Inventory Routing
A Strategic Management Accounting Perspective

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Inventory Routing: A Strategic Management Accounting Perspective

Key words: Inventory routing, strategic management accounting, information sharing, strategic cost management, uncertainty-based coordination, objective-based coordination

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PART I:
THEORETICAL FRAMEWORK AND CONTRIBUTIONS
1 INTRODUCTION

1.1. Background

What is the motivation of advancing a strategic management accounting perspective of inventory routing? The answer to this question is derived from the fundamental difference between a problem–centered approach and a means or technique-centered approach to the defining of science. Let me begin by illustrating the underlying idea of inventory routing first and contrast the concept with a traditional distribution-inventory system.

In a traditional distribution-inventory system, the supplier receives orders from retailers and then solves the routing problem only for these retailers. Thus, inventory decision and delivery decision are taken sequentially. The supplier is forced to make the routing decision based on the individual inventory decisions taken by each retailer. This limits the possibility to coordinate replenishments of different retailers causing sub-optimization.

In the 1980s, a new concept called inventory routing started to gain the attention of researchers and practitioners. In an inventory routing system, the supplier takes full control of replenishments of inventory at the retailer. Thus, the supplier takes both the inventory decisions and distribution decision. This allows the supplier to coordinate replenishments among multiple retailers and subsequently reduce replenishment costs. In other words, integrating inventory and routing decisions into a joint decision model avoids sub-optimization and leads to cost-efficiency gains in form of lower total replenishment costs.

Today, the concept of inventory routing has a large number of existing and potential applications. Inventory routing systems have transformed the supplier-retailer relationship in many industries, including the oil and gas, retail, textile and automotive industry (see Andersson, Hoff, Christiansen, Hasle and Løkketangen, 2010; Campbell and Savelbergh, 2004). This makes it difficult to overstate the relevance of the inventory routing problem.

With a conceptual understanding of what constitutes inventory routing, the focus is shifted to the broader question – the scientific motivation. When is something worth doing well? Historically, there is a fundamental difference between a problem–centered approach and a means or technique-centered approach to the defining of science.

"By means-centering, I refer to the tendency to consider that the essence of science lies in its instruments, techniques, procedures, apparatus and its methods rather than in its problems, questions, functions or goals. In its unsophisticated form, means-centering confuses scientists with engineers, physicians, dentists, laboratory technicians, glass blowers, [...] Means-centering at the highest intellectual levels most usually takes the form of making synonyms of "science" and 'scientific method'. Inevitably stress on elegance, polish, 'technique', and apparatus, has as a frequent consequence a playing down of meaningfulness, validity, and significance of the problem and of creativeness in general." (Maslow, 1946, p. 326)

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1 A popular case is Wal-Mart’s vendor managed inventory program with Procter & Gamble (see Clark and McKenny, 1995). However, it is noted that vendor managed inventory programs make reference to the production system of the supplier and are often more loosely defined concepts than inventory routing.
While the original article raising this discussion appeared more than 60 years ago in the *Philosophy of Science* and targeted sciences in general, the relevance of it is even more eminent today. The basic question to be answered remains. When is something worth doing well? It is all too tempting to fall in love with the beauty and elegance of mathematics or operations research tools - which allow us to solve extremely complex problems such as inventory routing - rather than with the problem itself. The approach of operations research and management science to inventory routing typically begins by “Given the problem...”, and is followed by a mathematical formulation, and a “novel” technique to solve the given problem. Discussion of the value proposition of inventory routing, the sources and drivers of cost-efficiency has, however, been neglected. Instead of answering the basic question, researchers jump directly to trying to find more elegant ways to solve the given problem. Without really thinking of the structural and economic conditions under which the introduction of inventory routing systems is most beneficial, researchers engage in the race of finding better techniques rather than advancing the understanding of “how” and “when” the concept should be applied. The motivation is all too often derived from the intellectual challenge, complexity and difficulty that allow us to advance our favorite operations research tools rather than to gain a broader understanding of the problem context itself.

Regardless of how promising the concept of inventory routing may appear, the success of actual implementations can be mixed (Barratt, 2004; Claasen, van Weele and van Raaij, 2008; Dong, Xu and Dresner, 2007; Petersen, Ragatz and Monczka, 2005; Vereecke and Muylle, 2006). Quantitative studies are scarce. Often studies are qualitative in nature using survey results to explain the perceived performance outcomes of inventory routing and perceived enablers of success. However, the results of these studies are inconclusive. This suggest that the perceptions of broad constructs such as information sharing, quality of ICT systems and quality of the supplier-retailer relationship have only limited potential to accurately capture and explain the workings of inventory routing systems under study.

This dissertation attempts to address these shortcomings by advancing a strategic management accounting perspective of inventory routing and viewing inventory routing through the lens of strategic cost management. In that, this dissertation differs from a classical operations research study, not in the object of scientific inquiry, but rather in the research approach and tradition, namely theory framework, purpose of inquiry, and level of analysis.

1.2. Research problem

Accounting research in the context of integrated planning and supply chains is a fairly recent phenomenon and has been concerned with topics such as open book accounting (Agndal and Nilsson, 2010), information reliability, integration and sharing (Kulp, 2002; Kulp, Lee and Ofek, 2004), supplier selection, monitoring practices and firm performance (Iltner, Larcker, Nagar and Rajan, 1999), transaction costs, high-powered incentives and ex-post opportunism (Anderson, Glenn and Sedatole, 2000), control and incentive problems in buyer-supplier transactions and inter-firm relationships (Baiman and Rajan, 2002a, b; Dekker, 2004), supply chain structure and firm performance (Randall and Ulrich, 2001). It seems only natural to extend this recent literature in the area of strategic management accounting and structural cost management.
As Anderson and Dekker (2009a), Lord (1996), Roslender and Hart (2003), and Shank and Govindarajan (1992) have observed that management accounting research has primarily been concerned with executional cost management, which focuses on the cost effective execution of a given strategy. In contrast, structural cost management is aimed at establishing a competitive cost structure and its alignment with corporate strategy. Arguably, both forms constitute strategic management accounting, yet Anderson (2006) points out that “structural cost management has been the hallmark of exceptional firms that employ business models with radically different cost structures to deliver traditional products or services” (p. 497).

In the search for superior performance firms look increasingly beyond functional and organizational boundaries. This is reflected in the growing interest in collaborative planning, forecasting, and replenishment. In particular, firms have come to realize that integrated logistics and supply chain management are a source of operational efficiency and competitive advantage (Christopher, 2005).

This development is changing the traditional role of management accountants within the firm from scorekeeper to business partner. Hence, management accountants are increasingly required to look beyond the boundaries of functions and organizations and to take a proactive role in informing and influencing strategy formulation. This is a clear step forward from merely monitoring the execution and performance of a given strategy within the firm.

In an account on the state and direction of accounting research, Hopwood expresses his growing unease about the status quo:

“Within the enterprise, accounting has rapidly become a less isolated phenomenon as it has become embedded in massive, more generic enterprise wide management systems. It is now quite explicitly a part of a wider whole. At the same time, there also has been a significant diffusion of economic calculation throughout the whole enterprise. Accounting is now practiced by many others than just accountants. The forms of economic calculation that it creates are now a part of the functioning of operations, marketing, and a multitude of other departments in the firm. It has to be recognized that accounting research has experienced difficulty keeping up with these profound changes. (...) In the management accounting area, we still have the most minimal of understandings of the processes and pressures underlying the shifting locations of economic calculation and control. (...) Yet if innovation and new understandings are more prone to emerge from the margins of the subject that are in touch with different perspectives and bodies of knowledge, then accounting research seems to have become too stable and insufficiently innovative in a changing world. (...) Seen from such a perspective, accounting, as a practice, can be and indeed should be constantly examined, re-examined, interrogated, and criticize within the world of knowledge. Rather than being a discipline in its own right, accounting needs to draw on a variety of sources of illumination and understanding. It has been and must continue to be a site for interdisciplinary inquiry.” (Hopwood, 2007, pp. 1370-1371)

Supply chain management and operations research rely on cost structure and other management accounting information to model decision problems such as inventory control and distribution. Researchers in management accounting have a competitive advantage in engaging and contributing to research in this area. It provides the basis of this dissertation to employ a strategic management accounting perspective of inventory routing.
Advances in the area of information technology have provided novel mechanisms and viable options to share information and coordinate decisions of individual functions or organizations. In particular, information technology has enabled decoupling of the flow of materials from the flow of information, which has given rise to new approaches and more complex cost structures that integrate decision making of different stages of the logistics value chain in form of joint optimization models. The basic idea is to avoid sub-optimization by simultaneously determining decision variables in various stages that have traditionally been determined sequentially.

In that, inventory routing is a prominent example with a wide range of applications. Under an inventory routing system, the timing, magnitude and delivery route of replenishments for a set of multiple retailers are determined jointly on the basis of full information regarding each retailer’s inventory and sales data. The approach integrates inventory management and vehicle routing that have been initially regarded separately.

