogeneities. Experiments 6 - 9 depict penalty cost heterogeneities. Joint service price and penalty cost heterogeneities are introduced in experiments 10 - 13.

The baseline case shows that the RMO performs slightly better than the SRH in the non-heterogeneous situation. The variations in transportation costs for various customers are exploited by RMO for this improvement. The results also depict that the variation between RMH/RMH+ and SRH is insignificant for the non-heterogeneous situation. From experiment 2 onwards, we observe that RMO and RMH/RMH+ perform increasingly better than the SRH. This is intuitive since the SRH does not account for the customer base heterogeneities. In general, the variation between RMO and RMH/RMH+ tends to decrease with an increase in heterogeneity. For high heterogeneity situations, the benefits due to RM based approaches (RMO and RMH/RMH+) are quite significant (i.e. up to 9%).

We also analyze the effect of customer heterogeneity on the overall customer service provided to each customer. We take the case of joint variation of service price and penalty costs in Table 4.3 (i.e. experiments 10 - 13) and compare it with the non-heterogeneous case (i.e. experiment 1). We analyze the frequency of a customer being served from the

FSL network; this represents timely service provision to the customer. Table 4.4 depicts the realized customer service levels for various combinations of service prices and penalty costs.

Table 4.4: Heterogeneity in Service Prices and/or Penalty Costs - Customer Service

	Experiment	Realized Service from FSL Network					Globalized Service Level
		Customer 1	Customer 2	Customer 3	Customer 4	Customer 5	
RMO	1	76.81%	83.56%	83.06%	80.37%	70.64%	78.89%
	10	86.54%	86.58%	85.31%	77.28%	56.93%	78.53%
	11	90.34%	90.02%	87.82%	77.65%	39.34%	77.03%
	12	91.26%	91.45%	89.16%	77.64%	30.19%	75.94%
	13	92.84%	92.41%	89.99%	73.14%	24.93%	74.66%
RMH/RMH+	1	86.05%	71.10%	88.12%	61.97%	74.98%	76.44%
	10	90.41%	90.61%	83.60%	74.55%	43.95%	76.62%
	11	93.32%	90.79%	83.26%	74.56%	39.91%	76.37%
	12	93.92%	90.90%	84.89%	72.54%	39.11%	76.27%
	13	91.78%	91.73%	87.43%	76.36%	35.33%	76.53%
SRH	1	80.03%	79.44%	78.20%	79.83%	79.56%	79.41%
	10	79.91%	79.82%	78.98%	79.81%	78.65%	79.43%
	11	79.12%	79.90%	78.35%	79.47%	79.38%	79.25%
	12	79.64%	79.33%	79.54%	79.71%	79.54%	79.55%
	13	79.78%	79.74%	79.71%	79.42%	79.49%	79.63%

Together with the results of Table 4.3, the customer service level results in Table 4.4 help us understand the profit gains due to increased customer heterogeneities. In the case of SRH, we observe that all of the customers are provided with similar customer service. This is intuitive, since customer heterogeneities are not accommodated in the SR heuristic. For RMO and RMH/RMH+, the individual customer service results vary according to the degree of customer heterogeneity. Essentially a customer who is a high paying customer is more likely to be served from the FSL network as compared to the low paying customer. At various heterogeneity levels, the globalized service level for RMO decreases with an increase in customer base heterogeneity. At higher heterogeneity levels, the expected gains associated with serving a high value customer are higher. Therefore, the low value customers are increasingly served from the supplier via emergency shipments at an earlier t in the anticipation of high value customer arrivals. We also estimate the globalized service levels for all customers. The globalized service levels for the RM approaches (RMO and RMH/RMH+) are somewhat lower than for the SRH. In other words, the strategic nature of the RM approaches (RMO and RMH/RMH+) relies on the anticipation of high value customer arrivals for value gains. This leads to somewhat lower global customer service levels in the RM approaches.

Demand / Capacity Ratio

We analyze the D/C ratio for various joint heterogeneity levels of service price and penalty costs (i.e. experiments 10 - 13) and for the non-heterogeneous case (experiment 1). The cost parameters are depicted in Table 4.3.

Ideally, spare parts planning should match the stock requirements in the FSLs to the future demand in a precise manner. In many practical situations, this is not feasible. For example, various data and forecast quality errors lead to over or under estimation of future demand forecasts. In addition, demand uncertainty is accommodated in basestock levels by accounting for demand variance. The modeling approximations and service levels used in the planning models lead to a further mismatch between the FSL's stock requirements and incoming demand. We can estimate the impact of the under-estimation or over-estimation of stock requirements by varying the D/C ratio. We should note that demand parameter in D/C ratio is average realized demand in the horizon and capacity parameter reflects average stock units in the network at the start of horizon. In other words, the D/C ratio is an approximation that reflects the potentially realizable service level during spare parts logistics execution. In this section, we compare the SRH with the RM approach (RMO and RMH/RMH+) for its robustness to the D/C ratio at the levels of 0.6, 0.8, 1.0, 1.2, and 1.4. The various levels of the D/C ratio are induced by varying the demand rates λ_j in each experiment. The ratios of 0.6 and 0.8 represent the over-stocking situation. A D/C ratio of 1.0 is a situation where available capacity exactly matches realized demand. The D/C ratios of 1.2 and 1.4 represent an under-stocking situation. We should note that the above classification of over-stocked and under-stocked network is only valid for the problem characteristics that are considered in this chapter (i.e. spare parts network of Figure 2.7 with replenishment arrivals at the start of each horizon). For the network situation of Figure 2.6— where replenishments arrive at any time instance, the estimation of D/C ratios should be adapted. We shall further clarify this aspect and its association with under-stocking and over-stocking situations in realistic settings in

Section 4.7.

Table 4.5: Sensitivity to Various D/C Ratios - Average Profits

Experiment No.	$\frac{\text{Demand}}{\text{Capacity}}$	Average Profits			Loss from RMO	
		RMO	RMH/RMH+	SRH	RMH/RMH+	SRH
1	0.6	532	529	518	0.47%	2.57%
	0.8	679	675	659	0.64%	2.91%
	1.0	780	768	757	1.59%	2.96%
	1.2	845	820	819	3.02%	3.03%
	1.4	871	846	843	2.80%	3.19%
10	0.6	652	650	637	0.31%	2.36%
	0.8	827	823	807	0.43%	2.38%
	1.0	949	941	925	0.81%	2.48%
	1.2	1025	1009	988	1.50%	3.61%
	1.4	1060	1051	998	0.92%	5.92%
11	0.6	769	769	749	0.04%	2.60%
	0.8	971	968	949	0.33%	2.26%
	1.0	1123	1120	1091	0.28%	2.88%
	1.2	1216	1209	1155	0.58%	4.97%
	1.4	1274	1269	1153	0.34%	9.50%
12	0.6	1000	998	981	0.17%	1.91%
	0.8	1272	1262	1249	0.77%	1.84%
	1.0	1484	1470	1423	0.94%	4.13%
	1.2	1627	1626	1510	0.02%	7.15%
	1.4	1737	1721	1509	0.94%	13.14%
13	0.6	1474	1473	1449	0.02%	1.69%
	0.8	1896	1882	1860	0.73%	1.86%
	1.0	2226	2197	2104	1.30%	5.50%
	1.2	2492	2462	2241	1.20%	10.09%
	1.4	2677	2654	2252	0.84%	15.87%

Table 4.5 shows the effects of the D/C ratio at various customer heterogeneity levels. Consider experiment 1 with no customer heterogeneity for the SRH case. We observe small variations in losses from RMO (2.5% to 3.2%) due to variations in the D/C ratio. In the case of RMH/RMH+, we observe that losses from RMO in over-stocking situations are lower than the under-stocking situations. For the heterogeneous cases, we observe that the benefits from an RM approach (RMO and RMH/RMH+) are small for over-stocking situations. For the under-stocking situations, we observe that an RM approach

(RMO and RMH/RMH+) performs increasingly better than the SRH. Depending on the input parameters and customer heterogeneities, these benefits range up to 15%. The losses due to the approximation in RMH/RMH+ range from 0.02% to 1.50%.

Table 4.6: Sensitivity to Various D/C Ratios - Customer Service Levels

$\frac{\text{Demand}}{\text{Capacity}}$	Approach	Customer 1	Customer 2	Customer 3	Customer 4	Customer 5	Globalized Service Level
0.6	RMO	98.9%	98.7%	98.8%	97.9%	93.6%	97.6%
	RMH/RMH+	98.5%	98.4%	98.2%	97.3%	95.3%	97.5%
	SRH	98.2%	97.8%	97.8%	97.8%	97.8%	97.9%
0.8	RMO	96.6%	97.0%	96.4%	93.5%	75.1%	91.7%
	RMH/RMH+	96.4%	96.1%	94.8%	92.3%	84.6%	92.8%
	SRH	94.7%	94.5%	94.6%	94.0%	93.6%	94.3%
1.0	RMO	94.7%	94.8%	93.9%	87.0%	48.1%	83.7%
	RMH/RMH+	94.6%	92.9%	90.9%	83.7%	65.4%	85.5%
	SRH	87.8%	87.2%	87.4%	88.0%	87.6%	87.6%
1.2	RMO	93.2%	92.6%	89.6%	73.6%	23.9%	74.6%
	RMH/RMH+	93.7%	91.2%	85.2%	73.3%	37.1%	76.1%
	SRH	79.0%	79.7%	79.9%	79.9%	79.3%	79.6%
1.4	RMO	91.7%	91.5%	86.5%	49.8%	14.5%	66.8%
	RMH/RMH+	93.2%	89.1%	81.7%	49.7%	22.3%	67.2%
	SRH	70.8%	70.3%	69.4%	70.9%	70.2%	70.3%

We also analyze the effect of various D/C ratios on customer service behaviors of SRH, RMH/RMH+, and RMO for the experiments. For the non-heterogeneous case (i.e. experiment 1), we observe that the customers are increasingly served from the supplier (via emergency shipments) as the D/C ratio increases. This is intuitive since a high D/C ratio represents a lower stock availability in the FSL network. We also observe insignificant variation in the customer service levels for the SRH, RMH/RMH+ and RMO for the same D/C ratios. We do not depict the results of the non-heterogeneous case here (i.e. experiment 1) due to their intuitive nature. For heterogeneous cases (i.e. experiments 10-13), we observe variations in customer service levels for the SRH, RMH/RMH+, and RMO. In Table 4.6, we depict the customer service levels of the high heterogeneity case (experiment 13). For the SRH, the effects of the D/C ratio changes are similar to the non-heterogeneous case. For the RMH/RMH+ and RMO, the increasing rate of service from the supplier (via emergency shipments) with an increasing D/C ratio still persists. However, the rate is higher for a low paying customer and lower for a high paying customer. Similar to experiment 13 in Table 4.4, we again observe that the

RMH/RMH+ is slightly more conservative than the RMO in terms of serving a customer from the supplier.

4.5.3 Full Scale Scenario

In this section, we discuss the comparative performance of RMH, RMH+, and SRH on real life product data acquired from IBM spare parts logistics. As mentioned earlier, the full scale scenario consists of 133 customers, and 9 FSLs. Based on the typically observed demand rates for such products, and service level parameters, we estimate stock levels for all FSLs. A customer in our case is a machine in IBM's installed base. By assuming that all machines are of the same type, our demand rates (λ_j) from all customers become equal. The estimated stock levels for FSLs 1 to 9 are $\vec{x} = \{2, 2, 3, 2, 2, 1, 2, 2, 2\}$. The g_j is 700 for all customers. In other words, we do not assume any heterogeneity due to service prices. The customer heterogeneity is introduced via distinct penalty costs f_j^p and transportation costs f_{ij}^d for each customer. We calculate the f_j^p parameters, by subtracting the service prices g_j from the emergency shipment costs of sending a spare part from the supplier (via an emergency shipment) to each customer. The transportation costs from each FSL to each customer j are acquired from IBM. Due to the sheer volume of these parameters (i.e. 133 f_j^p and 1197 f_{ij}^d) and confidentiality reasons, we do not report the exact values of all these parameters. For illustration purposes, we only depict the regular and emergency transportation cost parameters of the customers that requested the parts during our single simulation run (see Table 4.8).

The comparative analysis for the RMH, RMH+, and SRH are performed at various D/C ratios (i.e. 0.6, 0.8, 1.0, 1.2, 1.4). We obtain the various D/C ratios at these levels by varying the $\lambda_j \ \forall \ j \in N$ equally. The length of $T = 25$ is chosen to ensure the technical assumption (i.e. $\sum_{j \in N} \lambda_j \leq 1$). The simulation program was encoded using .Net technology. CPLEX 11.0 is used as the solver for the LP approximation of $V_t(\vec{x})$. For each D/C ratio, we run the simulation for 1000 runs. At each t, the demand arrival process is simulated by using the random number generator. The random number generator follows a uniform distribution, therefore a demand arrival is equally likely from each customer (since the $\lambda_j \ \forall \ j \in N$ is the same). At each D/C ratio, identical random number streams are used for the SRH, RMH, and RMH+ to reduce the computational requirements.

Customer Heterogeneity and Demand / Capacity Ratio

We perform the numerical experiments at various D/C ratios. Table 4.7 depicts the results of the simulation experiments. First we discuss the average profits at various D/C ratios. Similar to the small scenario, we observe negligible gains for over-stocking situations. For under-stocking situations, the improvements over the SRH are quite significant. The improvements depict that the RMH performs increasingly better than the SRH with higher under-stocking of the stock network. The results also depict an insignificant difference between the RMH and the RMH+. This confirms our earlier argument that the local optimum in the vicinity of the customer is highly likely to be the global optimum.