Inventory routing models make various assumptions about cost structure, planning horizon, demand, service levels, vehicle fleet and related working constraints. There is now a sizeable literature on inventory routing and the development of corresponding solution methodologies (see Andersson et al., 2010; Campbell and Savelsbergh, 2004; Kleywegt, Nori and Savelsbergh, 2002a; Moin and Salhi, 2007). Clearly, integrating vehicle routing and inventory management enables efficiency gains and cost savings. As such, the potential of inventory routing is readily and intuitively supported by academics and practitioners alike. However, a rigorous investigation of the conditions under which the introduction of inventory routing is most beneficial or when it leads only to marginal improvements is lacking. In particular, empirical evidence on the size of the effect and the impact of the underlying cost structure is limited.

Given the strategic nature of the problem as well as the great number of existing and potential applications of inventory routing, it is surprising that management accounting research has not utilized its competitive advantage in strategic cost analysis to parallel the conceptual developments in supply chain management by advancing a strategic management accounting perspective and studying the role of the underlying cost structure and interactions with other strategic factors to explain the drivers and magnitude of cost efficiency gains expected from inventory routing.

While the potential of management accounting research has been identified, and normative arguments have been presented, little has been contributed by management accounting in explaining the “true” drivers of efficiency, the impact of cost structures and strategic implications for supply chains.

The research aim is to study the value proposition of inventory routing by employing a strategic management accounting perspective. In particular, the aim is to explain the conditions under which the introduction of an inventory routing system is most beneficial. The focus is on identifying the role of the underlying cost structure, demand, information sharing, forecasting accuracy, service levels, vehicle fleet, planning horizon and other strategic factors as well as the interaction effects among these factors with respect to performance outcomes.
The task is to enhance the knowledge of the strategic situations that favor the implementation of inventory routing systems, understanding cause-and-effect relationships, linkages and gaining a holistic view of the value proposition of inventory routing. This requires a methodology that enables testing and refining the inventory routing strategy through statistical analysis of cause-and-effect relationships. The approach of this dissertation is quantitative, combines normative and empirical research and is interdisciplinary in nature building on research from other disciplines, namely economics and strategy, and supply chain management and operations research (see Figure 1). While the models and methodologies developed in this dissertation are clearly contributions in their own right, their real value is derived from the application to the broader question of the strategic imperative of inventory routing for structural cost management in supply chains, to gain knowledge thereof and to provide empirical evidence.

![Diagram](image1)

**Figure 1. Developing a strategic management accounting perspective of inventory routing**

### 1.3. Structure and outline

The first part of this dissertation is organized as follows. The next section provides a review of relevant contributions from supply chain management, economics and strategy, and strategic management accounting. The objective of this section is to offer a critical perspective on the domain specific bodies of literature and the state of research in the area. It provides the theoretical groundwork and advances the understanding of the research problem. Section 3 presents the research framework with an outline of research models, research methodology and research setting of the three peer-reviewed research papers that constitute this dissertation. It provides the background for the case-based normative quantitative empirical research presented in Section 4, which contains summaries of the three research papers with an emphasis on the individual contribution and originality value. It is followed by concluding remarks in Section 5. The second part contains the complete research papers.
2 THEORY AND LITERATURE REVIEW

2.1. Supply chain management and operations research perspective

2.1.1. Supply chain management and evolution of integrated logistics

Introduced in the 1980s, the term supply chain management has gained tremendous attention in recent years and given rise to popular concepts, including Just-In-Time (JIT), Vendor Managed Inventory (VMI), and Collaborative Planning, Forecasting, and Replenishment (CPFR) (Chen and Paulraj, 2004; Holweg, Disney, Holmström and Småros, 2005; Oliver and Webber, 1992; Stadtler, 2008). However, the underlying ideas build on theories of industrial dynamics, materials management and physical distribution envisioned decades earlier. An example is Forrester, who provides a clear and conclusive description of the underlying concept already in 1958, well before the term supply chain management emerged.

Management is on the verge of a major breakthrough in understanding how industrial company success depends on the interactions between flows of information, materials, money, manpower, and capital equipment. The way these five flow systems interlock to amplify one another and to cause change and fluctuation will form the basis for anticipating the effects of decisions, policies, organizational forms, and investment choices. (Forrester, 1958, p.37)

Figure 2. Evolution of supply chain management and integrated logistics

Adapted from: Hesse and Rodrigue (2004).
<table>
<thead>
<tr>
<th>Author</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jones and Riley (1985)</td>
<td>An integrative approach to dealing with the planning and control of the materials flow from suppliers to end-users.</td>
</tr>
<tr>
<td>Ellram (1991)</td>
<td>Supply chain management is defined as an integrative approach to dealing with the planning and control of the materials flow from supplier to end-user.</td>
</tr>
<tr>
<td>Lee (1992)</td>
<td>Networks of manufacturing and distribution sites that procure raw materials, transform them into intermediate and finished products, and distribute the finished products to customers.</td>
</tr>
<tr>
<td>Kopczak (1997)</td>
<td>The set of entities, including suppliers, logistics services providers, manufacturers, distributors and resellers, through which materials, products and information flow.</td>
</tr>
<tr>
<td>Tan (1998)</td>
<td>Supply chain management encompasses materials/supply management from the supply of basic raw materials to final product (and possible recycling and re-use). Supply chain management focuses on how firms utilise their suppliers' processes, technology and capability to enhance competitive advantage. It is a management philosophy that extends traditional intra-enterprise activities by bringing trading partners together with the common goal of optimisation and efficiency.</td>
</tr>
<tr>
<td>Bowersox, Closs and Stank (1999)</td>
<td>Supply chain management can be defined as collaborative-based strategy to link interorganizational business operations to achieve a shared marked opportunity.</td>
</tr>
<tr>
<td>Handfield and Nichols (1999)</td>
<td>The integration of all activities associated with the flow and transformation of goods as well as the associated information flows through improved supply relationships to achieve sustainable competitive advantage.</td>
</tr>
<tr>
<td>Ballou, Gilbert and Mukherjee (2000)</td>
<td>The supply chain refers to all those activities associated with the transformation and flow of goods and services, including their attendant information flows, from the sources of raw materials to end users. Management refers to the integration of all these activities, both internal and external to the firm.</td>
</tr>
<tr>
<td>Mentzer, DeWitt, Keebler, Soonhoong, Nix, Smith and Zacharia (2001)</td>
<td>Supply chain management is defined as the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole.</td>
</tr>
<tr>
<td>Christopher (2005)</td>
<td>The management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole.</td>
</tr>
<tr>
<td>Simchi-Levi, Kaminsky and Simchi-Levi (2007)</td>
<td>Supply chain management is a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize systemwide costs while satisfying service level requirements.</td>
</tr>
</tbody>
</table>
The evolution of supply chain management and integrated logistics over the past 50 years can be distinguished in four phases (see Figure 2). In the 1960s, individual manufacturing and distribution activities were largely fragmented. Towards the 1980s, distinct concepts were formulated and activities consolidated. *Physical distribution* combined outbound logistics, including inventory, distribution planning, order processing, transportation, and customer service. *Materials management* combined demand forecasting, purchasing, requirements planning, production planning, and manufacturing inventory. However, inbound logistics and outbound logistics remained separate.

In the 1990s, logistics integrated materials management, physical distribution, warehousing, materials handling, and packaging, essentially linking inbound and outbound logistics (Hesse and Rodrigue, 2004). The functional integration raised the importance of the flow of information besides the movement of materials. The past 10 years, integration, coordination, and information sharing shaped supply chain management by integrating logistics, information technology, marketing and strategic planning (Ballou et al., 2000; Mentzer et al., 2001). Today, supply chain management is an integrative concept that spans the flow of materials and information from the raw materials producer to the final consumer across functions and organizational boundaries, advancing a trend that had its origin in industrial dynamics studies more than 50 years ago.

In the past, practitioners and academics have referred to the subject of supply chain management using multiple terms, including value stream management, value chain management, supply pipeline management, and network sourcing (Croom, Romano and Giannakis, 2000). Adding to the ambiguity of the term, supply chain management has been used to explain various aspects connected with planning and control of materials and information flows between functions and organizations (Chen and Paulraj, 2004; Croom et al., 2000; Harland, Lamming, Walker, Phillips, Caldwell, Johnsen, Knight and Zheng, 2006; Mentzer et al., 2001). Subsequently, the literature has struggled to agree on a single, encompassing definition of supply chain management (see Table 1).

Despite the differences in the definition, there is consensus on the fact that supply chain management is a more holistic concept and clear step forward from physical distribution and pure logistics. This is reflected in five key aspects. The literature agrees on supply chain management as an *integrative concept* that builds on coordination and collaboration across functions and organizational boundaries facing different and competing objectives. This is closely linked to a *process orientation* that spans from the supplier of raw materials to the end-consumer. In addition, it combines aspects of *planning, operations and control*. Further, supply chain management encompasses the flow of *materials as well as information*. Finally, supply chain management is linked to a *strategic orientation by emphasizing* value creation and competitive advantage in supply chains. The five aspects describe the multidimensional complexity of supply chain management and point out its closed links to various other disciplines, including operations research, industrial economics, organizational studies, operations management, accounting, and strategy.