Table 4.7: Average Profits and Globalized Service Levels at various D/C ratios

Demand / Capacity Ratio	Average Profits			Gains from SRH	Loss from RMH+	Globalized Service Levels		
	SRH	RMH	RMH +			SRH	RMH	RMH+
0.6	6,367.9	6,374.1	6,373.5	0.10%	-0.01%	100.00%	100.00%	100.00%
0.8	8,355.5	8,389.3	8,392.3	0.40%	0.04%	99.56%	99.58%	99.44%
1.0	9,460.4	9,683.9	9,694.7	2.36%	0.11%	94.68%	94.41%	93.53%
1.2	9,439.2	10,124.2	10,118.4	7.25%	-0.06%	88.52%	86.56%	85.94%
1.4	8,591.0	10,742.1	10,764.0	25.04%	0.20%	72.00%	71.98%	71.98%

It is impractical to report the customer service level of each individual customer for the large scale scenario. Therefore, we restrict ourselves to present the globalized service levels for the large scale scenario. The results of the globalized service levels follow a similar pattern to that of the small scenario. For over-stocking situations, globalized service is close to 100%. Since we have enough stock in the FSL network, it would be pointless to serve a customer from the supplier (via emergency shipments) and save the FSL stock. The behavior of the SRH, RMH and RMH+ is quite similar to the small scenario for over-stocking situations. For the D/C ratios of 1.0, 1.2 and 1.4, we observe that the globalized service levels of the RMH and RMH+ are slightly lower than the SRH. The RM approaches result in lower globalized service levels, since the attempt is to save the FSL network stock in anticipation of higher value customer demand. We highlight this fact by depicting the fulfillment behavior of one specific run from the large scale scenario simulation. In Table 4.8, we present the regular transportation costs from various FSLs to the customers that arrived in this specific simulation run. We also present the emergency transportation costs from the supplier to each customer j.

Table 4.8: Regular and Emergency Transportation Costs

	Field Stock Location (FSL)									Emergency Transportation
Customer No.	1	2	3	4	5	6	7	8	9	Costs from Supplier
1	356	170	37	276	349	395	373	338	403	1222
6	356	172	42	275	346	394	373	337	403	1214
8	356	168	42	276	346	395	373	338	403	1216
12	357	166	43	276	347	395	373	338	403	1215
13	337	184	124	238	322	390	378	343	383	1251
16	307	103	254	241	326	342	366	404	354	1278
36	378	244	348	116	25	256	471	548	309	833
41	352	206	358	127	133	214	482	560	267	705
57	224	288	326	265	349	271	316	393	270	691
59	252	299	311	225	309	249	345	422	290	755
62	331	239	279	128	212	280	423	485	321	741
91	104	445	403	353	437	260	174	324	204	659
99	185	298	392	418	503	340	66	217	284	959
105	169	464	376	403	487	324	34	171	269	931
113	260	353	280	419	503	402	123	05	351	1277
121	256	204	307	439	523	412	123	84	356	1302
133	273	246	282	230	314	296	366	378	319	756

Table 4.9 depicts the customer arrivals, the ordered sequence of the stock locations for the arriving customer, the network stocks at each time t for stock locations 1 to 9 and the fulfillment behavior of the SRH and RMH. Observe the fulfillment behavior of the SRH. We depict the initial network stock at time t, and the accept (A) or reject (R) decision. In the case of an accept decision, we serve from the nearest non-empty location, whereas for the reject case, we serve via an emergency shipment. Depicted next is the stock location number from which the stock unit is consumed for the fulfillment of the arriving customer and the rank of the stock location in the ordered set. Finally, the revenue of the demand realization and the cumulative revenues are given. The RMH situation is identical except for the fact that we may choose not to serve the customer from the nearest location, thereby saving the nearest location's stock unit for later use. It is easy to note by comparison that RMH postpones the decision to serve the customer from the nearest FSL in order to attain a higher value at a later stage. In the example depicted, the postponement strategy of the RMH yields benefits since the penalties are incurred for the low value customers instead of the high value customers. The comparison

of the location rank for the SRH and RMH also reveals that by serving the incoming customer from the supplier or the non-nearest location early on, the RMH is better able to manage the stock units such that more customers are actually served from their closest location. This is due to the fact that each customer has a distinct, ordered list of stock locations and the RMH, due to its strategic nature, is better equipped to exploit the interdependencies in the FSLs ordering of various customers for the overall gains.

Time Index (t)	Customer Number	Ordered Stock Locations Set for *j* (Descending)									SRH						RMH					
											Initial Stock at t for FSLs (1 to 9)	Accept / Reject	Location to Serve	Location Rank	Revenue	Cumulative Revenue	Initial Stock at t for FSLs (1 to 9)	Accept / Reject	Location to Serve	Location Rank	Revenue	Cumulative Revenue
1	No Arrival	Not Applicable									{2,2,3,2,2,1,2,2,2}	N/A	N/A	N/A	0	0	{2,2,3,2,2,1,2,2,2}	N/A	N/A	N/A	0	0
2	No Arrival	Not Applicable									{2,2,3,2,2,1,2,2,2}	N/A	N/A	N/A	0	0	{2,2,3,2,2,1,2,2,2}	N/A	N/A	N/A	0	0
3	62	4	5	2	3	6	9	1	7	8	{2,2,3,2,2,1,2,2,2}	A	4	1	572	572	{2,2,3,2,2,1,2,2,2}	A	4	1	572	572
4	8	3	2	4	8	5	1	7	6	9	{2,2,3,1,2,1,2,2,2}	A	3	1	657	1230	{2,2,3,1,2,1,2,2,2}	A	3	1	657	1230
5	6	3	2	4	8	5	1	7	6	9	{2,2,2,1,2,1,2,2,2}	A	3	1	658	1887	{2,2,2,1,2,1,2,2,2}	A	3	1	658	1887
6	121	8	7	2	1	3	9	6	4	5	{2,2,1,1,2,1,2,2,2}	A	8	1	617	2504	{2,2,1,1,2,1,2,2,2}	A	7	2	578	2465
7	41	5	4	2	3	6	9	1	7	8	{2,2,1,1,2,1,2,1,2}	A	5	1	557	3061	{2,2,1,1,2,1,1,2,2}	A	5	1	557	3022
8	133	4	2	1	3	6	5	9	7	8	{2,2,1,1,1,1,2,1,2}	A	4	1	471	3532	{2,2,1,1,1,1,1,2,2}	R	CSL	N/A	- 56	2967
9	113	8	7	1	3	9	2	6	4	5	{2,2,1,0,1,1,2,1,2}	A	8	1	694	4226	{2,2,1,1,1,1,1,2,2}	A	8	1	694	3661
10	62	4	5	2	3	6	9	1	7	8	{2,2,1,0,1,1,2,0,2}	A	5	2	488	4714	{2,2,1,1,1,1,1,1,2}	A	4	1	572	4233
11	36	5	4	2	6	9	3	1	7	8	{2,1,1,0,1,1,2,0,2}	A	2	3	455	5170	{2,2,1,0,1,1,1,1,2}	A	5	1	674	4908
12	62	4	5	2	3	6	9	1	7	8	{2,0,1,0,1,1,2,0,2}	A	2	3	461	5630	{2,2,1,0,0,1,1,1,2}	R	CSL	N/A	- 41	4867
13	No Arrival	Not Applicable									{2,0,1,0,1,1,2,0,2}	N/A	N/A	N/A	0	5630	{2,2,1,0,0,1,1,1,2}	N/A	N/A	N/A	0	4867
14	12	3	2	4	8	5	1	7	6	9	{2,0,0,0,1,1,2,0,2}	A	3	1	657	6287	{2,2,1,0,0,1,1,1,2}	A	3	1	657	5524
15	13	3	2	4	5	1	8	7	9	6	{2,0,0,0,0,1,2,0,2}	A	1	5	363	6651	{2,2,0,0,0,1,1,1,2}	A	1	5	363	5887
16	59	4	6	1	9	2	5	3	7	8	{1,0,0,0,0,1,2,0,2}	A	6	2	451	7102	{1,2,0,0,0,1,1,1,2}	A	6	2	451	6338
17	57	1	4	9	6	2	7	3	5	8	{1,0,0,0,0,0,2,0,2}	A	1	1	476	7578	{1,2,0,0,0,0,1,1,2}	A	1	1	476	6815
18	105	7	1	8	9	6	3	4	2	5	{0,0,0,0,0,0,2,0,2}	A	7	1	665	8243	{0,2,0,0,0,0,1,1,2}	A	7	1	665	7480
19	1	3	2	4	8	5	1	7	6	9	{0,0,0,0,0,0,1,0,2}	A	7	7	327	8570	{0,2,0,0,0,0,0,1,2}	A	2	2	529	8009
20	No Arrival	Not Applicable									{0,0,0,0,0,0,0,0,2}	N/A	N/A	N/A	0	8570	{0,1,0,0,0,0,0,1,2}	N/A	N/A	N/A	0	8009
21	99	7	1	8	9	2	6	3	4	5	{0,0,0,0,0,0,0,0,0,2}	A	9	4	416	8986	{0,1,0,0,0,0,0,1,2}	A	9	4	416	8426
22	91	1	7	9	6	8	4	3	5	2	{0,0,0,0,0,0,0,0,0,1}	A	9	3	497	9483	{0,1,0,0,0,0,0,1,1}	A	9	3	497	8922
23	16	2	4	3	1	5	6	9	7	8	{0,0,0,0,0,0,0,0,0,0}	R	CSL	N/A	- 578	8905	{0,1,0,0,0,0,0,1,0}	A	2	1	597	9519
24	No Arrival	Not Applicable									{0,0,0,0,0,0,0,0,0,0}	N/A	N/A	N/A	0	8905	{0,0,0,0,0,0,0,1,0}	N/A	N/A	N/A	0	9519
25	133	4	2	1	3	6	5	9	7	8	{0,0,0,0,0,0,0,0,0,0}	R	CSL	N/A	- 56	8849	{0,0,0,0,0,0,0,1,0}	A	8	9	322	9842

Table 4.9: Fulfilment Behavior of a Simulation Run

Computational Complexity

In this section, we compare the computational complexity of the SRH, RMO and RMH. For the SRH, at each demand realization, a short operation is performed to identify the nearest non-empty stock location. Therefore, the computational complexity of the SRH relies on finding the stock location with minimum transportation costs, which has a computational complexity of $O(|M|)$. For all T, the complexity can be stated as $O(T|M|)$.

For the RMO, due to the multidimensional nature of $\vec{x}$, we have $\prod_{i\in M}(x_i+1)$ states for each j and t. For the inner maximization of each state, we can find the maximum in $O(|M|)$. Therefore, for each j and t, the complexity of the inner maximization for all states is $O(|M|\prod_{i\in M}(x_i+1))$. For all T and $|N|$, the complexity of the MDP formulation can be stated as $O(T|N||M|\prod_{i\in M}(x_i+1))$.

For the RMH+, we need to find the maximum of $\left[R_{ij} - \triangle_i V_{t+1}(\vec{x})\right]$ over the set M at each t. The complexity of finding the maximum is $O(|M|)$. In addition, we need to solve $|M|$ linear programs at each t.

In the case of RMH, it is likely that the local search terminates before we reach the last element in M. In the worst case scenario, retrieving all maximum values (in an iterative manner) would require $O(|M|^2)$ operations. For a practical sized problem, we performed computational complexity experiments for the linear assignment problem. Table 4.10 depicts the solution times for the various problem size and D/C ratio configurations. We observe that even a very large sized problem (i.e. $|N| = 4013$, $|M| = 25$) can be solved in less than a second.

Table 4.10: Large Scale Experiments - Computational Times of LP Formulation

$\lvert M \rvert$	$\lvert N \rvert$	Demand/Capacity Ratio	Solution Times (CPLEX 11.0, Intel 3.36 GHZ Processor)
10	133	0.6	0.02 sec
10	133	0.8	0.73 sec
10	133	1.0	0.02 sec
10	133	1.2	0.08 sec
10	133	1.4	0.03 sec
25	4013	0.6	0.42 sec
25	4013	0.8	0.42 sec
25	4013	1.0	0.58 sec
25	4013	1.2	0.33 sec
25	4013	1.4	0.30 sec

In our large scale simulation experiments of the RMH, we also calculate the extent to which we need to search through $|M|$ value functions for any demand arrival. We know from Section 4.4.3, that to serve from the nearest location, we need to solve the linear programs of $(\vec{x})$, $(\vec{x}-\vec{e}_1)$, and $(\vec{x}-\vec{e}_2)$. Similarly, for the second iteration (i.e. 2nd nearest location as a candidate serving location), we need to search one more perturbation of $(\vec{x} - \vec{e}_3)$. In Table 4.11, we depict the serving behavior of the RMH at each D/C ratio. For example, if the D/C ratio is 0.6, then 91.07% of the customers in 1000 simulation runs are served from the nearest location. As the D/C ratio increases, we observe that less customers are served from the nearest location. This is due to the strategic nature of the RMH. However, the nearest location still serves the highest numbers of customers. It is easy to observe from the table, that the actual computational complexity of the RMH is considerably lower than the theoretical upper bound.

Table 4.11: Large Scale Experiment - Serving Behavior of RMH

Stock Location Rank	Demand / Capacity ratio				
	0.6	0.8	1.0	1.2	1.4
1	91.07%	86.42%	83.55%	81.99%	75.78%
2	8.70%	12.81%	15.07%	16.11%	20.59%
3	0.22%	0.73%	1.25%	1.65%	3.10%
4	0.01%	0.03%	0.13%	0.23%	0.48%
5	0.00%	0.00%	0.00%	0.02%	0.06%
6	0.00%	0.00%	0.00%	0.00%	0.00%
7	0.00%	0.00%	0.00%	0.00%	0.00%
8	0.00%	0.00%	0.00%	0.00%	0.00%
9	0.00%	0.00%	0.00%	0.00%	0.00%

4.6 Conclusions

In this chapter, we studied a real life spare parts logistics situation. Specifically, we focused on the situation where spare parts stock planning has already been performed and the objective is to execute the spare parts logistics. We observed that the approach typically practiced in spare parts logistics such as the SRH follows the principle of First In First Out (FIFO). The SRH fails to accommodate prevalent characteristics of spare parts logistics (such as customer heterogeneity and sourcing flexibility). In this chapter, we addressed these shortcomings by devising an execution technique that follows the flexible service concepts from RM and uses detailed customer information provided by the installed base data.