The key of integrated logistics is the improvement of supply chain performance through the substitution of inventory for information. Integrated logistics has deep roots in the management of inventory and transportation (Hesse and Rodrigue, 2004), but...
emphasizes channel performance rather than performance of individual entities (Tan, 1998). In other words, supply chain management captures the benefits of vertical integration by coordinating logistics of individual entities in the supply chain. It comprises internal and external activities, including inventory management, distribution, transportation, and delivery services. Subsequently, integrated logistics is directly linked to strategic choices (Chen and Paulraj, 2004).

Based on the aim and the scope of the dissertation, this work explores relevant contributions from supply chain management and operations research, economics and strategy, and strategic management accounting. However, the focus of the work is clearly to establish a link with the strategic management accounting literature, by focusing on the role of information sharing and the interrelation of cost structures and supply chain efficiency. This is illustrated through the integration of inventory management and distribution in the supplier-retailer relationship (i.e. single-supplier, multiple-retailer model) encapsulated in inventory routing.

2.1.2. Information flow and supply chain coordination

Information flow in supply chains is a lever for efficiency and competitive advantage (Simchi-Levi et al., 2007). Decoupling of information and materials flow enables coordination within the supply chain and improves performance through enhanced asset utilization, lower inventory cost and shorter cycle times. For example, radio-frequency identification, barcode scanners and electronic data interchange enable near real-time sharing of information within the supply chain, including performance metrics, point-of-sales data, inventory levels, demand forecasts, and orders. In particular, demand and inventory information, when shared, reduce the upstream amplification of demand variability and enable the reduction of total inventory in the supply chains (Baganha and Cohen, 1998; Chen, Drezner, Rayan and Simchi-Levi, 2000; Chen and Rungson, 2004; Forrester, 1958; Kahn, 1987; Lee, Padmanabhan and Whang, 1997, 2004). In contrast, distortions resulting from a lack of coordination include inadequate capacity and production planning, inadequate inventory and customer service, and poor asset utilization.

The Forrester Effect (see Forrester, 1958), also known as bullwhip effect, describes the implications of time delay in the flow of information and decision rates in a planning loop.² In contrast, the inventory routing problem addresses primarily the coordination problem of simultaneous, non-concurrent goals in distribution and inventory management between a supplier and multiple retailers; rather than time delays in a planning loop of more than two stages. In fact, the inventory routing problem exists independent of time delays, and even as information becomes available instantly and lead time for deliveries becomes zero. While the Forrester Effect is certainly a key motivation for shorting lead times and sharing timely information in multi-stage supply chains, the primary focus of this dissertation is on the coordination of non-concurrent goals rather than the time delays and decision rates.

² Forrester (1958) observed in a company manufacturing consumer durables that variations in retail sales amplified variations in production by a factor four-to-one. Modeling a simple business system consisting of (1) customers, (2) retailer, (3) distributor, (4) factory warehouse, and (5) factory, showed that a onetime increase in retail sales of 10% amplified production by a factor of four-to-one and took more than 1 year to stabilize. Forrester concluded that the operation would be more stable if the demand information from all distribution points can be simultaneously shared with all the in-between stocking locations instead of through the chain.
Although the motivation for an expanded flow of information in supply chains is intuitively supported, drivers and magnitude of efficiency gains from information sharing are not obvious and quantification of the benefits needed. In other words, under what circumstances is a particular form of information sharing and coordination most beneficial and when only marginally useful.

2.1.2.1. Coordination in centralized supply chains

Centralized supply chains are characterized by a single decision maker. Historically, the focus in this area has been on advancing forecasting accuracy. Much of the early work concerns the use of shared historical demand information to improve the forecasting accuracy using Bayesian updates (Azoury, 1985; Iglehart, 1964; Lovejoy, 1990; Scarf, 1959; Scarf, 1960) and the modeling of time series with autocorrelated demand (Johnson and Thompson, 1975; Miller, 1986). Later developments include the Martingale model of forecast evolution (Güllü, 1997; Heath and Jackson, 1994; Toktay, 2001) and modeling the distribution of demand based on Markov chains (Sethi and Cheng, 1997; Song and Zipkin, 1993).

In recent years, vendor managed inventory (VMI) has gained prominence in the field of supply chain management (Arora, Chan and Tiwari, 2010; Aviv and Federgruen, 1998; Bernstein, Chen and Federgruen, 2006; Çetinkaya and Lee, 2000; Darwish and Odah, 2010; Disney, Potter and Gardner, 2003; Disney and Towill, 2003; Dong and Xu, 2002; Mishra and Raghunathan, 2004; Southard and Swenseth, 2008; van der Vlist, Kuik and Verheijen, 2007; Waller, Johnson and Davis, 1999; Xu and Leung, 2009; Yao and Dresner, 2008; Yao, Evers and Dresner, 2007). While VMI has received much attention in the literature, quantitative studies rigorously analyzing the drivers and the magnitude of VMI cost benefits are rare. One notable exception is Aviv and Federgruen (1998), who analyze a two-stage distribution system, where a single supplier monitors and replenishes the inventory of N retailers facing stochastic demand. They distinguish three different variants of information sharing. In a traditional, decentralized system, the retailer places orders with the supplier and determines magnitude and timing of replenishments. Under a VMI strategy, this responsibility is handed over from the retailer to the supplier, who is granted access to information on the retailer’s inventories and sales. These two forms are contrasted with “pure” information sharing, where the supplier has knowledge of the retailer’s inventory policy and gains access to sales data, but is not involved in determining replenishments. The numerical study shows that system-wide costs under the VMI strategy are consistently lower than under pure information sharing. The cost advantage of the VMI strategy compared to the decentralized system is 4.7 percent on average and varies in the range from 0.4 percent to 9.5 percent. In contrast, the cost advantage of “pure” information sharing strategy compared to the decentralized system is 2 percent on average. The benefits of VMI vary with the characteristics of the supply chain. The relative benefit of VMI increases with tighter capacity constraints. Similarly, relative benefits of VMI increase when retailers are non-identical (7 percent to 30 percent versus 10 percent to 41 percent) and when product availability at the supplier is very high or very low (11 percent and 14 percent).
Darwish and Odah (2010) study the impact of order cost, holding cost, inventory capacity, and penalty costs on total cost in a VMI setting. However, the research design focuses on total costs, not distinguishing the effects of information sharing and coordination. Subsequently, the study does not provide insights regarding the conditions under which the introduction of a VMI system is most beneficial.

Closely related to VMI systems is the concept of inventory routing, which allows not only direct shipments, but also shipments that combine multiple retailers on a joint delivery route. There is now a sizeable literature on the topic, which extends the basic idea of inventory routing to account for various assumptions about planning horizons, demands, service levels, vehicle fleets and related working constraints (see Andersson et al., 2010; Campbell and Savelbergh, 2004; Kleywegt et al., 2002a; Moin and Salhi, 2007).

The potential of inventory routing is readily and intuitively supported by academics and practitioners. However, empirical evidence on the effect size and cost trade-offs is limited. Most of the earlier work has focused on the deterministic case and suggests cost reductions between six and ten percent offering limited insight into the impact of factor levels and interaction effects (Bell, Dalberto, Fisher, Greenfield, Jaikumar, Kedia, Mack and Prutzman, 1983; Federgruen and Zipkin, 1984; Golden, Assad and Dahl, 1984). Gaur and Fisher (2004) present a randomized heuristic for a fixed partition policy with deterministic time varying demand and periodic deliveries for a supermarket chain, where they expect cost savings of up to 20 percent. However, their model is limited to transportation costs and does not account for inventory holding costs.

In a recent study, Raa and Aghezzaf (2009) study explicitly cost trade-offs governing inventory routing problems. The authors adopt a long-term cyclical approach with deterministic constant demand rates to identify three-way cost trade-offs among vehicle fleet size, distribution and inventory costs. However, the study does not distinguish the effects of information sharing and coordination and does not analyze the effect of set-dependent cost structures and subadditive transaction cost.

Moreover, in recent years, researchers have increasingly addressed the stochastic nature of demand and modeled the stochastic inventory routing problem as a Markov decision process solved by approximate dynamic programming approaches, where stockouts are captured using penalty costs (Adelman, 2004; Hvattum and Lokketangen, 2009; Hvattum, Lokketangen and Laporte, 2009; Kleywegt, Nori and Savelbergh, 2002b; Schwartz, Ward and Zhai, 2006). However, none of these studies distinguishes the effects of information sharing and coordination in order to analyze the drivers and the magnitude of IRP cost benefits. Overall, the literature falls short of providing insights regarding the conditions under which the introduction of inventory routing systems is most beneficial.

2.1.2.2. Coordination in decentralized supply chains

Decentralized supply chains are characterized by multiple decision makers potentially being subject to conflicts of interest with the overall supply chain. The literature on value of information sharing in decentralized supply chains can be broadly classified into two streams. One stream looks at contracting in decentralized competitive supply chains (Burnetas, Gilbert and Smith, 2007; Cachon, 2003; Cachon and Lariviere, 2001; Chen, 2003; Iyer, Narasimhan and Niraj, 2007; Mishra, Raghunathan and Yue, 2007;
Miyaoka and Hausman, 2008; Özer and Wei, 2006; Ren, Cohen, Ho and Terwiesch, 2010; Taylor and Xiao, 2010). This stream is concerned with the optimal design and evaluation of outcomes of contracts. Specifically, the focus is on recognizing obstacles to overcome information asymmetries and information sharing, such as incentives to restrict or potentially misrepresent information in relations with other supply chain members.