We devise the execution technique by modeling the spare parts logistics execution situation as a discrete time finite horizon MDP formulation. The detailed analysis of the MDP formulation reveals the similarities between the spare parts logistics execution problem and airline network RM problem. The differences are in terms of penalty costs and underlying inventory network structure. The similarities are such that spare parts logistics execution borrows many structural properties of airline RM problem. We further devise a greedy search based online algorithm that reduces the computational complexity of the solution approach significantly as compared to the execution algorithms proposed in airline network RM.

In this chapter, we also demonstrated that the devised approach is better suited to account for customer heterogeneities and provides superior results than the typically used spare parts logistics execution techniques such as the SRH. We numerically studied the performance of the RMH for various aspects. It follows that even in the most unfavorable situations, the proposed heuristic performs at least as well as or better than the SRH. Following Section 2.8, we argue that these benefits are a result of the availability of high quality installed base data for decision making and a supply chain analytic that optimally uses the installed base data for performance gains by extending the existing decision space in spare parts logistics execution. The numerical experiments also show that RMH performs increasingly better for higher customer heterogeneities and understocking situations. Such situations exist in spare parts logistics.

4.7 Limitations and Generalization

The solution technique presented in this chapter only considers the inventory network situation of Figure 2.7. Such situations only exist in the case of constrained supplies. Note that the inventory network in Figure 2.7 can also be considered a special case of the country / region 2 situation of Figure 2.6, where the review periods are long and replenishment ordering is performed at the identical time for all field stock locations. Still, the prevailing inventory planning situations of Figure 2.6 are not fully accounted for. A possible extension of the results in this chapter is to develop a similar execution technique for these inventory network situations. We should mention that during the course of this research, we also investigated the possibility of developing a similar execution technique for these situations. We shall report on the detailed method and results at a later stage in a separate publication.

In Section 4.5.2, we highlighted that estimation of D/C ratios should also be adapted if the replenishment ordering is not limited to identical times. In such situations, replenishment order can be placed at any time during horizon and it arrives after given replenishment lead time. The D/C ratio estimation needs to be adapted since that demand order can also arrive at a particular FSL while replenishment order for that FSL is in pipeline inventory. This temporal mismatched should be accounted in available capacity parameter of D/C ratio.

It should also be noted that in most realistic situations, base stock level is usually higher than average demand forecast to account for demand uncertainty and service levels. In such situations, if realized demand during execution is equal to average demand forecast, then in most execution horizons, we operate with spare parts logistics system that is analogous to overstocking situation of Section 4.5. In such horizons, execution behavior of RMH becomes closer to SRH, as identified in Section 4.5.3. However, due to demand uncertainty there shall be some horizons, where realized demand exceeds average demand forecasts. In such horizons, spare parts logistics system behaves as in understocked situation and attempt to attain higher profit by exploiting the strategic nature of RMH (see Section 4.5.3 for details).

Chapter 5

Returns Management in Spare Parts Logistics

5.1 Introduction

New product returns occur in a range of business environments. In the literature, such returns are termed commercial returns. Guide et al. (2006) cite the reasons for commercial returns as defective products, improper marketing, convenience returns, and products not meeting the buyer's expectation. Hewlett Packard and the Robert Bosch Tool Corporation report that a significant percentage of commercial returns (80% and 40% respectively) is the return of a non-defective new product (Guide et al., 2006). Such commercial returns are returned to the inventory for resale (De Koster et al., 2002; Blackburn et al., 2004; Thierry et al., 1995).

In spare parts logistics, returns of new and used spare parts originate during after sales service execution (Fleischmann et al., 2003; Blackburn et al., 2004; De Brito and Dekker, 2003a; Thierry et al., 1995). As discussed earlier in Section 2.2.3, new spare part returns can constitute up to 27.4% of all spare part returns. Due to the substantial repair requirements of used spare parts (which are typically performed at a centralized facility), the replacement of used spare parts into the network inventory is only possible after a significant remanufacturing delay. New spare part returns typically do not face such delays. After little or no testing and repackaging (performed locally), these spare parts can be readily placed back in the network inventory (Tan et al., 2003; Thierry et al., 1995; De Brito and Dekker, 2003a). We highlighted in Section 2.2.3, that new spare part returns occur due to incorrect remote diagnostics or pessimistic ordering policies of service engineers. In case of incorrect remote diagnostics, a new (different) spare part needs to be shipped to customer location after correct on-site diagnostics. We argue that the results presented in Chapter 4 are also applicable for subsequent spare part forward shipment.

In this chapter, we focus on the execution of new spare part returns, and attempt to address the question — at which field stock location should a returned spare part be placed? The problem can also be viewed as an attempt to rebalance the network inventory given that a new spare part return has occurred. Network inventory rebalancing refers to the optimal placement location of a returned spare part in an inventory network with a time based service level and a geographically distributed installed base. The aspects of time based service deadlines and installed base size in each geographical area are important due to the following reasons. First, for each customer, the time based service deadline restricts the set of stock locations that can service the customer without any penalties. Second, the variations in installed base size among various sub-regions imply that demand rates are not homogeneous throughout the entire geographical region. Due to the stochastic nature of past demand realizations, network inventory rebalancing may result in additional benefits by addressing short term fluctuations in demand. In this chapter, we study these aspects in a comprehensive manner.

The IB data is relevant for the current study since it allows us to identify the location of each customer, its service requirements, transportation costs and potential demand rates. For details, on how to extract this information from IB data, we refer to the discussion in Sections 2.6 and 2.7.2. In this chapter, we use all of this information to study returns management in spare parts logistics. Subsequently, we devise an execution technique that uses transportation cost information (deduced from IB data) to address the primary question of this chapter. Although the current study is focused on new spare part returns, our results are also applicable in other similar settings. In Section 5.7, we discuss applicable settings in reverse logistics from retail and other sectors for their relevance. To summarize, the contributions of this chapter are as follows:

- In this chapter, we study interaction of execution decision in spare parts logistics and disposition execution decision in spare parts returns management. We argue that explicit consideration of this interaction yields additional value.

- We present two MDP formulations to study interaction of spare parts logistics execution and spare parts returns disposition execution in simultaneous and sequential manner. The results reveal that sequential decision making is computationally efficient than simultaneous decision making while it performs quite similarly in terms of profits.

- We compare the performance of MDP formulations with various simple heuristics. It follows that the performance of a specific heuristic (i.e. reverse spiral router) is close to the MDP formulations and superior to other simple heuristics. The superior performance of reverse spiral router heuristic is due to its ability to accommodate the interrelation between spare parts logistics management and spare parts returns management in a manner similar to MDP formulations.

- In terms of inventory rebalancing benefits, our results indicate that inventory rebalancing of spare parts logistics network only shows potential for an under-stocked network. For an over-stocked spare parts logistics network, inventory rebalancing attempt shows little potential.

This chapter is organized as follows. In Section 5.2, we discuss the relevant academic literature on reverse logistics. In Section 5.3, we present integrated and sequential MDP formulations to analyze the interaction between spare parts execution and returns management processes. In Section 5.5, we compare the performance of the proposed heuristic solutions with the MDP formulations. In Section 5.5.1, we discuss our results and conclude in Section 5.6. We finalize this chapter in Section 5.7 with a discussion on the limitations and generalizations of the results presented in this chapter.

5.2 Literature Review

The concepts of reverse logistics (return flows management) and network inventory rebalancing in supply chain are not new. A comprehensive body of literature exists in the area of supply chain management (i.e. stock rebalancing) and reverse logistics. First, we focus on the reverse logistics literature. According to Rogers and Tibben-Lembke

(1999), reverse logistics is the process of planning, implementing and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or ensuring proper disposal. The European Working Group on Reverse Logistics (Revlog) gave it a somewhat broader definition by replacing the word 'consumption' by 'use' in above definition, since reverse logistics also involves handling of new or unused returns that are not consumed (Revlog, 2002). In the next few paragraphs, we discuss the reverse logistics literature on spare parts as well as the reverse logistics literature on return distribution management.

5.2.1 Reverse Logistics

The reverse logistics literature on spare parts can be broadly classified into two subdivisions. One stream of literature attempts to integrate classical reverse logistics from commercial supply chain management with spare parts logistics. In this stream, the relation between the spare parts logistics and the commercial supply chain exists since the returned product can be harvested to source spare part inventories. Product recovery, disposition and disassembly decisions are important characteristics of this stream. Relevant work in this area includes Fleischmann et al. (2003, 2002); Fleischmann and Kuik (2003); Blackburn et al. (2004); De Brito and Dekker (2003a); Spengler and Schroter (2003), and Thierry et al. (1995), in which the authors discuss strategic, operational and tactical issues, such as network design, disassembly decisions, inventory management, and disposition decisions. For details, we refer the reader to Sasikumar and Kannan (2008a). A second stream of literature focuses on spare part returns that originate during maintenance actions. In this work, strategic issues such as distribution network design are discussed by Blackburn et al. (2004), and Thierry et al. (1995). Operational issues such as inventory management with returns are discussed by De Brito and Dekker (2003b); Fleischmann et al. (2002); Fleischmann and Kuik (2003), and Cohen et al. (1980). The distribution strategies for new spare parts in the logistics network is discussed by Tan et al. (2003). The authors present a rule based approach to distribute the spare part returns in the stock location network.

The earliest discussion on the importance of reverse distribution channels and associated infrastructure is provided by Ginter and Starling (1978). In the following literature, various authors discuss the aspects of reverse logistics network design, integration of forward and reverse distribution channels and infrastructure, third party reverse logistics, and vehicle routing aspects for reverse logistics. Reverse logistics network design literature follows the concepts of classical network design literature in operations management; mixed integer linear programming based location-allocation formulations are commonly observed. Issues such as integrated or sequential design of forward and reverse channels are discussed. Fleischmann et al. (2001) show the potential cost savings from following an integrated approach. The authors also presented a generic mixed integer formulation for integrated and sequential network design. Vehicle routing problems in reverse logistics involve the routing of vehicles to account for the delivery and backhaul of products.

Jennings and Scholar (1984); ReVelle et al. (1991); Dethloff (2001); Mouro and Amado (2005); Prive et al. (2006); Aras and Aksen (2008), and Krikke et al. (2008) have studied the routing aspects in various forward and reverse network configurations. The performance of tabu search methods is discussed as appropriate for such problems. For details, we refer the reader to Sasikumar and Kannan (2008b).

We should note that most of the above literature follows reverse logistics activities in waste management or the commercial sectors, where the reverse logistics activities are initiated due to potential value gains or governmental legislations. Distribution and transportation in these sectors typically involve significant quantities of commercial, end of life, or end of use materials. Contrary to this situation, spare part returns in after sales service involve small quantities or single units, slow moving demand and return rates. Despite the rich body of work in reverse logistics, the only work that is similar to our problem setting is presented by Tan et al. (2003), where the authors present a rule based approach to distribute new spare part returns into the network inventory. In the next section, we explore the network inventory rebalancing literature for similar problems.

5.2.2 Network Inventory Rebalancing

Inventory rebalancing has received significant interest from various researchers in the area of supply chain management. Inventory rebalancing or shipment coordination concepts can be traced back to the classical work of Eppen and Schrage (1981). The primary idea in inventory rebalancing literature is to react to short term demand fluctuations by relocating the network inventory according to the potential future demand from each geographical sub-region. In a broad sense, the network inventory rebalancing literature follows two (somewhat overlapping) streams. The first stream follows the vendor managed inventory (VMI) settings, where the objective is to study the benefits of real time demand information to coordinate stock allocation among various retailers. Cheung and Lee (2002) discuss the benefits of using demand information to achieve economies of scale by shipment consolidations (i.e. full truckloads) and value addition by the reallocation of stocks among n retailers before the actual shipment is unloaded. Cachon and Fisher (2000) discuss the benefits of using realtime demand information to reallocate stock in a VMI system with n retailers, an (R, nQ) inventory replenishment policy, and backordering. Moinzadeh (2002) complements this study by using realtime demand information and a reallocation strategy to update the supplier's inventory policy. Cetinkaya and Lee (2000) discuss a VMI system where the supplier has an opportunity to hold the shipments until an agreed deadline. The objective is to decide which orders should be delayed such that the most economical shipment size is achieved before the agreed deadlines. Economic feasibility is achieved by consolidating many small orders into full truckloads, thereby inducing economies of scale.

The second stream of literature in network inventory rebalancing follows the concept of risk pooling in a one warehouse, n retailers supply chain setting. An OEM receives the entire shipment (accumulated stock requirement of the retailers) from its supplier. Instead of forwarding the entire stock to the retailers, a central warehouse is utilized to distribute the inventory at certain discrete time instances until the next shipment arrival from the supplier. In addition to the shipments from the risk pooled inventory at the warehouse, lateral transshipments among retailers are also allowed. McGavin et al. (1993) discuss the optimal allocation of inventory units in a specific shipment given that the time horizon between two supplier shipments is subdivided into two periods. In McGavin et al. (1997), the authors extend the analysis of a similar system with a subdivision into T time periods. At each time period, the decision is to identify the optimal stock allocation among n retailers after observing the demand pattern and the current retailer stocks. Agrawal et al. (2004) discuss a similar setting with dynamic determination of when to rebalance instead of depending on a prefixed time to rebalance. Kiesmuller and Minner (2009) discuss a one warehouse, two retailer system for fashion products with the objective of determining the appropriate timing for network inventory rebalancing. The authors note that the optimal rebalancing time depends on the system parameters and may lie between the middle and the end of the horizon.

We now highlight the differences between the above literature and our problem setting. The network inventory rebalancing literature in VMI is primarily focused on using economies of scale and allocation quantities for value addition. In the second stream of literature, the focus is more towards identifying the appropriate timing and amount for inventory rebalancing. Our problem setting is different since the rebalancing opportunity is dependent on the spare part return instance. Due to the random timing of a false demand situation, a network inventory rebalancing opportunity could occur at any given instance, whereas in the above literature network inventory rebalancing follows prespecified time instances. Moreover, the originating location of the spare part return is also a candidate for the consumption of the spare part in the future, which is different from the settings discussed in most of the above literature. Finally, the amount of inventory units available for network inventory rebalancing is an exogenous parameter in our setting and is dependent on the probability of false demand. Given these considerations, our focus in this chapter is to identify an appropriate stock location in the logistics network for the placement of returned spare part.