Another stream assumes a collaborative supply chain and investigates the value from truthful sharing of information in decentralized supply chains (Aviv, 2001, 2002, 2003, 2007; Cachon and Fisher, 2000; Gavirneni, Kapuscinski and Tayur, 1999; Lee, So and Tang, 2000). This stream is interested in quantifying the value of information sharing and identifying the drivers of efficiency gains as well as the magnitude attributed to these drivers.

The rational of inventory routing is that sharing of inventory data and demand information takes place in a cooperative environment where retailers can be assumed to truthfully share information with the supplier. Important contributions that have been made in this stream are context specific and subsequently need to be discussed in more detail to gain understanding of the drivers and magnitude of efficiency gains.

Aviv (2001) presents a stylized supply chain model with one supplier and one retailer for investigating the benefits of local and collaborative forecasting involving dynamic forecast updates. He concludes that benefits from co-managed forecasting are substantial, but require the supply chain members to possess unique forecasting capabilities. Aviv (2002) extends the work to a situation of autocorrelated demand and shows that the benefits of collaborative forecasting and replenishment become larger with increasing levels of intertemporal correlation in the demand process. In a generalized form, Aviv (2003) provides a matrix based unified time-series framework for forecasting and inventory control in supply chains. The framework unifies a wide collection of models that form special cases of the presented linear state space model and accounts for different forms of information sharing (e.g. restricted versus full disclosure of demand information). In addition, Aviv (2007) models explicitly the internal service performance. Computational results show that collaborative forecasting lowers supply chain cost by about 4 percent. However, the analysis points out that the cost savings vary substantially with supply chain characteristics and parameter configurations. In particular, supply chain benefits are larger when the supplier has relatively more explanatory power than retailers. The reasoning is that suppliers gain information simply by observing the order stream. Further, supply chain benefits are by an order of magnitude larger when the supply side is more agile. In other words, information sharing is only valuable if supply chain partners can act upon the information. Subsequently, the potential benefits of information sharing are smaller in supply chains with long lead times and large batch sizes. However, complementary benefits of information sharing and improved supply side agility are relatively small. Finally, results show that adjustments in the internal service rate yield the potential to make information sharing for supply chain partners more attractive.

Gavirneni et al. (1999) study the value of information sharing in a model with one supplier having limited capacity and one retailer facing random positive integer demand that is independent and identical distributed (i.i.d.). Both supplier and retailer incur linear holding cost for inventory and linear penalty cost for demand that is not satisfied from current stock. Orders incur a fix cost and are placed with the supplier according to a continues review, order-up-to level inventory policy (s,S). Gavirneni et al.(1999) contrast three forms of information sharing. In its simplest form information
sharing is restricted to order information. A more collaborative form of information sharing contains additionally the demand distribution, the inventory policy \((s,S)\) and the specific parameters \((s\) and \(S\)). Finally, in its most advanced form the supplier has additionally access to the latest inventory data of the retailer. Gavirneni et al. (1999) investigate the conditions that make information sharing more valuable. In particular, they study the impact of supplier capacity, penalty cost, holding cost, demand distribution and variance, or gap between \(S\) and \(s\) \((\Delta=S-s)\). They provide evidence supporting the intuitive presumption that disclosure of additional information is always beneficial. Computational results show that total costs get smaller as information sharing is expanded. However, their results suggest that information sharing is only marginally beneficial when demand variance at the retailer is high, or \(\Delta\) is high or very low, or respectively when supplier capacity is low. In other words, information sharing is most beneficial when \(\Delta\) and demand variance are moderate and supplier capacity moderate or high.

Lee et al. (2000) analyze a model similar to Gavirneni et al. (1999), but assume that demand at the retailer is autocorrelated. Their results show that the value of information sharing increases when demand at the retailer is highly correlated between periods, or variability in periods is high, or when the lead time is long. Moreover, Lee et al. (2000) extend their analysis to a situation with multiple retailers under the assumption that demand at each retailer follows an i.i.d. first-order autoregressive process. For this specific case, they report cost savings growing linearly with the number of retailers sharing their demand information with the supplier.

Cachon and Fisher (2000) study the value of information sharing in the context of a model with one supplier, \(N\) identical retailers, stationary stochastic consumer demand with a known distribution, batch ordering policy, inventory holding costs and back-order penalty costs. The value of information sharing is measured by the difference in supply chain costs under two levels of information sharing. In the simple form the supplier has only knowledge of the retailer’s order information. In the advanced form the supplier has in addition access to the most recent inventory and sales data of a retailer. Cachon and Fisher (2000) argue that information sharing enabled by modern technology, such as electronic data interchange (EDI), not only expands the information flow to the suppliers, but also enables shorter lead times and reduced batch size of orders that result from speeding up the exchange of information and reducing the cost of processing orders. Their computational results provide evidence that information sharing in the context of reorder point inventory policies reduces supply chain costs on average by 2.2 percent. However, the “true” value of information sharing may be higher, since the selected inventory policies are not guaranteed to be optimal. Cachon and Fisher (2000) use simulation to identify the best inventory policy among all feasible policies and report a lower bound of 3.4 percent on average. Their study shows further that a reduction in lead time from five days to one day lowers cost by 43 percent on average. Similarly, reducing the batch size from sixteen to eight reduces cost by 36 percent on average. Cachon and Fisher (2000) conclude that the value derived from a shorter lead time and a reduced batch size enabled through the use of information technology is an order of magnitude greater than the value derived from an expanded flow of information or information sharing in the strict sense.

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3 Overall results show that total cost decrease as holding cost or demand variance decrease, or capacity increases. (Gavirneni et al., 1999, p. 20)
4 Reported mean cost reductions from reducing the retailer lead-time are 43 percent (5 to 1), 21 percent (5 to 3), and 29 percent (3 to 1). (Cachon and Fisher, 2000, p.1046)
5 Reported mean cost reductions from reducing the batch size are 36 percent (16 to 8), 27 percent (8 to 4), 17 percent (4 to 2), and 10 percent (2 to 1). (Cachon and Fisher, 2000, p.1046)
2.1.3. Routing

The inventory routing problem has two distinct sub-problems, both being NP hard (see Garey and Johnson, 1990). One is the inventory allocation problem, which determines the replenishment quantity and frequency. The second sub-problem is the routing problem, which determines the delivery route in every period.

The operations research literature distinguishes primarily two variants of routing, designing optimal routes that visit a set of given geographical points (e.g. delivery of mail packages) and designing routes that traverse all the streets of a specific area (e.g. cleaning and sweeping of streets). Respectively, the two problem classes are referred to as node-covering and edge-covering (Larson and Odoni, 1981).

Inventory routing falls into the first category and entails the vehicle routing problem (VRP), which is a generalization of the traveling salesman problem (TSP), representing the most prominent and basic subsets of the node-covering class (Gutin, 2003). Over the years this problem class has received extensive attention in mathematics and operations research (Punnen, 2002). Research in this area primarily focuses on improving speed and solution quality of the computational algorithms and falls mainly outside the scope of this dissertation. Consequently, the literature review focuses on the underlying ideas and outlines only the main lines of research in this area.

Bell et al. (1983) and Federgruen & Zipkin (1984) were among the first to study a combined vehicle routing and inventory allocation problem, also referred to as inventory routing problem (IRP). Original applications include frequently replenished consumables such as chemical gases (Bell et al., 1983; Campbell, Clark, Kleywegt and Savelsbergh, 1998), heating oil (Dror and Ball, 1987) and heating gas (Golden et al., 1984).

Inventory routing is a long-term, multiple-periods problem and more difficult to solve than short-term, single-period problems (Kleywegt et al., 2002a). Multi-period models, in contrast to single-period models, do not have the tendency to defer replenishments to the next period, which typically results in much higher costs during the following period. However, single-period models may be well suited for instances with stochastic demand where forecasting accuracy is extremely low.

The complexity of inventory routing increases quickly as the number of nodes increases (Chien, Chien, Balakrishnan and Wong, 1989). Instances of inventory routing involving stochastic demand and multi-periods are solved typically by heuristic solution methods. Applying a rolling horizon approach to multi-period long-term planning problems essentially reduces the complexity by substituting a single long-term horizon for several shorter planning horizons which overlap (Campbell et al., 1998). Thus, an initial planning horizon of one year may be reduced to a planning horizon of one month, which is updated and rolled forward throughout the year. Therefore, algorithmic complexity and long-term optimization benefits are constantly balanced. Moreover, a two-phase solution approach handles sub-problems individually. Consequently, the output of the first phase is utilized as the input to the second phase. For example, one approach may assigns retailers to time periods first and solves the vehicle routing problem only afterwards, while an alternative approach assigns retailers to specific time periods as well as a particular vehicle first and solves the traveling-salesman problem for each vehicle and period during the second phase (Dror, Ball and Golden, 1985).
The traveling-salesman problem refers to a traveling salesman wishing to find the shortest route visiting each of \( N \) cities exactly once and then returning to his home city. The problem implicitly assumes that it is possible to find a tour with such a property. A more general definition specifies that each city must be visited at least once ensuring the existence of such a tour (Applegate, Bixby, Chvátal and Cook, 2006). Flood (1956) is credited with popularizing the perhaps most studied discrete optimization problem. The traveling-salesman problem has led to development of a large number of variations and generalizations of the traveling-salesman problem to fit other applications (see Lawler, Lenstra, Rinnooy and Shmoys, 1985; Punnen, 2002). Despite the fact that the traveling-salesman problem is relatively simple to formulate, it remains difficult to solve. The traveling-salesman problem is considered to be NP-complete \(( P \neq NP ; P \text{-complete} \subseteq NP ; NP \text{ “hard”})\) and thus belongs to the most challenging problems among all decision problems that can be solved by nondeterministic algorithms in polynomial time (Garey and Johnson, 1990). Consequently, the traveling-salesman problem is governed by algorithmic complexity, directing research primarily to improving speed and solution quality of solution algorithms.

Several authors discuss the application of integer programming methods for solving TSP to optimality. These methods include branch-and-bound (Balas and Toth, 1985; Fischetti, Lodi and Toth, 2002), branch-and-cut (Naddef, 2002) and dynamic programming (Papadimitriou and Steiglitz, 1982). In contrast, heuristics are approximation algorithms that find solutions, which are not necessarily optimal but require fewer computations and are fast to obtain. Therefore, heuristic solution methods are far more feasible for large problem instances and applications that rely on fast solutions.

Construction heuristics build a tour by adding new nodes and stop when an acceptable solution is found. This method includes greedy-type algorithms (e.g. Nearest Neighbor, Greedy Heuristic), minimum spanning tree heuristics (e.g. Double Minimum Spanning Tree, Christofides Heuristic) and insertion algorithms (e.g. Vertex Insertion) (Garey and Johnson, 1990; Gendreau, Hertz and Laporte, 1992; Glover, Gutin, Yeo and Zverovich, 2001).

A second group, referred to as improvement heuristics, typically applies a construction heuristic to find a feasible tour and iteratively improves on it by altering parts of it until no better solution can be found or a time limit is exceeded. A method called Edge Exchange (e.g. Lin-Kernighan Local Search) is considered to be the best performing improvement heuristics (Johnson, Gutin, McGeoch, Yeo, Zhang and Zverovich, 2002). It typically produces solution close to optimal and is much faster than exact methods according to a detailed comparative performance analysis carried out by Johnson & McGeoch (2002). Exponential Neighborhood local search heuristics are potentially even more powerful, but have been tested mainly experimentally (Ahuja, Ergun, Orlin and Punnen, 2002).

The traveling-salesman problem may further be generalized by introducing additional constraints. The vehicle routing problem, originally referred to as “Truck Dispatching Problem”, was introduced by Dantzig & Ramser (1959) and has historically been considered one of the most applicable of all TSP generalizations (Christofides, Mingozzi and Toth, 1978). Variants include vehicle scheduling (Clark and Wright, 1964; Gaskell, 1967), vehicle dispatching (Christofides and Eilon, 1969; Gillett and Miller, 1974), multiple-salesman traveling-salesman problem (m-TSP) (Sveska and Huckfeldt, 1973) and delivery problem (Balinski and Quandt, 1964; Hayes, 1967) highlighting the central role of the vehicle routing problem in distribution management.
The vehicle routing problem in contrast to the traveling-salesman problem consists of designing a set of tours of least total costs, each starting and ending at a given point (depot), such that every retailer is visited exactly once. Additional constraints may be imposed in a capacitated vehicle routing problem (CVRP) (Poot, Kant and Wagelmans, 1999). The literature addresses primarily four types of extensions or constraints: (1) heterogeneous vehicle fleet may cause vehicles in the fleet to vary in capacity, maximum trip length, fixed and variable costs, (2) capacity constraints (e.g. weight, volume, number of pallets), (3) geographic constrains (e.g. restricting tours to ensure that drivers are familiar with a region or customers), (4) time constrains (e.g. service intervals, time windows).

The literature on exact solution methods vehicle routing problem includes, branch-and-cut (Blasum and Hochstättler, 2000; Naddef and Rinaldi, 2001; Ralphs, Kopman, Pulleyblank and Trotter, 2003) and branch-and-bound (Toth and Vigo, 2001; Toth and Vigo, 2002). Exact solution methods have been successfully applied to instances with more than 100 nodes (Ralphs et al., 2003). Bramel & Simchi-Levi (2001) demonstrate that set-covering methods can be alternatively applied with great success since CVRP share properties of TSP and Bin Packing. However, the literature also reports sporadically difficulties in solving even small real-life problems with standard constraints using exact solution methods (Ralphs et al., 2003).

Heuristic solution methods for VRP as well as CVRP face a strong trade-off between optimality and computing time (Laporte, Gendreau, Potvin and Semet, 2000). Classical heuristics (e.g. Savings Algorithms, Sequential Savings Algorithm, Sequential Improvement, Sweep Algorithms, Petal Algorithms, Cluster-First-Route-Second Algorithms, and Improvement Heuristics) produce CVRP tours relative quickly but tend to deviate substantially from the optimal tour. So called metaheuristics, tabu search heuristics or artificial intelligence based approaches produce near optimal solutions but require a substantial number of computations. (Rego and Roucairol, 1996; Rochat and Taillard, 1995; Taillard, 1993; Toth and Vigo, 1998; Xu and Kelly, 1996).

### 2.2. Economics and strategy perspective

#### 2.2.1. Economics of scale and scope

The literature on supply chain management motivates inventory routing through cost efficiency gains derived from information sharing and coordination. However, there seems to be no reference explaining the cost efficiency gains from an economics perspective.

This thesis argues that cost efficiency gains in inventory routing are derived from information sharing and coordination, but are ultimately based on sub-additive cost structures and economies of scope. In particular, this thesis disagrees with statements claiming that cost efficiency gains in inventory routing are the consequence of economies of scale. This is supported by the following reasoning. Economies of scale refers to the behavior of total costs as output expands and states that the cost per unit of a homogenous product declines as the output quantity increases (Besanko, Dranove, Shanley and Schaefer, 2010). Hence, total costs should be dependent only on the number of retailer or replenishments, irrespectively of their location in an inventory routing setting.
However, inventory routing is precisely motivated by jointly determine inventory and delivery decisions of geographically dispersed retailers combining individual deliveries to reduce the total costs. Strictly speaking, economies of scale would only apply to larger replenishments with the very same retailer. Instead, replenishments of geographically dispersed retailers need to be considered a sharable service or networked products (Bailey and Friedlaender, 1982; Helfat and Eisenhardt, 2004), where the total costs of producing the sharable service is lower than providing the same services independently (Bailey and Friedlaender, 1982; Gorman, 1985; Panzar and Willig, 1981). Thus, serving an additional retailer expands the scope of the replenishment service and not merely the output. Subsequently the change in costs is dependent on the location and not the number of the retailer or replenishments. Consequently, it is argued that cost efficiency gains in inventory routing exhibit economies of scope from local cost complementarity and joint fixed costs captured through centralization and coordination (Hill, Hitt and Hoskisson, 1992).

2.2.2. Coordination, transaction cost and network-based view

Supplier-retailer relationships are undergoing fundamental change in recent years. Vendor managed inventory, inventory routing, just-in-time as well as collaborative planning, forecasting and replenishments are supply chain initiatives aimed to provide coordination mechanisms that enable tightly coupled and responsive supply chain operations (Fliedner, 2003; Hadaya and Cassivi, 2007; Simatupang and Sridharan, 2005). On theoretical grounds, the evolution and strategic imperative of the supplier-retailer relationship can be viewed from the perspective of coordination theory, transaction cost economics, capability-based or resource-based theory of the firm, and network-based view (Hoyt and Huq, 2000; Patnayakuni, Rai and Seth, 2006).

The coordination problem in supplier-retailer relationships can be decomposed in uncertainty-based coordination problems and objective-based coordination problems (Clemons and Row, 1993). In particular, the literature on strategic information systems advances the proposition that IT reduces the cost of information and subsequently the cost of coordination. The argument is that the problem of coordination results from uncertainty due to a lack of sufficient information or information processing capacity. Therefore, coordination is linked, if not equated with information sharing and the availability of timely and reliable information. Agency theory and game theory address the other aspect of coordination, namely the problem to manage competing objectives (Bierman and Fernandez, 1998; Ross, 1973; Stiglitz, 2000). Supplier and retailer are interested in maximizing their own objectives, potentially at the expense of the other party. From a systems view, optimizing individual objectives generally leads to suboptimal results of the system as a whole. Coordination is not only linked to information flows, but also to structural changes in the supplier-retailer relationships.

Consequently, inventory routing can be attributed to both information flow and structural change in the supplier-retailer relationships. The uncertainty-based coordination problem is addressed by expanding the information flow giving the supplier access not only to order information, but also to timely and detailed inventory and demand information of retailers. On a structural level, competing objectives of inventory management and delivery are addressed centrally rather than individually avoiding sub-optimization.
However, both information flow and structural change require transaction specific investments that have little or no value outside the relation between a particular supplier and retailer. This is the subject of transaction cost economics, which views coordination as the trade-off between transaction cost and optimal governance structures. In particular, transaction cost economics study how transactions that take place within the boundaries of a firm differ from the “same” transaction placed within a market (Williamson, 1979, 1994).