5.3 Problem Formulation

In this section, we provide a more formal problem description, notations, and a Markov Decision Process (MDP) formulation. First, we describe the network configuration in further detail. Figure 5.1 depicts various typical configurations of the forward and return logistics network.

Sub-figures A and B in Figure 5.1 represent the situation, in which some or all of the stock locations in the network play a dual role of candidate sourcing and return locations. Sub-figure C represents the situation, in which a return decision involves some processing (such as visual inspection and repackaging) at the remanufacturing facility before the spare part can be placed back into the network stock. In spare part returns, the decision relates to choosing the appropriate stock location. Clearly, the potential future demand of spare parts in various regions plays a role in this decision.

We start our problem formulation by considering the inventory network configuration discussed in Figure 4.1. The main difference extends from the fact that in Chapter 4,

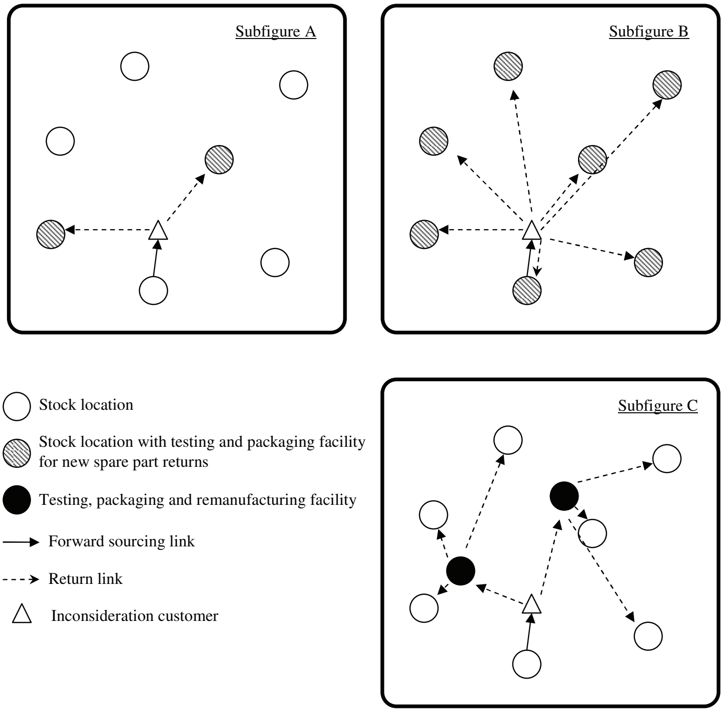


Figure 5.1: Forward and Return Network

we primarily considered the situation of full lateral transshipments. In this chapter, we extend the situation to accommodate full and partial lateral transshipments in spare parts execution management. The adaption is trivial and can be attained without any consequences to the results discussed in Chapter 4.

Given this definition of the spare parts system, we formulate the problem as a discrete time finite horizon MDP, where the entire horizon length represents the interval between two consecutive replenishment arrivals from the supplier. In other words, all field stock locations are replenished at the start of horizon. The index t in $\{1, 2, 3, \dots, T\}$ represents the discretized time step of the entire horizon T. It should be noted that time instants $t = \{1, 2, \dots, T\}$ represent the beginning of each period t. The end of the last period is denoted by $T + 1$. The set of inventory source locations (including the supplier location and FSLs) is denoted by M (finite set of nonnegative integers) and indexed by i, where $i = 0$ is fixed for the supplier location and $i \in M \setminus \{0\}$ for all FSL locations. We define the set of candidate return stock locations L (finite set of nonnegative integers) with each candidate stock location indexed as l. Similar to the source locations, $l = 0$ is fixed for the supplier location and $l \in L \setminus \{0\}$ for all other candidate return locations. The customers are dispersed geographically at various locations. Let j denote a customer in the customer location set N (finite set of positive integers). The inventory at each FSL is denoted by x_i. The inventory at all FSL in the network can be denoted by a vector as follows $\vec{x} = \{x_1, x_2, ..., x_i\}$.

5.3.1 Demand Characteristics

We assume that demand requests from various customers follow an independent Poisson process. The Poisson demand assumption is common in spare parts logistics. A demand request originates due to a machine failure. It is plausible to assume that machine failures at various customer locations occur independently and each machine failure requires a single spare part unit. Note that the spare part may represent a carefully composed kit of spare parts for satisfying (generic) demand requests. We denote the demand rate from each customer j at each t as λ_j. We denote the probability that a demand request is false by q_j. Furthermore, there is a probability that no demand arrives during any time period t which is denoted by λ_0.

5.3.2 Cost Structures

A customer is charged a service price g_j for the performed maintenance according to the agreed contract. The transportation costs from each stock location i (either FSL or supplier location) to each customer location j are known and denoted as f_{ij}^d (superscript d identifies the forward transportation aspect). The transportation costs are linearly increasing in distance with a fixed cost component. The return transportation costs from customer j to return stock location l are denoted as f_{lj}^r (superscript r identifies the return transportation aspect). Note that even if $l = i$, then f_{lj}^r and f_{ij}^d may or may not be equal. If the demand realization is served later than its service deadline, then penalty costs are also incurred. The penalty cost function is zero for demand fulfillment within the service deadline and exponentially increasing in the elapsed time after the service deadline, as depicted in Figure 5.2. For an incoming demand signal from customer j, who can be served from location i, we denote the penalty cost as f_{ij}^{p} (superscript p denotes the penalty aspect) .

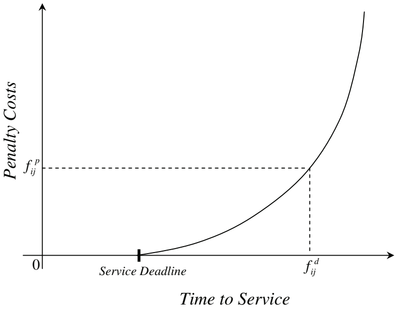


Figure 5.2: Penalty Cost Function

5.3.3 Spare Part Sourcing Decision

Similar to the situation discussed in Chapter 4, we first focus on the spare part sourcing decision. Our objective is to maximize the profits while deciding to serve a demand signal from any of the stock locations. For this purpose, we need to observe the following tradeoff: the profit of serving a customer j at time t from stock location i vs. the profit of serving a customer j at time t from stock location i'. We denote $V_t(\vec{x})$ as the value function representing the value of the inventory, $\vec{x}$, at time t, then we need to maximize the following profit function. We should note that $\vec{e}_i$ is unit vector notation with inconsideration i equals one and others as zero.

$$\max_{i \in M} \left\{ g_j - f_{ij}^{d} - f_{ij}^{p} + V_{t+1}(\vec{x} - \vec{e}_i) \right\}$$

5.3.4 Spare Part Return Decision

Upon the arrival of the service engineer to the customer location, the validity of the demand signal is confirmed via on-site diagnostics. If the demand signal turns out to be false, then the spare part should be placed back into the network stock. Given the probability of a false demand signal, the spare part logistics need to decide the appropriate stock location for spare part return. Note that the spare part return decision depends on the earlier spare part sourcing decision. The costs of a false demand signal are $f^d_{ij} + f^r_{lj}$, where i represents the source stock location and l represents the candidate return stock location. Suppose that we decided to source the spare part from stock location i and a false demand occurred, then we need to maximize the following function to identify the candidate stock location for spare part return. Similar to the previous section, $\vec{e}_l$ is unit vector notation with inconsideration l equals one and others as zero.

$$\max_{l \in L} \left\{ V_{t+1}(\vec{x} - \vec{e}_i + \vec{e}_l) - f^d_{ij} - f^r_{lj} \right\}$$

5.4 Markov Decision Process Formulation

Figure 5.1 highlights the interaction between sourcing and return decisions. In this section, we present two MDP formulations to accommodate this interaction. In the first formulation, we account for the probability of false demand and consequent spare part return while deciding for the forward sourcing decision. Similarly, for the return decision, we account for the preceding sourcing decision from the current time instance t. In the subsequent text, we term this as a bi-directional interaction of the forward sourcing and return decision. To formalize this interaction, we present the following two stage MDP formulation. The value of stock $\vec{x}$ at time t equals the expected revenue given the optimal use of the available resources.

$$\begin{aligned} V^{in}_t(\vec{x}) = \sum_{j \in N} \lambda_j \max_{i \in M, l \in L} \Big[&(1 - q_j)\{g_j - f^d_{ij} - f^p_{ij} \\ &+ V^{in}_{t+1}(\vec{x} - \vec{e}_i)\} + q_j \{V^{in}_{t+1}(\vec{x} - \vec{e}_i + \vec{e}_l) - f^d_{ij} - f^r_{lj}\} \Big] \end{aligned}$$

Observe that we may write,

$$\begin{aligned} V^{in}_t(\vec{x}) = \sum_{j \in N} \lambda_j \max_{i \in M} \Big[&(1 - q_j)\{g_j - f^d_{ij} - f^p_{ij} + V^{in}_{t+1}(\vec{x} - \vec{e}_i)\} \\ &+ q_j \max_{l \in L} \left\{ V^{in}_{t+1}(\vec{x} - \vec{e}_i + \vec{e}_l) - f^d_{ij} - f^r_{lj} \right\} \Big] \end{aligned} \tag{5.1}$$

In this formulation, we account for the bi-directional interaction of the sourcing and return decision. Due to the combinatorial aspect of the interaction between sourcing and return, the above formulation is computationally intensive. An alternative to the above approach is a sequential approach. The sequential formulation for the two stage MDP is as follows:

$$\begin{aligned} V_t^{sq}(\vec{x}) = & \sum_{j \in N} \lambda_j \Big[(1-q_j) \max_{i \in M} \left\{ g_j - f_{ij}^d - f_{ij}^p + V_{t+1}^{sq}(\vec{x} - \vec{e}_i) \right\} \\ & + q_j \max_{l \in L | i^*} \left\{ V_{t+1}^{sq}(\vec{x} - \vec{e}_i + \vec{e}_l) - f_{ij}^d - f_{lj}^r \right\} \Big] \\ \textit{where} \quad & i^* = \arg\max_{i \in M} \left\{ g_j - f_{ij}^d - f_{ij}^p + V_{t+1}^{sq}(\vec{x} - \vec{e}_i) \right\} \end{aligned} \tag{5.2}$$

In this case, we make the forward sourcing decision, without formal consideration of the return decision. The return decision fully accounts for the preceding sourcing decision from the current t. In the subsequent text, we refer to this as a one-directional interaction of the sourcing and return decision. Moreover, we refer to Equation 5.1 as the integrated formulation and to Equation 5.2 as the sequential formulation. The superscripts in and sq are used to identify the value function for the integrated formulation and sequential formulation, respectively. We should note that the sequential formulation is less computationally intensive than the integrated formulation, since the set of admissible solutions is smaller for the sequential formulation. Before we analyze the integrated and sequential formulation further, we should clarify some aspects. Similar to the MDP formulation in Chapter 4, $V_{T+1}(\vec{x}) = 0$ and $V_t(\vec{0}) = 0$ for both the sequential and integrated formulations. In addition, we can observe from Equations 5.2 and 5.1, that the state space $\vec{x}$ is unbounded. To restrict the state space, we assume that there is no value of any additional inventory unit, if the current stock level at any location i is at or above its base stock or order up to level (S_i). The base stock level S_i for location i relates our execution problem to the planning phase, where $S_i \ \forall \ i \in \ M$ may not be identical. Here, we define the notion of shortfall at a stock location, which is used throughout the remaining chapter. According to this definition, a stock location has a shortfall, if the current stock level x_i is below its base stock or order up to level S_i. In other words, the shortfall at stock location i equals $(S_i - x_i)^+$.

The comparative analysis of the integrated and sequential formulations provides an opportunity to analyze the potential benefits of fully integrating the forward sourcing and return decisions. Although the sequential approach is computationally less intensive; one may argue that the one-directional consideration of the sourcing and return decisions may lead to suboptimal decisions at times. In other words,

Proposition 5.1

$$V_t^{in}(\vec{x}) \geq V_t^{sq}(\vec{x})$$

Proof We show that the inequality holds by induction. Assume that the inequality $V_{t+1}^{in}(\vec{x}) \geq V_{t+1}^{sq}(\vec{x}) \ \forall \ \vec{x} \in \mathbb{Z}_M^+$ holds. Now we show that it holds for t. We know,

$$\begin{aligned}
V_t^{in}(\vec{x}) = & \sum_{j \in N} \lambda_j \max_{i \in M, l \in L} \Big[(1-q_j)\{g_j - f_{ij}^d - f_{ij}^p + V_{t+1}^{in}(\vec{x} - \vec{e}_i)\} \\
& + q_j \big\{ V_{t+1}^{in}(\vec{x} - \vec{e}_i + \vec{e}_l) - f_{ij}^d - f_{lj}^r \big\} \Big] \\
\geq & \sum_{j \in N} \lambda_j \max_{i \in M, l \in L} \Big[(1-q_j)\{g_j - f_{ij}^d - f_{ij}^p + V_{t+1}^{sq}(\vec{x} - \vec{e}_i)\} \\
& + q_j \big\{ V_{t+1}^{sq}(\vec{x} - \vec{e}_i + \vec{e}_l) - f_{ij}^d - f_{lj}^r \big\} \Big] \\
\geq & \sum_{j \in N} \lambda_j \Big[(1-q_j) \max_{i \in M} \Big\{ g_j - f_{ij}^d - f_{ij}^p + V_{t+1}^{sq}(\vec{x} - \vec{e}_i) \Big\} \\
& + q_j \max_{l \in L | i^*} \big\{ V_{t+1}^{sq}(\vec{x} - \vec{e}_i + \vec{e}_l) - f_{ij}^d - f_{lj}^r \big\} \Big] \\
= & V_t^{sq}(\vec{x}). \ \square
\end{aligned}$$

Proposition 5.1 implies that bi-directional integration would lead to a higher expected value than the sequential formulation. In other words, we may infer that the decisions made while accounting for the bi-directional interaction between sourcing and returns should lead to a higher value. To analyze the extent of losses incurred by sequentially accommodating the interaction between sourcing and return decisions, we perform detailed numerical experiments.