Transaction cost theory rests on assumptions about the human nature, namely bounded rationality, opportunism and self-interest that gives rise to transaction costs (Williamson, 1979, 1994). At the core of transaction cost economics is the postulate that transactions tend to be placed in ways that maximize the net benefit after accounting for the cost of the transaction (Roberts and Greenwood, 1997). Consequently, firms select the governance structure that provides the best trade-off between benefits and transaction costs (Chiles and McMakin, 1996).

Transaction cost economics draw on asset specificity, extend of uncertainty, and the frequency of a transaction to explain the provisioning of different forms of governance structures (Williamson, 1979, 1994). Asset specificity refers to the degree transaction specific investments are made in physical resources, training, and developing common procedures. Transaction specific investments are unique to support a particular task and can typically not be redeployed to an alternative use. Extend of uncertainty is closely linked to bounded rationality. It refers to contingencies and information asymmetries that are costly to anticipate or to provision within a classical contract. In addition, frequency of the transaction refers to the ability to absorb additional costs of a specialized governance structure that is better suited to mitigate the contingencies of a specific transaction.

The theory suggests that transactions characterized by high asset specificity, high extend of uncertainty and high frequency are effectively internalized by one party (Williamson, 1979, 1994). In other words, a unified governance structure is selected with one side taking ownership of all the transaction assets. In contrast, the theory suggests that transactions characterized by low or no asset specificity and low uncertainty to take place in markets, as the risk of opportunism is expected to be lower and complete contracts can be specified. Hierarchies are based on incomplete contracts providing a compromise between the market and unified governance structure.

Resource-based or competency-based theories and by extension network-based views challenge assertions of transaction cost theory by arguing that collaborative governance structures enable firms to develop complementary strategic resource combinations and unique capabilities that generate relational rents (Dyer and Singh, 1998; Ghoshal and Moran, 1996; Klein, 2009; Kogut and Zander, 1992; Madhok, 1996; Oliver, 1997). Subsequently firms may not be choosing vertical integration over market-based transactions, but rather establish partnerships, alliances and networks (Provan, 1993). Voluntary information sharing and trust in buyer-supplier relationships create unique capabilities to reduce uncertainty and are expected to enable better coordination of supply and demand (Patnayakuni et al., 2006). Hence, collaboration and sharing of information represent a key source of value creation and sustainable competitive advantage (Barney, 1991; Duschek, 2004).

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6 By extension, this implies that firms do not initiate any transactions that outweigh the benefits.
Consequently, both transaction cost economics and network-based views, when applied to inventory routing, provide a rational explanation why retailers jointly determine replenishment decisions or the supplier takes ownership of replenishment decisions of retailers in instances of high frequency of transactions and situations where the supplier is required to make specific investments to support the transaction. For example, this describes very well the situation of a supplier of a major supermarket chain. High frequency transactions are coupled with high asset specificity on the side of the supplier who is required to make specific investments in production capabilities, packaging, warehousing and delivery in order to provide very large quantities and meet the requests of the supermarket chain.

2.3. Strategic management accounting perspective

Simmonds (1981, 1982) coined the expression ‘strategic management accounting’ to refer to accounting information that guide strategic decision-making. The concept introduces a strategic dimension and links management accounting with the formulation and monitoring of business strategy to ensure the competitive position of the firm and to meet the firm’s overall objectives. Simmonds coined the term ‘strategic management accounting’ to contrast with traditional management accounting that emphasizes internally oriented, historical, and financial information. He argued that a user oriented management accounting system needs to expand the scope to include non-financial, externally oriented and non-historical information in order to contribute to strategic decision-making.

The literature attributes a wide range of practices to strategic management accounting. Examples include attribute costing, activity-based costing, balanced scorecard, brand valuation, competitor cost assessment, competitive position monitoring, competitor appraisal based on published financial statements, life cycle costing, quality costing, strategic costing, strategic pricing, target costing, value chain costing, and strategic investment appraisal (see Carr and Tomkins, 1996, 1998; Carr, Tomkins and Bayliss, 1991; Guilding, Cravens and Tayles, 2000; Tillmann and Goddard, 2008). However, there is a vibrant debate about what distinctively constitutes strategic management accounting, the usefulness of the concept and perception by practitioners as well as how strategic management accounting contributes to sense-making in organizations.


Bromwich (1988, 1990) advocates the concept of strategic management accounting and presents theoretical support from economic theory. He distinguishes two approaches to strategic management accounting. One approach focuses on product attributes measured in terms of benefits from a customer as well as from a firm’s perspective. The other approach focuses on measurement of value creation in individual business functions from a value chain perspective. Both approaches are attempts to identify the firm’s relative position in the competitive market.

Shank and Govindarajan (1992) extend the approach of activity-based costing to strategic cost management and discuss the process of analyzing the value chain to identify strategic cost drivers. Their work points to the challenges in calculating costs and benefits in the value chain, but acknowledge that the process of performing value chain analysis itself is insightful.
Bromwich and Bhimani (1994) argue that strategic management accounting offers the opportunity for management accounting to regain relevance and to play a more useful role by making accounting information available in a form that contributes to strategy. They point out that strategic management accounting differs from traditional management accounting in its combination of internal and external orientation, and focus on the relative position of a firm to competitors.


Hergert and Morris (1989) discuss the challenges in utilizing accounting data for the purpose of strategic planning. They examine the value chain framework for strategic planning proposed by Porter (1985) and identify obstacles imposed by the lack of correspondence with available accounting data in quantifying implications of joint optimization and coordination among different parts of the firm as well as coordination with the firm's supplier and customers. Hergert and Morris conclude that it is the process of value chain analysis itself that provides valuable insights despite the lack of precision in quantifying costs and benefits.

Roslender (1995) questions the feasibility of the techniques advocated by strategic management accounting. He is in doubt that establishing the firm's competitive position and configuration of a competitor's value chain is possible with ease and not prohibitively expensive, particularly in a dynamic environment that would require monitoring and reviewing on an ongoing basis. In addition, he doubts that accounting education and training enable accountants to embrace a genuinely managerial form of accounting and pointed to problems in the communication between accounting, engineering, marketing and others disciplines. His observations suggest that many accountants find it difficult to come to terms with non-financial, externally oriented and non-historical information as these are regarded soft accounting numbers.

Lord (1996) is skeptical regarding the notion of strategic management accounting. She argues that elements and techniques of what the literature coined ‘strategic management accounting’ are already located with the operational management of the firm. Information for strategic decision-making may not be collected by management accountants and may not be quantified in accounting terms. Lord (1996) uses a case study to illustrate her argument and questions the relevance of the concept as well as the need of management accountants to get involved in aspects ascribed to strategic management accounting. She challenges Simmonds (1981, 1982) proposition that management accountants are particularly qualified to collect and analyze information on the competitive position of the firm.

Dixon (1998), investigates the practical application of strategic management accounting and concludes that a formal strategic management accounting process is not prerequisite to the collection of competitor data. He questions the cost/benefit of such an approach, if it was to be implemented. Moreover, he argues that the contribution of management accounting to strategic management is limited to providing historical data.

Bhimani and Keshtvarz (1999) suggest that companies do not perceive themselves as being actively engaged in strategic management accounting. However, they report that management accountants envision to extent their role from information providers to a greater involvement in strategic planning activities.
Guilding, Carvens, and Tayles (2000) compare the perceived value and the extent to which strategic management accounting practices are applied in the U.K., U.S., and New Zealand. They find that strategic management accounting practices are not widely in use and only minor differences among usage and perception exist in the different countries. However, the reported perceived benefits of strategic management accounting techniques indicate the potential for wider usage. Findings suggest further that practitioners do not identify the techniques as distinctively in the domain of strategic management accounting and do not identify themselves with the term ‘strategic management accounting’.

Roslender and Hart (2003) perceive strategic management accounting not merely as an extension of management accounting to strategy, but rather as a generic approach to account for strategic positioning by focusing on the cooperation between management accounting and marketing management. They contrast strategic management accounting with the tradition of marketing accounting and emphasize the need for interfunctional co-ordination between management accounting and marketing management within a strategic management framework. Three different relationships are discussed in their work: traditional, transitional, and synergetic. The cooperation in a traditional relationship is limited to a relative narrow range of practices, whereas in the synergetic relationship both functions embrace a joint agenda to facilitate a truly interdisciplinary form so as to evolve accounting for strategic positioning.


Roberts and Scapens (1985) discuss the role of accounting and how accounting practices are embedded in the organizational context. They argue that the use of accounting information not only informs about the situation of an organization, but also through different forms shapes the perception of reality.

Dent (1990), in his study on strategy, organization and control, discusses the possibilities for interpretive research at the interface between accounting and strategy. In particular, he points to the relationship between accounting systems and the process of strategic decision-making. In case studies, Ahrens (1997) studying a UK conglomerate and Roberts (1990) comparing German and UK brewers, articulate the inherent tensions among management accounting and strategy. The debate is reflected in a larger body of publications aiming to understand the role and organizational context of strategic management accounting (see Scapens and Bromwich, 2001).