5.4.1 Integrated vs. Sequential Decisions - Numerical Experiments

We first describe the simulation test bed used to numerically analyze the integrated and sequential formulations. We consider a logistics network consisting of three customers, two finitely stocked field stock locations, and one emergency supplier location. The stock units at FSLs one and two are five units and three units respectively. The inter-arrival time between two consecutive replenishments is fixed at 20 periods. The heterogeneities in the customer base are induced via distinct customer locations and contractual agreements (different service prices and penalty costs). Table 5.1 depicts the cost parameters used in the numerical experiments.

Table 5.1: Service Prices, Transportation and Penalty Costs

j	g_j	$f^d_{ij} = f^r_{lj}$			f^p_{ij}		
		$i = l = 1$	$i = l = 2$	$i = l = 0$	$i = l = 1$	$i = l = 2$	$i = l = 0$
1	400	15	45	115	1.25	4.77	108.42
2	300	10	20	90	0.00	1.56	35.53
3	200	45	15	55	4.77	1.25	7.45

The simulation is designed in the following manner. We analyze the difference between integrated and sequential decisions at various demand (λ_j) and return rates (q_j). By varying the demand rates, we induce various demand / capacity (D/C) ratios to represent over-stocking and under-stocking situations in the stock location network.

For the simulation experiments, we use the integrated and the sequential MDP formulations to decide on the execution decisions for sourcing and returns. For example, in the sequential case, we first make the sourcing decision by using the first maximization of Equation 5.2. Subsequently, the return decision is made by using the second maximization of Equation 5.2, which accounts for the previous sourcing option to decide on the return decision. As mentioned previously that the integrated formulation is different since it accounts for the bi-directional interaction of the sourcing and return decisions. We account for this combinatorial aspect by performing the search in an iterative manner. First, the profit function of the sourcing decision is maximized over the set M by using an arbitrary return decision l. Subsequently, we use the identified sourcing decision i to find the the maximized return decision l. This return decision is inserted back into the sourcing profit function to find the updated sourcing decision i. Such iterations are performed until the value function cannot be improved further. By using this iterative procedure, we handle the combinatorial aspect of the sourcing and return interaction. The demand arrivals and the false demand indications are randomly generated according to the chosen demand and return rates. The decisions derived from the MDP formulations are used in the simulation to decide on these random arrivals and return requests. Accordingly, we record the resulting profits. The simulation is run for 1000 runs. Similar random number streams are used in comparative cases (integrated and sequential) to obtain consistency with a reduced number of simulation runs.

5.4.2 Results

Table 5.2 depicts the results of the simulation experiments. As mentioned earlier, the aspects of under-stocking and over-stocking are induced by varying demand / capacity ratios (i.e. $\sum_t \sum_j \lambda_j / \sum_i x_i$). We also analyzed the performance of integrated and sequential formulations at various return ratios (i.e. $\sum_j q_j / \sum_j \lambda_j$). Next, average profits are depicted along with confidence intervals in parenthesis. In our extensive simulation experiments, we observe an insignificant difference between the integrated and the sequential formulation. At first, it seems that these results conflict with the inequality $V_t^{in}(\vec{x}) \geq V_t^{sq}(\vec{x})$. However, during our simulation experiments, we also compared $V_t^{in}(\vec{x})$ and $V_t^{sq}(\vec{x})$ for various $\vec{x}$ and t. The comparison revealed that the difference between integrated and sequential formulations ranges from 0.00% to 0.80%. In other words, the integrated formulation is expected to perform only slightly better than the sequential formulation. The simulation results also show the difference in the same ranges.

The results provide a number of interesting insights. Since the sequential formulation performs almost equally to the integrated formulation, it can be argued that there is not much to gain from bi-directional integration of the sourcing and return decision. As a result, the computational effort is significantly reduced. In other words, there are no significant losses if the sourcing decision is made without explicit consideration of the return decision. The above results open an avenue to develop heuristic solutions that are not necessarily based on integrated decision making. For the return decision, the sequential formulation accounts for the preceding sourcing decision. What is the potential gain by this one-directional integration? We test this in the next section by devising various return heuristics that do not account for a preceding sourcing decision. We pursue these ideas and describe them in detail in the next section.

Table 5.2: Simulation Results - Average Profits, Sequential and Integrated Formulations

Scenario	D / C Ratio	Return Ratio	Sequential	Integrated	% Difference
1	0.9	5%	1941.79 (4.08)	1941.79 (4.08)	0.00%
2	0.9	10%	1905.31 (4.29)	1905.31 (4.29)	0.00%
3	0.9	15%	1870.02 (4.73)	1870.02 (4.73)	0.00%
4	0.9	20%	1834.76 (4.57)	1834.76 (4.57)	0.00%
5	0.9	25%	1798.99 (5.32)	1798.99 (5.32)	0.00%
6	0.9	30%	1762.85 (5.21)	1762.85 (5.21)	0.00%
7	0.9	35%	1724.94 (5.31)	1724.94 (5.31)	0.00%
8	0.9	40%	1687.56 (4.80)	1687.56 (4.80)	0.00%
9	0.9	45%	1648.53 (4.13)	1648.53 (4.13)	0.00%
10	0.9	50%	1611.71 (4.21)	1611.71 (4.21)	0.00%
11	1.2	5%	2457.07 (4.26)	2457.07 (4.26)	0.00%
12	1.2	10%	2403.88 (4.17)	2403.88 (4.17)	0.00%
13	1.2	15%	2349.75 (4.83)	2349.75 (4.83)	0.00%
14	1.2	20%	2293.67 (5.83)	2293.67 (5.83)	0.00%
15	1.2	25%	2237.73 (5.54)	2237.73 (5.54)	0.00%
16	1.2	30%	2179.46 (5.05)	2179.46 (5.05)	0.00%
17	1.2	35%	2118.77 (4.54)	2118.77 (4.54)	0.00%
18	1.2	40%	2058.63 (4.28)	2058.63 (4.28)	0.00%
19	1.2	45%	2001.55 (4.42)	2001.55 (4.42)	0.00%
20	1.2	50%	1939.45 (4.64)	1939.45 (4.64)	0.00%
21	1.5	5%	2887.19 (4.77)	2887.20 (4.77)	0.00%
22	1.5	10%	2816.72 (4.80)	2816.73 (4.81)	0.00%
23	1.5	15%	2744.56 (6.13)	2742.55 (6.17)	-0.07%
24	1.5	20%	2671.50 (5.98)	2667.92 (5.98)	-0.13%
25	1.5	25%	2591.29 (5.69)	2587.55 (5.62)	-0.14%
26	1.5	30%	2508.56 (6.17)	2505.01 (6.06)	-0.14%
27	1.5	35%	2429.13 (5.73)	2425.78 (5.63)	-0.14%
28	1.5	40%	2343.39 (5.54)	2340.29 (5.45)	-0.13%
29	1.5	45%	2256.30 (5.26)	2253.48 (5.22)	-0.13%
30	1.5	50%	2165.13 (5.40)	2162.74 (5.36)	-0.11%
31	1.875	1%	3474.13 (3.27)	3474.13 (3.27)	0.00%
32	1.875	2%	3454.86 (3.24)	3454.86 (3.24)	0.00%
33	1.875	3%	3436.12 (3.36)	3436.12 (3.36)	0.00%
34	1.875	4%	3415.68 (3.65)	3415.68 (3.65)	0.00%
35	1.875	6%	3376.25 (3.88)	3376.25 (3.88)	0.00%
36	1.875	10%	3294.48 (4.38)	3294.48 (4.38)	0.00%
37	1.875	12%	3252.62 (4.88)	3252.62 (4.88)	0.00%
38	1.875	18%	3124.51 (5.15)	3124.50 (5.14)	0.00%
39	1.875	20%	3080.18 (5.13)	3080.17 (5.13)	0.00%
40	1.875	24%	2988.80 (5.93)	2988.82 (5.90)	0.00%
41	1.875	30%	2850.35 (6.04)	2850.53 (6.00)	0.01%
42	1.875	40%	2602.07 (6.41)	2602.29 (6.38)	0.01%
43	2.25	5%	4009.61 (3.85)	4009.57 (3.84)	0.00%
44	2.25	10%	3867.05 (5.31)	3863.99 (5.33)	-0.08%
45	2.25	15%	3713.76 (5.65)	3709.24 (5.71)	-0.12%
46	2.25	20%	3549.57 (6.23)	3531.90 (6.00)	-0.50%
47	2.25	25%	3379.96 (6.36)	3361.92 (6.27)	-0.54%
48	2.25	30%	3191.85 (7.67)	3186.71 (7.41)	-0.16%
49	2.25	35%	2998.06 (8.11)	2995.56 (7.95)	-0.08%
50	2.25	40%	2804.38 (7.21)	2797.30 (7.14)	-0.25%
51	2.25	45%	2607.27 (7.39)	2603.15 (7.41)	-0.16%
52	2.25	50%	2402.90 (6.82)	2399.29 (6.89)	-0.15%
53	2.25	60%	1967.88 (5.09)	1973.08 (5.01)	0.26%
54	2.25	70%	1522.09 (5.32)	1533.32 (5.27)	0.73%
55	2.25	80%	1058.73 (6.74)	1067.33 (6.84)	0.80%
56	2.25	90%	573.50 (3.64)	576.93 (3.67)	0.59%
57	2.25	100%	76.59 (4.80)	77.14 (4.83)	0.72%

5.5 Heuristic Solutions for Returns Management

In this section, we discuss various heuristic solutions that can be used to manage the execution of returns in spare parts logistics. We should note that these heuristics use considerably less information in comparison to the MDP approach. In this section, we first define these heuristics. Next, we compare the performance of these heuristics against the MDP formulations presented in Section 5.4. We then discuss the aspects that play an important role for the performance of each of these methods.

Return to Original In this heuristic, the sourcing decision is made by using the MDP formulation. In an instance of false demand, the spare part is returned back to its source location. In other words, we do not use the false demand instance to rebalance the network inventory.

Random Assignment In this heuristic, we randomly choose any stock location with shortfall for spare part return (by using uniform distribution to decide on the candidate return location). If there is no network stock location with shortfall, then the spare part is returned to the emergency shipment location. This return heuristic does not account for the preceding sourcing decision. Network inventory rebalancing is based on the random placement of the returned spare part in the network inventory.

Reverse Spiral Router This heuristic is a reverse logistics version of the forward spiral router heuristic described in Section 2.7.1. In an instance of spare part return, we search for the nearest stock location with available shortfall in capacity. If there is no stock location with shortfall in the inventory network, then the spare part is returned to the emergency shipment source. It should be noted that by performing a local search, this return heuristic accounts for the preceding sourcing decision. Network inventory rebalancing is performed by a proximity search to place the returned spare part in the network inventory.

5.5.1 Heuristics vs. MDP - Numerical Experiments

In this section, we present the results of the numerical experiments to compare the performance of the information enriched return MDP formulations vs. the return heuristics.

To ascertain that the performance of the return heuristics is independent of the sourcing method, we also compare the performance of the spiral router sourcing heuristic vs. the return heuristics discussed in Section 5.5.

First, we describe the details of the simulation test bed design and the parameters used in the numerical experiments. The simulation test bed is similar to the simulation test bed used in Section 5.4.1. For the information enriched methods, we use the decisions calculated by the sequential MDP formulation. In the case of the return heuristics, we estimate the return decisions according to the heuristics and insert the return decisions into the MDP formulations of Section 5.4 to obtain the forward sourcing decisions. The heuristic based return decisions together with the sourcing decisions from the MDP formulations are used in the simulation experiments to calculate the average profits. Simulation experiments are performed at various demand and return rates to observe the behavior of each method. By varying demand rates, we induce over-stocking and under-stocking situations in the stock location network. Each simulation experiment consists of 1000 runs, where the same random number streams are used to obtain consistent results with a reduced number of simulation runs.

5.5.2 Results

We now discuss the results of our simulation experiments. Similar to the numerical experiments discussed in Section 5.4.1, we perform simulation experiments with heterogeneities in the customer base by using the parameters described in Table 5.1. In the first set of experiments, the sourcing decision is based on the sequential MDP formulation (i.e. Equation 5.2). The results are depicted in Table 5.3.

We perform the experiments at various D/C and return ratios. In Table 5.3, we depict the average profits of the proposed heuristic solutions and their comparison with the MDP formulation. It is easy to note that all of the proposed heuristics perform at a level that is inferior to the MDP formulation. However, the degree to which the performance is degraded varies. The performance of the return to original heuristic appears to be the worst among all of the heuristics. The losses as compared to the sequential MDP formulation range from 0.18% to 7.09%. The random assignment heuristic performs slightly better than the return to original heuristic. However, the losses as compared to the MDP formulation range from 0.24% to 2.66%. In Section 5.5, we highlighted that the

Table 5.3: Average Profits of Heuristics vs. MDP - Sourcing Logic: Sequential MDP Formulation

			Return Decision Logic						
No.	D / C Ratio	Return Ratio	Return to Original	% Loss from MDP	Random Assignment	% Loss from MDP	Reverse Spiral Router	% Loss from MDP	Seq. MDP Formulation
1	0.90	5%	1,938 (4.31)	0.18%	1,932 (4.25)	0.37%	1,939 (4.29)	0.12%	1,942 (4.08)
2	0.90	10%	1,900 (4.58)	0.28%	1,887 (4.56)	0.65%	1,903 (4.56)	0.14%	1,905 (4.29)
3	0.90	15%	1,863 (4.73)	0.37%	1,844 (4.84)	0.75%	1,867 (4.73)	0.17%	1,870 (4.73)
4	0.90	20%	1,827 (4.74)	0.45%	1,801 (4.84)	0.97%	1,831 (4.74)	0.19%	1,835 (4.57)
5	1.20	5%	2,448 (4.64)	0.38%	2,437 (4.66)	0.29%	2,454 (4.59)	0.12%	2,457 (4.26)
6	1.20	10%	2,389 (4.28)	0.61%	2,369 (4.26)	0.37%	2,402 (4.27)	0.08%	2,404 (4.17)
7	1.20	15%	2,329 (4.77)	0.90%	2,296 (4.85)	0.63%	2,347 (4.79)	0.13%	2,350 (4.83)
8	1.20	20%	2,270 (4.83)	1.02%	2,226 (4.90)	0.94%	2,291 (4.85)	0.10%	2,294 (5.83)
9	1.50	5%	2,863 (4.94)	0.83%	2,853 (5.11)	0.25%	2,884 (4.87)	0.12%	2,887 (4.77)
10	1.50	10%	2,776 (4.78)	1.44%	2,754 (4.88)	0.24%	2,813 (4.77)	0.12%	2,817 (4.80)
11	1.50	15%	2,692 (4.98)	1.93%	2,653 (5.21)	0.82%	2,741 (5.12)	0.11%	2,745 (6.13)
12	1.50	20%	2,608 (5.11)	2.37%	2,553 (5.19)	1.25%	2,668 (5.18)	0.15%	2,672 (5.98)
13	2.25	5%	3,923 (3.99)	2.15%	3,937 (3.96)	0.64%	3,992 (4.15)	0.43%	4,010 (3.27)
14	2.25	10%	3,708 (4.99)	4.11%	3,725 (4.72)	1.15%	3,830 (5.29)	0.96%	3,867 (3.24)
15	2.25	15%	3,504 (4.66)	5.65%	3,513 (4.69)	1.53%	3,658 (5.17)	1.50%	3,714 (3.36)
16	2.25	20%	3,298 (4.76)	7.09%	3,292 (4.84)	2.66%	3,471 (5.48)	2.21%	3,550 (3.65)

network inventory rebalancing aspect is not supported by the return to original heuristic. The random assignment heuristic supports the network inventory rebalancing aspect in a naive manner by randomly placing the stock unit in the network inventory. We argue that the performance difference between the return to original heuristic and the random assignment heuristic is enabled by the network inventory rebalancing ability of the random assignment heuristic. The results show that the performance of the reverse spiral router is significantly better than the other two heuristics. The results also show that, except in very high under-stocking situations, the performance of the reverse spiral router is close to sequential MDP formulation with very small losses. The similar performance of the reverse spiral router heuristic can be attributed to its ability to account for the preceding sourcing decision in a manner similar to the sequential MDP formulation. To corroborate our results and to confirm that the forward sourcing decision logic does not significantly impact the behavior of each of these heuristics, we now present the results of the simulations where the forward sourcing decision is based on the spiral router heuristic described in Section 2.7.1. The parametric settings of the simulation experiments are similar to those in the previous set of experiments. The results are depicted in Table 5.4.

Table 5.4: Average Profits of Heuristics vs. MDP - Sourcing Logic: Spiral Router

			Return Decision Logic						
No.	D / C Ratio	Return Ratio	Return to Original	% Loss from MDP	Random Assignment	% Loss from MDP	Reverse Spiral Router	% Loss from MDP	Seq. MDP Formulation
1	0.90	5%	1,935 (4.29)	0.06%	1,929 (4.27)	0.18%	1,936 (4.28)	0.00%	1,936 (4.28)
2	0.90	10%	1,897 (4.53)	0.14%	1,884 (4.60)	0.35%	1,899 (4.54)	0.00%	1,899 (4.54)
3	0.90	15%	1,860 (4.69)	0.20%	1,841 (4.75)	0.51%	1,864 (4.71)	0.00%	1,864 (4.71)
4	0.90	20%	1,824 (4.72)	0.25%	1,798 (4.74)	0.69%	1,828 (4.73)	0.00%	1,828 (4.73)
5	1.20	5%	2,420 (4.42)	0.27%	2,409 (4.43)	0.25%	2,426 (4.40)	0.00%	2,426 (4.40)
6	1.20	10%	2,362 (4.14)	0.54%	2,341 (4.21)	0.51%	2,375 (4.16)	0.00%	2,375 (4.16)
7	1.20	15%	2,304 (4.62)	0.77%	2,271 (4.73)	0.78%	2,322 (4.67)	0.00%	2,322 (4.67)
8	1.20	20%	2,247 (4.72)	0.94%	2,201 (4.91)	1.07%	2,269 (4.75)	0.00%	2,269 (4.75)
9	1.50	5%	2,808 (4.92)	0.69%	2,796 (4.93)	0.34%	2,827 (4.81)	0.00%	2,827 (4.81)
10	1.50	10%	2,722 (4.71)	1.29%	2,698 (4.87)	0.70%	2,758 (4.64)	0.00%	2,758 (4.64)
11	1.50	15%	2,637 (4.93)	1.81%	2,597 (5.13)	1.08%	2,685 (4.99)	0.00%	2,686 (5.00)
12	1.50	20%	2,553 (4.95)	2.27%	2,498 (5.27)	1.47%	2,612 (5.00)	0.00%	2,612 (5.00)
13	2.25	5%	3,658 (4.31)	2.07%	3,672 (4.44)	0.49%	3,735 (4.15)	0.00%	3,735 (4.15)
14	2.25	10%	3,439 (5.19)	4.08%	3,456 (5.10)	1.03%	3,585 (4.93)	0.00%	3,585 (4.94)
15	2.25	15%	3,231 (4.67)	5.96%	3,244 (4.80)	1.60%	3,435 (4.45)	0.00%	3,436 (4.45)
16	2.25	20%	3,026 (4.72)	7.72%	3,024 (5.16)	2.27%	3,279 (4.74)	0.01%	3,280 (4.74)

The results follow a similar pattern for the return to original and the random assignment heuristics. The average loss from the MDP formulation for the return to original heuristic ranges from 0.06% to 7.72%. Similar to our earlier experiments, we observe that the losses in the case of the random assignment formulation range from 0.18% to 2.27%. These results show that for these heuristics the change in the forward sourcing decision logic has no impact on the return decisions. One may attribute this aspect to the complete independence of the forward sourcing and return decisions. In the reverse spiral router heuristic, we see a deviation in the results for the D / C ratio of 2.25 (highly under-stocked situation). In the preceding experiments, we observed that the MDP formulation was performing better (up to 2.21%) than the reverse spiral router for such a D / C ratio. In Table 5.4, we observe that these losses drop to 0.01%, which shows that only in the highly under-stocked situation, does the MDP formulation (with forward and return MDP decision) shows marginal potential. For other situations, we do not observe any gains by using the MDP formulation.

Finally, we synthesize our numerical experiment results in Table 5.4 and Table 5.3 to observe the gains from the spiral router based sourcing decision as compared to the MDP based sourcing decision, while keeping the return decision logic constant. The results are depicted in Table 5.5.

Table 5.5: Average Losses for Spiral Router Sourcing Logic

No.	D / C Ratio	Return Ratio	% Loss from MDP Sourcing Logic			
			Return to Original	Random Assignment	Reverse Spiral Router	Seq. MDP Formulation
1	0.90	5%	0.19%	0.12%	0.19%	0.31%
2	0.90	10%	0.18%	0.01%	0.18%	0.32%
3	0.90	15%	0.16%	0.09%	0.16%	0.33%
4	0.90	20%	0.15%	0.07%	0.16%	0.35%
5	1.20	5%	1.14%	1.21%	1.14%	1.25%
6	1.20	10%	1.14%	1.35%	1.13%	1.21%
7	1.20	15%	1.06%	1.34%	1.06%	1.19%
8	1.20	20%	1.01%	1.22%	0.99%	1.09%
9	1.50	5%	1.93%	2.16%	1.96%	2.07%
10	1.50	10%	1.95%	2.55%	1.98%	2.10%
11	1.50	15%	2.04%	2.41%	2.04%	2.15%
12	1.50	20%	2.12%	2.44%	2.08%	2.22%
13	2.25	5%	6.76%	6.70%	6.43%	6.84%
14	2.25	10%	7.27%	7.18%	6.40%	7.30%
15	2.25	15%	7.79%	7.56%	6.08%	7.49%
16	2.25	20%	8.23%	7.23%	5.52%	7.60%

As we observe, if the return heuristic is constant (return to original, random assignment, reverse spiral router, or sequential MDP formulation), then the losses due to using the spiral router heuristic for sourcing decisions range from 0.01% to 8.23%. These results confirm our findings of Chapter 4, which indicate that using an information enriched (MDP) method for the sourcing decisions leads to value addition. We only observe the deviations from the above value addition range for the high D/C ratios in the reverse spiral router situation, which shows that if sourcing decision is based on spiral router, then reverse spiral router appears to perform better as compared to MDP formulation.

5.5.3 Discussion

We observe in our numerical experiments, that the reverse spiral router heuristic performs almost similar to the information enriched MDP formulation for the return decision. We should note that this is contrary to our earlier observations in Chapter 4 and the results for the MDP based sourcing logic in Chapter 5. For the sourcing logic, we observed that the benefits of information enrichment via the MDP formulation are quite significant in comparison to the spiral router heuristic. In most of the situations, a similar argument does not hold for the return decision when we compare the return MDP formulation with the reverse spiral router. In this section, we highlight the aspects of the return situation that play a strong role in supporting this observation.

The performance comparison of various return heuristics versus the MDP formulation reveals that accounting for the preceding sourcing decision has an important role to play in the higher performance of the reverse spiral router heuristic. One may argue that in essence, the reverse spiral router is a somewhat restricted version (or a special case) of the return MDP formulation. In the reverse spiral router, we restrict the return candidate location to the nearest stock location with shortfall. In the return MDP formulation, we have no restriction on the nearest location. In other words, the benefits of introducing flexibility for the return decision are limited. Primarily, there are two aspects that play an important role for this result. First, the return decision in the MDP formulation is primarily based on the transportation costs. Service prices and penalty costs only have a marginal role to play via the recursive terms from the remaining time periods. Therefore, we observe that there is not much benefit in accounting for customer based heterogeneities in the return decision logic, except for in the highly under-stocked situations. Secondly, the geographical nature of the service network also has a role in our results. Suppose that the return MDP formulation logic decides on the 2^{nd} nearest location as an optimal return location. On the other hand, the reverse spiral router decides to place the part at the nearest (1^{st}) stock location. Now suppose that we choose the return decision according to the reverse spiral router heuristic. As a result, some of the customers, who have the 2^{nd} stock location as their primary stock location and who are situated in-between these two stock locations, would now find the 1^{st} stock location a more attractive option for demand fulfillment. In other words, the flexibility in future sourcing decisions provides the robustness (to some extent) against the inflexibility of the current return decision. Due to this structure, we do not observe significant losses from the return MDP formulation in the case of the reverse spiral router heuristic.

5.6 Conclusions

In this chapter, we extended our study of spare parts logistics execution to accommodate the impact of demand inaccuracies, namely, the return of new (unused) spare parts to the network inventory from the customer location. We studied this aspect in an integrated and a sequential manner. An integrated decision was calculated by using a two stage MDP formulation, where the forward (or sourcing) decision is made by considering the potential spare part return, and the return decision is made while accounting for the preceding sourcing decision. In the sequential formulation, we made the sourcing decision without considering the potential future return of the spare part. However, the return decision accounts for the preceding sourcing decision. We highlighted that at the execution level, the value addition, due to the full integration of sourcing and return decisions, is limited in comparison to the sequential decision. This observation promoted the development of various segregated and sequential decision heuristics. The comparison of return heuristics revealed that the reverse spiral router heuristic, which is a sequential decision making heuristic performs quite closely to the sequential MDP formulation. We also highlight that the performance of the reverse spiral router heuristic can be attributed to the fact that it is a special case of the sequential MDP based return logic.

The results in this chapter also highlight an important aspect regarding our overall discussion in this thesis. Recall our discussion in Chapters 1 and 2, regarding the benefits of information enrichment in after sales service management. At first, the results observed in this chapter are somewhat contrary to this discussion. We observed in this chapter that a simple heuristic (i.e. reverse spiral router), not accounting for customer based heterogeneities and demand information, still manages to perform almost equally to the information enriched methods. Only transportation cost information is used to determine the appropriate stock location for a spare part return in the reverse spiral router heuristic. However, a detailed review of this heuristic and the nature of the information enriched techniques reveals the synergy between these two methods; such that the reverse spiral router heuristic is a special case of the information enriched methods. Other simple heuristics such as the return to original or the random assignment do not perform in a similar manner. From this discussion, one may argue that it is the detailed understanding provided by the information enriched methods that allows us to qualify the performance of each of the heuristics and subsequently, choose a heuristic which is simple but follows a rationale for decision making similar to the information enriched methods. It is this rationale for decision making that allows a simple heuristic to perform equally to the information enriched method.

Finally, we comment on the network inventory rebalancing aspect of the decision situation analyzed in this chapter. We observed in this chapter that in over-stocking situations, there is not much benefit in promoting network inventory rebalancing. For under-stocking situations, the results depict a different behavior. There is a benefit in using the techniques that promote network inventory rebalancing. For such situations, to decide where the stock is to be placed in the network, the reverse spiral router heuristic proves to be a simple and effective method.

5.7 Limitations and Generalization

We now discuss some of the limitations of the results presented in this chapter. In this chapter, we restricted the spare part returns to a single item. Although the assumption seems logical in the specific context of spare parts; in the broader context of reverse logistics, this assumption may not hold. However, we can argue with some confidence that reverse spiral router heuristic may also perform reasonably well in situations where returns are of more than one units.

In this chapter, we compared various approaches for the situation where returned items can be directly placed back into the network inventory. In Section 5.2.1, we observed that the academic literature discussing returns flows of new and old items makes no distinction between them from the return distribution standpoint. Similar to the used items, the new items are also shipped to a testing / refurbishing facility for onwards transit to the network inventory. We should note that such an approach could potentially result in transportation cost savings via consolidation as well as extra distribution and administration related delays. The resulting delays in the placement of parts into the network inventory may induce additional service deadline violations and consequent penalty costs. For these reasons, a detailed comparison of the consolidation approach with the approach proposed in this chapter is needed for a comprehensive answer.

Another limitation of the results presented in this chapter extends from the small scale nature of the analyzed simulation test beds. In addition to the structural analysis of the decision making situation, a comprehensive analysis by using a realistically sized scenario as a simulation test bed is needed for conclusive evidence. Meanwhile, we observed that there is no particular difference between the results of the small and large scale scenarios in Chapter 4. Due to this similar behavior and the similarities of the decision making situations in Chapters 4 and 5, we can claim with some confidence, that the results from the small scale scenario in Chapter 5 should hold. As mentioned earlier, a comprehensive analysis using a realistically sized scenario as a simulation test bed is, however, needed for conclusive evidence.