Tillmann and Goddard (2008) specifically discuss how strategic management accounting contributes to sense-making in organizations and informs strategic decision making. Sense-making in strategic management accounting refers to those activities of management accountants that aim at understanding the past, present and future situation of the organization. The concept reflects the need to increase organizational transparency and to enhance understanding of strategic situations by understanding cause-and-effect relationships, linkages and gaining a holistic view of the strategic situation. At the core of their model of sense-making in strategic management accounting are subtasks such as structuring and harmonizing, compromising and balancing, and bridging and contextualizing. Their model argues that sense-making is contingent on internal and external contextual conditions, and intervening conditions such as information sets, professional know-how, and what they call ‘feel for the game’.
The review of literature on strategic management accounting shows consensus on the fact that data for strategic planning differ from data for other internal purposes and that data provided by traditional management accounting do not satisfy the information needs of modern strategic planning frameworks. This is highlighted by inherent difficulties in analyzing the value chain of a firm based on historical cost accounting data. Critique addresses the need for a sound theoretical framework and the lack of recognition by practitioners. Despite its growing presence in the academic literature and text books, evidence for a wide spread use of strategic management accounting techniques, such as strategic cost analysis, is yet to be presented.

2.3.1. **The role of strategic performance measures in strategy development**

Strategy development is the process that leads to the definition of long-term objectives, direction and scope of a firm (Gimbert et al., 2010; Langfield-Smith, 1997). It involves establishing the way the firm intends to create value based on the configuration of its activities and resources. A strategy can be seen as the firm’s hypothesis for creating value. Following the seminal work of Porter (1985, 1991, 1996), strategy formulation focuses on developing the firm’s competitive position, sustaining a competitive advantage and enhancing its performance. In contrast, strategy implementation refers to the process that translates strategy into action, and monitors and assesses results. While conceptually different, the two concepts are interdependent. Formulation, refinement and reformulation of strategy need to account for ways to implement strategy and subsequently for learning from the operationalization and assessment of results.

However, there is an ongoing debate within the field of strategic management on how strategies emerge in organizations. The main schools of thought are summarized in Mintzberg, Ahlstrand, and Lampel (2009). In analyzing the role of strategic performance measures in strategy development, the focus is on two different positions. One constitutes the ‘design school’ and by its extension the ‘planning school’, where the top management team establishes the strategy through deliberate planning. This position argues that strategy is essentially the outcome of a deliberate, ‘prescriptive’ process, acknowledging little overlap and interplay between strategy formulation and strategy implementation. By contrast, the ‘learning school’ argues that strategy is the outcome of an ‘iterative’ process that emerges from the interdependence of strategy formulation and strategy implementation in a multi-level decision making process, positing strategic performance measures an important role in strategy development.

Performance measures are financial or non-financial metrics that are designed to monitor performance and support decision-making. Strategic performance measures form a subset of performance measures that monitor strategy implementation and inform strategy development (i.e. formulation, refinement and reformulation of strategy). Strategic performance measurement systems are formed by concise sets of strategic performance measures integrating operational goals and long-term strategy, capturing cause-and-effect relationships, establishing a cross-functional perspective and enabling the provision of multiple objectives (Chenhall, 2005; Chenhall and Langfield-Smith, 2007; Gimbert et al., 2010). Well-established frameworks for strategic performance measurement systems include balance scorecard (Kaplan and Norton, 1992, 1996, 2001), tableaux-de-bord (Bourguignon, Malleret and Nørreklit, 2004; Epstein, 1997), performance prism (Neely, Adams and Kennerley, 2002), and performance pyramid (Cross and Lynch, 1988/89; McNair, Lynch and Cross, 1990).
Most studies on strategic performance measurement systems have focused on the role in strategy implementation (see Bourne, Mills, Wilcox, Neely and Platts, 2000; Braam and Nijssen, 2004; Burkert, Davila and Oyon, 2010; Crabtree and DeBusk, 2008; Davis and Albright, 2004; De Geuser, Mooraj and Oyon, 2009; Hoque and James, 2000; Ittner, Larcker and Randall, 2003; Kald and Nilsson, 2000; Kaplan and Norton, 1996; Speckbacher, Bischof and Pfeiffer, 2003) rather than the role in strategy development, notable exceptions studying strategic performance measurement systems assisting the deliberate strategy formulation, refinement and reformulation include Kloot (1997), Marginson (2002), Campbell, Datar, Kulp and Narayanan (2002), Gimbert et al. (2010) and by extension to the bottom-up development of emergent strategies include Simons (1990, 1995) and Bisbe and Malagueño (2010).

Kloot (1997) illustrates through case studies the critical role of strategic performance measures in management control systems for adapting corporate strategy to changes in the environment. In particular, she discusses the importance for questioning perceptions and rationales of corporate strategy, structure and actions that allows firms to adapt to new environments and facilitates organizational learning.

Marginson (2002) studies the role of management control systems in the strategy process. He argues that the use of strategic performance measures systems influences corporate strategy by shaping the focus and perception of managers, and subsequently influencing the initiation and development of new corporate agendas.

Campbell et al. (2002) illustrate how strategic performance measurement systems can be utilized for assessing the validity of assumptions of the operating strategy, identifying potential problems with the intended strategy, and finding solutions that mitigate these problems. In particular, their study demonstrates how concise sets of strategic performance measures enable testing and refining of corporate strategy through statistical analysis of cause-and-effect relationships. Similarly, Davenport and Harris (2007) argue that strategic performance measures coupled with analytical skills provide a powerful tool for shaping corporate strategy. Likewise, Kaplan (2008) conceptualizes a closed-loop management system enabled by strategic performance measurement system, with strategy refinement and reformulation being an integral part.

Gimbert et al. (2010) argue that the strategy formulation process differs in organizations with strategic performance measurement systems and provide survey evidence that the informational effect of strategic performance measures influences corporate strategy development (i.e. formulation, refinement and reformulation of strategy). Their analysis suggest that strategic performance measures influence strategy development in providing better decision content, more rigor and efficient analytical capabilities, and providing a common language and forum for negotiation and legitimization. Further, Gimbert et al. (2010) conjecture a positive relation between the impact of strategic performance measures on strategy development and performance.

Simons (1990, 1995) discusses how the use of strategic performance measurement systems, primarily designed as control systems for the implementation of the firm’s intended strategy, can be extended to guide strategy development, particularly in guiding development of emergent strategies from within the firm. Tuomela (2005), in a case study building on Simons (1995), discusses the implications of the dual role of strategic performance measurement systems for beliefs control and boundary control.
Bisbe and Malagueño (2010) study mediating effects on corporate performance that result from strategic performance measurement systems influencing strategy development. Their results suggest that the ability to cope with environmental dynamism, as well as the increased number and variety of strategic decisions mitigated by the use of strategic performance measurement systems has a positive effect on corporate performance.

In summary, the literature review suggests that strategic performance measures have a positive impact on corporate performance and assist in closing the gap between the firm’s envisioned corporate strategy and implementation. Emphasizing the dual role, strategic performance measures enable a feedback-loop in strategy implementation as well as strategy development (i.e. refinement and reformulation) through monitoring causal-relationships and validating assumptions of the corporate strategy. Further, strategic performance measures yield the potential for organizations to dynamically adapt strategies in fast changing environments.

2.3.2. The role of strategic cost management in strategy development

More than 25 years ago strategic management accounting was defined for the first time (Simmonds, 1981, 1982) and subsequently multiple strands of research emerged, including strategic cost management. However, until recently, the field has lacked a comprehensive definition and conceptual framework for strategic cost management (Anderson, 2006; Carr and Tomkins, 1996; Roslender and Hart, 2003).

The literature distinguishes three streams of research within strategic cost management (Anderson, 2006; Anderson and Dekker, 2009a, b; Lord, 1996). One stream examines the way and extent to which organizations configure accounting data to support value chain analysis (Carr and Tomkins, 1996; Dekker, 2003; Hergert and Morris, 1989). A second stream studies the causal relation between activity levels and resource consumption (Anderson, 1995; Ittner, Larcker and Randall, 1997). A third stream investigates alignment of cost structures with choice and enactment of business strategy (Anderson, 2006; Anderson and Dekker, 2009a, b). In particular, the first two streams consider strategy and organizational structure as given; whereas the third stream constitutes that strategic cost management takes place through the deliberate choice of strategy (i.e. value proposition and organizational structure).

Management philosophies, such as the theory of constraints, just-in-time (JIT), lean manufacturing, total quality management (TQM), and six sigma, complement strategic cost management and provide the link to continuous improvement methodologies. The focus of this dissertation is on structural rather than incremental changes. Therefore, continuous improvement methodologies have been excluded from the literature review. A brief discussion of the theory of constraints and throughput accounting (TA) in the context of inventory routing is included in Appendix A.

Anderson (2006), following the later of the three streams of research, defines strategic cost management as:

"... deliberate decision making aimed at aligning the firm's cost structure with its strategy and optimizing performance of the strategy". (Anderson, 2006, p. 482)7

7 A more recent definition of strategic cost management differs in wording by referring to "optimizing performance of the strategy" as "tactics" and "enactment of the strategy" (see Anderson and Dekker, 2009, pp. 201-202).
The definition builds on Shank and Govindarajan (1992) and reflects two notions of strategic cost management. One is structural cost management, which refers to strategic choice among alternative cost structures and production functions. The other is executional cost management, which concerns the efficient enactment of a given strategy.