A primary assumption in Equations 5.1 & 5.2 for the integrated and sequential formulations is that a spare part return originating in period t arrives at the destination stock location in the same period. Due to the typical choice of slower transportation modes for return logistics, this assumption may be unrealistic. However, due to the slow demand rates in after sales service, one can argue for the validity of the assumption. By considering the inventory network situation of Figure 2.7, one may argue that the more prevalent situations of Figure 2.6 are not accounted for.

Finally, we would like to comment on similar situations in which the results presented in this chapter might also be applicable. In this chapter, we specifically focused on the spare part returns originating due to false demand alarms. However, as discussed in Section 2.2.3, new spare part returns also originate due to pessimistic ordering practices of the service engineers. The results presented in this chapter are also applicable for those situations. One may also argue that this approach can be extended to the situation of used products, where multiple identical remanufacturing locations (remanufacturing capacitates may be different) are available in the network to remanufacture, harvest, refurbish or dispose the returned products. A variant of the reverse spiral router heuristic can be used in such settings to choose the candidate remanufacturing facility for remanufacturing. This variant can be defined as the nearest remanufacturing facility that has unused capacity available for remanufacturing. A limiting aspect here is the unit return assumption, since product returns in traditional supply chains are typically in the form of batches. Finally, one may argue for the situation of high value products that are unsold and need to be strategically repositioned in the geographical network with multiple sales locations. The results of this chapter may also be applicable in such settings.

Chapter 6

Conclusions

Throughout this thesis, we observed the potential benefits of customer information enrichment in after sales service by matching service provider capabilities with the varying needs of a heterogeneous customer base. In this chapter, we summarize the results presented in this thesis by relating the results to our research objectives discussed in Section 1.3.2. Subsequently, we discuss the implications of the results for after sales service management. Finally, we discuss potential areas for future research.

6.1 Research Contributions and Results

6.1.1 Research Contribution 1 - Solution Methods for After Sales Service

The first research contribution is a solution method to account for the prevailing business characteristics of after sales service in spare parts logistics planning and execution. This solution method applies to spare parts inventory planning, spare parts logistics execution and returns management in after sales service. We should note that our objective was to devise or utilize a solution method or methods that could use IB information to account for the service requirements of a heterogeneous and geographically dispersed customer base. In this respect, we devised or utilized a solution method, where the unit of analysis is an installed machine.

Chapter 3 - Inventory Planning & Information Enrichment

We reviewed the extensive spare parts inventory planning literature in Chapter 2. We observed that the work of Kranenburg and Van Houtum (2009) and Erke et al. (2003) accounts for the characteristics of multiple service deadlines and lateral transshipments in after sales service. These solution methods are also able to utilize IB data for spare parts inventory planning by having an installed machine as a unit of analysis. We therefore utilized the above work to analyze the value of IB information for spare parts inventory planning.

Chapter 4 - Spare Parts Execution Management

Our review of the literature for spare parts logistics execution revealed no particular solution method that fits the characteristics of our problem. In Chapter 4, we devised an execution technique for spare parts logistics by providing segmented services to the heterogeneous customer base. In this regard, we studied the relevant literature in revenue management and inventory rationing. We devised an execution technique that allows us to match the available spare parts resources to the incoming demand in a differentiated manner. The devised technique uses the concept of segmented service from revenue management. We extended the work of Lautenbacher and Stidham (1999) to account for the multi-dimensional settings of a spare parts logistics network. We then devised a greedy solution algorithm to execute the spare parts logistics execution in an online manner. The computational complexity estimations of the devised technique showed promising results for large scale practical application in after sales service.

Chapter 5 - Returns Management in Spare Parts Logistics

In Chapter 5, we studied reverse logistics in after sales service. Our particular interest here was to identify candidate field stock locations for the placement of the returned spare parts into the inventory network. Two questions were key in this scheme. One, what are the potential benefits of integrating the sourcing and return execution decisions? Two, what are the potential benefits of utilizing the returned spare parts for network rebalancing? To investigate the first question, we devised two integrated techniques representing full and partial integration of the sourcing and return decisions. The partial integration case represented a situation in which the sourcing decision is made without any formal consideration of potential returns. The return decision however accounts for the previous sourcing decision. The fully integrated situation differs in the sense that the sourcing decision also accounts for potential returns. Both of these techniques use IB data to support decision making and network rebalancing. We compared the performance of the above techniques with various heuristic based solutions that do not use extensive IB data. The results indicated that network rebalancing, coupled with the integration of the sourcing and returns decision, induce value addition in returns management. However, the value gained from partial integration to full integration was negligible. Simultaneously, we observed that the performance of the reverse spiral router heuristic was similar to the partially integrated solution technique. This heuristic solution is cost efficient, computationally efficient and provides a simple mechanism for decision making in returns management of after sales service.

6.1.2 Research Contribution 2 - Value of Installed Base Information

Our second research contribution in this thesis was to observe the value of IB information to support operations management in after sales service. For this purpose, we compared information enriched solutions with equivalent solution methods in after sales service that do not use IB information. Similar to the previous discussion, we organize our discussion according to the operational and tactical decisions that were discussed in Chapters 3, 4, and 5 of this thesis.

Chapter 3 - Inventory Planning & Information Enrichment

In this chapter, we analyzed the value of IB information. We compared the inventory planning performance of IB information enriched scenarios against the inventory planning performance without IB information. Scenario analysis revealed that IB information enriched scenarios consistently performed better than scenarios without IB information. The additional value was enabled by more accurate decision making in the IB information enriched scenarios. In this chapter, we also studied the impact of data quality variations in IB information on inventory planning performance. By studying the real life spare parts inventory planning situation at IBM, we established the common business conditions that induce various types of data quality errors in IB data. We categorized the errors according to their structural characteristics. For example, incorrect data entry and related human errors occur at random and induce data quality variations that are homogeneously distributed with respect to the geographically dispersed installed base. In some cases, data quality errors are concentrated in a specific geographical area; thus it is termed as a heterogeneously distributed error. We further analyzed the impact of these data quality errors on spare parts inventory planning and highlight the role of the error's structural characteristics. The results showed that the error's structural characteristics have significant impact on the planning performance. We observed that in some cases the impact of the data quality errors is significant enough to negate the value addition enabled by IB data usage. Further analysis of such cases revealed that these cases belong to the specific error scenarios where the error's structure is able to disturb the original geographical distribution of demand. If the error structure is homogeneous or it does not disturb the original demand distribution, then the impact on the inventory planning performance is insignificant. Meanwhile, the data quality related losses, due to homogeneously distributed error, do not negate the benefits induced by installed base data usage. In other words, the "Garbage In - Garbage Out" concept does not always hold.

Chapter 4 - Spare Parts Execution Management

In this chapter, we studied the benefits of using IB information for spare parts logistics execution. We again showed that IB information enrichment induces value addition in after sales service. In the first study, we specifically focused on information enrichment by neglecting the role of the planning method for value addition. In this chapter, we highlighted that an appropriate decision engine or a supply chain analytic tool utilizing the detailed information for gains is equally important. By using IB information, we can derive each customer's cost information (i.e. service prices, transportation costs, penalty costs) and associated demand information. By using this information and borrowing the concepts of differentiated service, we analyzed the benefits of using IB information to support spare parts execution. The value addition was due to the additional decision space that was enabled by IB information. In this specific case, the additional decision space was the decision regarding differentiated service provision to the heterogeneous customer base. This allowed us to better match the incoming demand to the available inventories in the stock location network, which resulted in value addition.

Chapter 5 - Returns Management in Spare Parts Logistics

In this chapter, we studied returns management in after sales service. Similar to previous chapters, we studied and compared the decision making performance of various heuristics, where some of the heuristics do not use IB data. The comparison revealed that using IB data does not provide significant value additions against reverse spiral router heuristic that does not use IB data. A careful analysis revealed that the decision making rationale of the IB information enriched technique is quite similar to the heuristic that performs comparably. In other words, the decision making logic of the heuristic under consideration is a special case of the information enriched method. A comparable decision can be made without using the extensive penalty costs, service price and customer demand data from the IB information. The only data needed is transportation cost data. Due to this, the performance difference between the heuristic and IB enriched techniques is negligible. From the discussion, we argue that it is the detailed understanding provided by the information enriched methods, that allows us to qualify the performance of each of the heuristics, and subsequently, choose a heuristic which is simple but follows a similar rationale as the information enriched methods for decision making.

6.2 Discussion

Are there any benefits of using customer data to drive after sales service? If so, then how and why does customer data enable the value addition in after sales service? These are the questions that we attempted to understand in this thesis. We consistently observed the benefits of utilizing IB data in after sales service. We also highlighted that the value addition is due to the manner in which IB data enables us to more effectively accommodate and satisfy the various service needs of a heterogeneous customer base.

We now relate these observations to the broader discussions on supply management and demand management in the supply chain management literature. Throughout this thesis, we make a distinction between logistics planning and execution. Logistics planning is a supply management task with an intention to manage the supply side of spare parts logistics while accounting for future demand forecasts. On the other hand, spare parts logistics execution can be considered a demand management task (to some extent) that aims to complement logistics by matching the incoming customer demand to the available supplies. In recent years, demand management has received considerable interest in the supply chain management literature. Various researchers such as Elmaghraby and Keskinocak (2003), Agatz et al. (2008), Quante et al. (2009), and Talluri and Van Ryzin (2004) have discussed pricing and quantity based approaches for demand management in retail, e-retail, manufacturing, airline and hotel sectors. It should be noted that demand management in these sectors has two aspects to it. One aspect relates to planning demand with the goal of influencing customer demand behavior. The second aspect relates to segmenting the customer base and matching the available supplies to the segmented customer demand in a real-time manner. We should however clarify that the notion of demand management in after sales service should be much more strict than in the above-mentioned sectors. It is widely discussed in the literature that demand management practices in the airline, hotel, retail, and e-retail sectors involve planning demand in such a way that also influences the customer demand behaviors. In after sales service, customer demand behavior is an exogenous variable originating solely due to machine reliability and usage aspects. Therefore, any consideration of demand management concepts to influence or manage customer demand behavior in after sales service is meaningless — especially in the case of a reactive maintenance policy. In after sales service, differentiated service offerings and pricing structures are commonplace, but discussions with a specific focus on demand management (or differentiated execution or event driven execution) are scarce in the academic literature. The focus in after sales service literature to accommodate customer heterogeneities is limited to account for the differentiated service offerings in the planning phase (see Section 2.5.2 for details). The introduction of flexibility is limited to lateral transshipments and static critical levels, which are devised during the inventory planning phase. A truly dynamic setting which reacts to available resources and incoming customer demand during execution, in a real-time manner, is more or less unaddressed. The available execution solutions do not fully accommodate variations in cost or price structures and incoming demand patterns for a heterogeneous customer base in after sales service. However, as we show in Chapter 4, addressing such aspects leads to value addition in after sales service.

Weatherford and Bodily (1992); McGill and Van Ryzin (1999) discuss information management practices and their contribution to demand management developments in the airline and hotel sectors. More specifically, they highlight that the practice of gathering and retaining detailed customer data can serve to define customer segmentations, playing an important role for demand management advances in these sectors. In after sales service, customer segmentations can be readily devised by using the IB data. On the other hand, the presence of multiple cost or price structures, and multiple inventory replenishment policies makes the application of demand management principles in after sales service quite difficult.

We should note that the benefits of utilizing IB data are not limited to demand management in after sales service. As we witnessed in Chapter 3, accounting for the varying service needs of a heterogeneous customer base also leads to improved supply management in after sales service. We observed that by using more information, we were able to induce a higher level of accuracy in planning decisions. This higher level of accuracy in turn drives the addition of value in after sales service.

Finally, we discuss the interrelation between various strategic, tactical and operational decisions in after sales service. Throughout Chapter 2, we highlighted this aspect on various occasions. For example, the interrelation between spare parts logistics network design and spare parts inventory policy is discussed in Section 2.3.2. The interrelation between planning and execution has been highlighted in Sections 2.4.2 and 2.5.2. In Chapter 5, we consider this issue in a more formal manner by studying the interaction between spare parts logistics execution decisions and spare parts returns execution. Through simulation analysis, we are able to understand the benefits of this interaction. We also noted that accounting for this interaction, and operationalizing it by performing a greedy search from the return origin location (i.e. the reverse spiral router technique), leads to benefits. Meanwhile, we also noticed that although both sourcing and return decisions are execution level decisions, similar levels of data enrichment is not required for (near) optimal performance. We should however caution that these observations are only valid for the considered new spare parts returns situation. A more generic setting that accounts for all different types of returns should be studied in order to attain baseline results. Similarly, in Sections 2.4.2 and 2.5.2, we noted the interactions between spare parts inventory planning and spare parts logistics execution decisions. A formal study of the interaction between these two decisions is still an open research question. With these words, we move to discuss potential areas of future research in a comprehensive manner and conclude this thesis.

6.3 Areas of Future Research

In Chapter 2, we identified the gaps in the academic literature to support profit driven after sales service operations. The gaps exist due to the inability of various solution methods to account for the varying service needs of a heterogeneous customer base and the design of flexible service operations. This thesis contributes by developing solution methods (for tactical and operational decisions in spare parts logistics management), accounting for customer base heterogeneities and providing flexible service. The development of similar solutions for other after sales service operations (e.g. maintenance service management) can lead to value additions in after sales service.

Focussing on potential extensions specifically related to the problems discussed in this thesis, we note that the spare parts inventory planning problem discussed in Chapter 3 relates to the inventory network of the country or region 2 situation of Figure 2.6. An inventory planning solution for the multi-echelon situation of the country or region 1 situation in Figure 2.6, that accounts for full and partial lateral transshipments, is still unaddressed. Addressing these items represents a useful extension, since similar inventory network situations commonly exist in after sales service in practice.

As discussed earlier, the solution methods presented in Chapters 4 and 5 relate to the inventory network situation of Figure 2.7. As we noted earlier, this inventory network is a special case of the country / region 2 situation of Figure 2.6, where the review periods are long and replenishment ordering is performed at the same time for all field stock locations. Development of execution techniques that are not restricted to this special case and are inclusive of all cases of the country or region 1 & 2 situations in Figure 2.6 is an important research extension, since these configurations are commonly used to manage (plan and execute) inventories in after sales service practice. We should however mention (as discussed earlier in Section 4.7) that during the course of this research, an investigation was made to account for these aspects of the spare parts logistics execution decision of Chapter 4. We shall report on these findings in a separate publication.

In Chapter 3, we discussed the issue of data quality for spare parts inventory planning. We observed that the impact of data quality variations depends on the error's structure and the decision making rationale of the OR based planning model. We also highlighted, in Chapter 3, the limitations of the supply chain management related OR literature regarding data quality aspects. In this respect, we argue for the importance of data quality analysis or robustness analysis of OR based models, since data quality variations can be observed in almost all practical situations. We specifically argue that data quality analysis or robustness analysis of OR models should be studied with explicit consideration of the decision making context.

We highlighted the importance of the interaction among various after sales service operations in Section 6.2. The detailed survey of the after sales service management literature in Chapter 2 revealed that most of the literature to support operations management in after sales service does not account for these interactions. Instead, the primary focus is to study these operations independently of others. We argue for the need to study these operations while explicitly accounting for the interactions among different operations. For example, a jointly optimized planning of service engineering and spare parts resources may lead to additional value in after sales service management. One may also argue that accounting for the maintenance network configuration while designing the spare parts logistics network could allow for better coordination among these operations and ultimately improve operations management in after sales service. Similarly, a formal study of the interaction of spare parts inventory planning and spare parts logistics execution decisions would lead to a better understanding of the coordination issues and potentially improve after sales service operations.

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Summary in English

Over the years, after sales service business in capital goods and high tech sectors have experienced significant growth. The drivers for growth are higher service profit, increased competition, and primary market contraction. The enablers for growth include information driven service processes and a move from a one-size-fit-all oriented warranty contracts to multiple service contract offerings that aim to align service provision to varying service needs of a heterogeneous customer base. The efficient management of after sales service involves a close coordination among various service operations such as maintenance management, spare parts logistics, and spare part returns management.

Installed base information including machine location and contract information can be used to drive performance in after sales service. This is particularly valid for after sales service operations, where service response requirements are stringent, customers are geographically dispersed, and service contracts promise quick on-site service response. Such business characteristics of after sales service commonly exist in capital goods and high-tech sectors.

We study the benefits of using installed base data in spare parts inventory planning (a tactical decision) in Chapter 3. The first part of this chapter presents a comparative analysis between scenarios where no installed base information was used to support inventory planning versus scenarios where installed base information was used. No installed base scenario refers to the situation where historical demand at each stock location is extrapolated to estimate next period demand forecast and used as an input to spare parts inventory planning. Scenario with installed base information refers to the situation, where acquired stock location level demand forecast is spread over the postal codes in the entire region proportionally to the number of installs at each postal code. The

comparison reveals the additional benefits of using installed base information to support spare parts inventory planning are significant.

Next, we analyze to what extent additional benefits of using installed base data are negated due to installed base data quality errors. We first classify the errors in installed base data as homogeneous errors and heterogeneous errors depending on their geographical distribution. Homogeneous errors refer to the situation where the concentration of errors in installed base is similar throughout the geographical area. Heterogeneous errors are present if the errors are concentrated in a specific geographical area. The results show that errors in installed base information do not always negate the additional benefits of using installed base information. For example, the performance of spare parts inventory planning does not deteriorate due to homogeneous errors, even at very high error frequencies. On the other hand, heterogeneous errors impact the planning results to an extent that additional benefits of using installed base information to support spare parts inventory planning are negated.

In Chapter 4, we focus on spare parts logistics execution (an operational decision). Upon demand arrival, a spare part needs to be delivered to the customer location to support machine maintenance. From which stock location shall the spare part be delivered? In this chapter, we present an execution technique that uses detailed information about each customer (such as service prices, transportation costs, penalty costs, and demand rates that are derived by using installed base information). The key idea in this technique is to match the available resources to the segmented customer demand. We show that the presented technique is computationally efficient and yields higher profits in comparison to the traditional practice of using first in - first out for spare parts logistics execution.

In Chapter 5, we notice that inaccuracies in spare parts demand order information leads to return management issues in spare parts logistics. We analyze this issue from various perspectives. First, a spare part that was delivered to customer location due to an inaccurate demand order needs to be returned to the stock network. Therefore, we need to decide to which stock location the spare part should be returned? In other words, what are the benefits of using spare part returns as an opportunity to rebalance the stock network? Secondly, should the return execution decision be made while accounting for the previous forward sourcing execution decision? Our analyses in this chapter indicate that rebalancing the stock network results in additional value. We also show that accounting for the interrelation between forward sourcing execution decision and return execution decision yields additional value. We account for this interaction in simultaneous and sequential manners. The results reveal that sequential decision making is computationally efficient than simultaneous decision making while it performs quite similarly in terms of profits. Finally, we present a computationally efficient solution technique for return decision execution.

Samenvatting (Summary in Dutch)

De afgelopen jaren heeft de handel in after sales diensten van kapitaalgoederen en hightech producten zich gekenmerkt door een aanzienlijke groei. De oorzaken hiervan zijn de hogere winstgevendheid van dienstverlening, de toegenomen concurrentie, en krimpende primaire markten. Deze groei wordt mede mogelijk gemaakt door informatie aangestuurde dienstverleningsprocessen en de overstap van garantiecontracten met een gestandaardiseerde en uniforme benadering naar service contracten met meerdere opties die gericht zijn op het afstemmen van de dienstverlening op de verschillende behoeften van een heterogeen klantenbestand.

Efficiënte besturing van after sales diensten vereist nauwe cordinatie tussen diverse operationele activiteiten zoals onderhoud en de (retour) logistiek van reserveonderdelen. Installed base informatie, hetgeen informatie over contracten en de locaties van machines omvat, kan worden gebruikt om prestaties in after sales diensten te verbeteren. Dit geldt met name voor after sales diensten waar een snelle respons wordt vereist, klanten geografisch verspreid zijn, en waar service contracten een spoedige dienstverlening ter plaatse garanderen. Dit komt geregeld voor bij het onderhoud aan kapitaalgoederen en hightech producten bij zakelijke klanten.

We bestuderen de voordelen van het gebruik van installed base informatie in de voorraadplanning van reserveonderdelen (een tactische beslissing) in Hoofdstuk 3. Het eerste deel van dit hoofdstuk betreft een vergelijkende analyse tussen de scenarios waar geen installed base informatie werd gebruikt ter ondersteuning van de voorraadplanning, versus scenarios waarbij installed base informatie wel werd gebruikt. Een scenario zonder installed base informatie verwijst naar de situatie waarbij de historische vraag op elke voorraadlocatie wordt geëxtrapoleerd voor een schatting van de vraag in de volgende periode en deze prognose wordt vervolgens gebruikt als input voor de voorraadplanning van reserveonderdelen. Een scenario met installed base informatie heeft betrekking op de situatie waarbij de prognose gebaseerd wordt op informatie over voorraadniveaus per locatie en wordt verspreid over postcodes in de hele regio in verhouding tot het aantal installaties bij elke postcode. Deze vergelijking toont aan dat de voordelen van het gebruik van installed base gegevens ter ondersteuning van de voorraadplanning reserveonderdelen aanzienlijk zijn.

Vervolgens analyseren we in welke mate de voordelen van het gebruik van installed base gegevens worden teniet gedaan door foutieve data. We classificeren de fouten in de installed base gegevens eerst als homogene en heterogene fouten, afhankelijk van hun geografische spreiding. Homogene fouten hebben betrekking op de situatie waarin de concentratie van fouten in de installed base data gelijkelijk verdeeld is in het gehele geografische gebied. Heterogene fouten komen voor wanneer de fouten zijn geconcentreerd in een bepaald geografisch gebied. De resultaten tonen aan dat fouten in installed base gegevens niet altijd de voordelen van het gebruik van installed base gegevens teniet doen. De prestaties van de voorraadplanning van reserveonderdelen verslechteren bijvoorbeeld niet als gevolg van homogene fouten, zelfs niet bij zeer hoge frequenties van fouten. Aan de andere kant, heterogene fouten hebben bij een hoge foutenfrequentie een dusdanige invloed op de planning dat de bijkomende voordelen van het gebruik van installed base gegevens ter ondersteuning van voorraadplanning voor reserveonderdelen teniet kunnen worden gedaan.

In Hoofdstuk 4 richten we ons op uitvoering van de logistiek van reserveonderdelen (een operationele beslissing). Wanneer de vraag zich aandoet, moet er een reserveonderdeel worden afgeleverd bij de klant op locatie voor onderhoud van de machine. De vraag is vanuit welke voorraadlocatie het reserveonderdeel geleverd moet worden. In dit hoofdstuk presenteren we een uitvoeringstechniek die gedetailleerde informatie over elke klant gebruikt (zoals service prijzen, transportkosten, boetes, en de vraagniveaus die zijn afgeleid met behulp van installed base informatie). De gedachte die ten grondslag ligt aan de gepresenteerde techniek is om de beschikbare middelen af te stemmen op de gesegmenteerde klantvraag. We tonen aan dat de gepresenteerde techniek numeriek efficiënt is en hogere winsten oplevert in vergelijking met het traditionele gebruik van de

First-In First-Out methode voor de executie van de logistiek van reserveonderdelen.

In Hoofdstuk 5 merken we op dat van inaccurate informatie over de vraag naar reserveonderdelen leidt tot vraagstukken in de retourlogistiek van reserveonderdelen. We analyseren dit probleem vanuit verschillende perspectieven. Als eerste moet een reserveonderdeel dat door een verkeerde diagnose is geleverd aan een locatie van de klant worden teruggestuurd naar het voorraadnetwerk. Daarvoor moet er worden beslist naar welke voorraadlocatie het onderdeel wordt teruggestuurd. Met andere woorden, wat zijn de voordelen van het gebruik van retouren om het voorraadnetwerk te herbalanceren? Ten tweede is de vraag of de uitvoering van de retour beslissing moeten geschieden in samenhang met de uitvoering van de bevoorrading van het netwerk? Onze analyses in dit hoofdstuk geven aan dat het in evenwicht brengen van het voorraadnetwerk resulteert in toegevoegde waarde. We tonen eveneens aan dat rekening houden met de relatie tussen de uitvoering van het bevoorradingsbesluit en de uitvoering van het retour besluit toegevoegde waarde oplevert. Tot slot presenteren we een numeriek efficiënte oplossingstechniek voor de uitvoering van de retourbeslissing. We tonen in het bijzonder aan dat een volledige integratie van de bevoorrading- en retourbeslissingen niet nodig is, en dat kan worden volstaan met een numeriek efficiënte benadering.

About the author

Muhammad Naiman Jalil (1974) was born in Faisalabad, Pakistan. After getting his higher secondary school diploma, he studied Metallurgical Engineering at the University of Engineering and Technology, Lahore.

After the completion of Bachelor's degree, he started working as a process and product quality engineer at Treet Corporation. It is a leading razor blade manufacturing company in Lahore, where sharp edged razor blades are diligently produced with utmost process and product quality. The process improvement projects at Treet Corporation inspired Muhammad and instigated curiosity in him towards best practices in Operations Management. The result was that he landed in New Jersey to pursue a Master's degree in Industrial and Systems Engineering at Rutgers, The State University of NJ, New Jersey.

At that time, White House Commission on Aviation Safety and Security had recommended a research program to develop next generation aviation technologies to improve aviation safety and reduce aviation system risk. Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA) were leading this effort by developing Aviation Safety and Security Program (AvSSP) Technologies. Muhammad joined Center of Advanced Risk and Decision Analysis (CARDA) at Rutgers University, where as a part of research team, he contributed to the development of Aviation System Risk Model (ASRM). NASA Langley Research Center used ASRM to estimate relative safety risk reductions due to AvSSP technologies.

In 2006, he started as a PhD student at the Rotterdam School of Management at Erasmus University Rotterdam. He became interested in supply chain management issues in service industries and extensively collaborated with IBM Service Parts Organization and IBM Zurich Research Laboratory for his research. The successful research collaboration with IBM resulted in journal articles, book chapter, and PhD thesis for Muhammad. He has presented his research at major international conferences, such as the annual meetings of the Production and Operations Management Society (POMS), the European Conference on Operational Research (EURO), the Institute for Operations Research and Management Sciences (INFORMS), and the International Workshop of Distribution Logistics (IWDL). IBM benefited from this research collaboration with improved after sales service planning and state of art decision support system for after sales service execution.

Since October 2010, he is associated with Suleman Dawood School of Business, at the Lahore University of Management Sciences, Lahore as an Assistant Professor.

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CUSTOMER INFORMATION DRIVEN AFTER SALES SERVICE MANAGEMENT
LESSONS FROM SPARE PARTS LOGISTICS

Over the years, after sales service business in capital goods and high tech products has experienced significant growth. The drivers for growth are higher service profits, increased competition, and reduced revenues from product sales. The enablers for growth include information driven service processes and a move from one-size-fits-all oriented warranty contracts to service level agreement offerings that differ in service prices and response guarantees. Although, these trends provide an opportunity to the service providers to match their service resources to the time varying service requirements of a heterogeneous customer base, the tools and techniques to support decision makers are lacking to this date. In this thesis, we aim to make a contribution in closing this gap. We gain business environment related insights of after sales service by studying it at a major computer equipment manufacturer. After sales service is a complex task that is accomplished by making a series of strategic, tactical, and operational decisions in maintenance services management, spare parts logistics management, and spare part returns management. In the thesis, we focus on operational and tactical decisions in spare parts logistics management. We identify that customer information, or more specifically, installed base information is a valuable source to support spare parts logistics decisions at the operational and tactical levels. We present an execution technique for spare parts logistics that uses installed base information to provide differentiated service to a heterogeneous customer base and results in additional profits for the service provider. Finally, we study the interaction between execution decisions in spare parts logistics and spare part returns management, and derive additional benefits while doing so.

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