![Diagram of Strategic Cost Management in Supply Chains](image)

**Figure 3. Strategic cost management in supply chains**

Adapted from: Anderson and Dekker (2009a).
Anderson and Dekker (2009a) integrate both notions of strategic cost management within a single framework that links strategic cost management in supply chains and strategy development (see Figure 3). The framework posits that choices of value proposition and organizational structure determine the long-term cost structure and subsequently the competitive position of the firm. Hence, weak performance of the firm can be related to any of the two notions requiring analysis on the level of cost structures and on the level of execution.

Building on the framework by Anderson and Dekker (2009a), key elements of strategic cost management in inventory routing are joint process design and coordination within the logistics value chain. Consequently, this thesis investigates inventory routing from the perspective of structural cost management in supply chains in order to gain insights regarding the conditions under which the introduction of inventory routing systems is most beneficial.

2.4. Summary and implications for research

The review concludes that strategic management accounting has one-sidedly focused on the relationship between marketing and management accounting leading to strategic management accounting not leveraging insights from other fields such as economics, supply chain management and operations research.

Strategic management accounting is a response to the seminal work on strategy by Porter (1985) and the proclaimed lost relevance in management accounting following the critique of Johnson and Kaplan (1987). This dissertation shares the view of Roslender and Hart (2003) that the increased need for cross functional metrics and interfunctional co-ordination within a strategic management framework calls for interdisciplinary development and offers the potential for generic insights. However, in this dissertation it is argued that marketing is only one potential interface among many and that the predestined relation of marketing with management accounting in the academic literature is stylized. In contrast to Roslender and Hart (2003), this dissertation does not ascribe marketing a predestined role and questions the focus on product attributes rather than value chain thinking. The dissertation argues that strategic management accounting has much to gain from a broader view. Economics and strategy as well as supply chain management and operations research have valuable contributions to make in collaborating with management accounting and enabling strategic revenue and strategic cost management, which benefits value creation thinking in strategic management frameworks.

The debate on the type and configuration of data that is provided by strategic management accounting sidesteps the need to identify the role of strategic management accounting in an organization. If management accountants are to become true business partners, rethinking of their value creating role is required. Hence, the debate on strategic management accounting needs to refocus on the role within the organization and the way value is created by educating the organization through analysis and sense-making rather than mere collection and provision of data. This line of reasoning combines the tasks of integration and consolidation of data from multiple sources to serve strategic objectives with educating other functions about cause-and-effect relationships, linkages and implications of alternatives that are contingent on organizational context, value proposition, and cost structures as perceived by the choice of a particular management accounting system. It motivates this dissertation to study the interdependency of management accounting and strategic decision-making.
The literature review suggests that research on inventory routing has primarily focused on improving speed and solution quality of the available computational algorithms and has assumed an independently established cost structure. In other words, optimization models in operations research take cost structures as independently established truth and not as strategic choice or accounting convention. This thesis focuses on a different level of analysis by investigating characteristics of the production function and the respective cost structure. In particular, this thesis argues that cost structures and cost allocation influence strategy choice, yet both are subject to accounting conventions and neither independently established truth nor independent of the organizational context.

Supply chain management focuses on the coordination and integration of activities across the supply and value chain. As a consequence, firms share information, reconfigure organizational boundaries, shift resources, reengineer processes, reconfigure products and service offerings.

In particular, information sharing improves supply chain performance through better alignment of supply and demand, shorter lead times, and reductions in supply chain wide inventory. Most notably, information sharing improves supply chain performance by reducing the upstream amplification of demand variability, known as bullwhip effect. The literature points to many prominent examples, including Wal-Mart, Cisco, Dell, Honda, Warner-Lambert, Sara Lee, Heineken, and Procter & Gamble, to highlight the benefits from information sharing in supply chains (Aviv, 2001; Patnayakuni et al., 2006). However, computational results show that benefits of information sharing vary substantially with the configuration of the supply chain. In fact, the value derived from supply chain agility and common decision-making models is suggested to be an order of magnitude larger than the value derived from information sharing as such.

Key to information sharing is the decoupling of information and material flow in supply chains, which is enabled by advances in information technology. On the operational and tactical level, information sharing enables collaborative forecasting, planning and replenishments. Further, on the strategic level it enables value chain analysis, assessment of cost structures and identification of bottlenecks and inefficiencies.

The focus of this thesis differs from previous studies in the sense that it studies the value from information sharing not in a decentralized environment, but rather in the context of centralized decision making in an inventory routing system. Two aspects need to be considered. One aspect is the use of information sharing to improve forecasting accuracy. Another aspect, concern the value derived from collaborative planning and replenishments, namely the ability to coordinate activities among supply chain members.

Inventory routing exhibits economies of scope from integrating inventory management and deliveries of geographically dispersed retailers. Further, the coordination problem in inventory routing can be decomposed in an uncertainty-based coordination problem and objective-based coordination problem, where transaction cost economics and network-based theories provide a rational explanation for integration of the two distinct activities in the logistics value chain. It is argued that cost efficiency gains are captured through coordination and result from local cost complementarity as well as joint fixed costs. Subsequently, cost structures are directly linked to strategy choice.
Consequently, there is much to gain by leveraging insights from supply chain management and operations research, economics and strategy, and strategic management accounting. In particular, the thesis posits that strategic management accounting informed by operations research methods needs to highlight the implications of cost structures and cost allocations, which impact modeling and configuration of processes, ultimately determine strategic choice and impact strategic decision making. Subsequently, strategic management accounting needs to highlight the flexibility, stability and trade-offs that are determined by cost types, cost structures and cost allocation methods. Hence, simulation, sensitivity analysis, and analysis of variance are tools that offer valuable insights for strategic management accounting.
3 RESEARCH FRAMEWORK

3.1. Research phases

The dissertation comprises three research papers that successively build on each other. Analysis of the value proposition of inventory routing advances from a basic deterministic model to a stochastic model that accounts for forecasting accuracy, service levels and capacity constraints (see Figure 4). All three models are applied to cash supply chains and illustrated for networks of ATMs.

![Figure 4. Research papers and timeline of the study](image)

Research has been conducted by the author as part of the doctoral program at the Hanken School of Economics. While initial ideas for research were developed based on prior industry experience, the author has not entered any formal agreement with a company or industry consortium during the time the study was conducted.

The dissertation forms a research program rather than a single study. The task to “enhance the knowledge of the strategic situations that favor the implementation of inventory routing systems, understanding cause-and-effect relationships, linkages and gaining a holistic view of the value proposition of inventory routing” is addressed iteratively advancing from basic to more realistic assumptions.

Paper 1 studies the role of the underlying cost structure in a deterministic framework making “most minimalistic” assumptions. While the deterministic framework does not account for uncertainty and forecasting errors, contrasting the results with the originally implemented replenishment schedule allows decomposing and analyzing the inventory routing problem in an objective-based and uncertainty-based coordination problem.

Paper 2 analyzes the forecasting accuracy of demand under information sharing. In particular, the paper addresses aspects of inter-temporal correlation, spatial correlation, seasonality, and calendar effects that are important in advancing from a deterministic to a stochastic framework.
Paper 3 directly builds on these results and develops a novel stochastic inventory routing model that accounts for stochastic demand, forecasting accuracy, service levels and capacity constraints making “most realistic” assumptions.

3.2. Research methodology

The thesis combines normative and empirical research by applying an exploratory case study design, which is based on normative empirical quantitative research. Case research is known to be well suited to investigate why and how questions or more general as a method for developing, testing, and refinement of ideas (Yin, 1994). As a form of interpretivism it uses both quantitative and qualitative methodologies to understand a phenomenon (Meredith, 1998). The exploratory case study design lends itself to exploratory investigations where variables are yet unknown and the phenomenon not understood. Moreover, quantitative methodologies are employed in order to explain also the what and how of the research question. Thus, the study takes advantage of the reliability and availability of standard procedures provided by normative empirical quantitative research methods.

Table 2. Hypothetico-deductive research framework

<table>
<thead>
<tr>
<th>Paper</th>
<th>Object</th>
<th>Identified or hypothesized factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper I</td>
<td>Relative Cost Savings</td>
<td>• Demand Multiplier</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Fixed Replenishment Cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Holding Cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Routing Cost</td>
</tr>
<tr>
<td>Paper II</td>
<td>Forecasting Accuracy</td>
<td>• Seasonality and calendar effects *</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Co-variability among time series</td>
</tr>
<tr>
<td>Paper III</td>
<td>Relative Cost Savings</td>
<td>• Demand Multiplier</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Fixed Replenishment Cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Holding Cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Routing Cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Forecasting Accuracy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Rolling Horizon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Minimal Service Level</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Vehicle Capacity</td>
</tr>
</tbody>
</table>

Note: Paper I (Wagner, 2010a), Paper II (Wagner, 2010b), and Paper III (Wagner, 2010c).

* Seasonality and calendar effects include day-of-the-week, day-of-the-month, month-of-the year, and holiday effect.
A single case setting is used since the emphasis of the research question is on identifying the variables that affect efficiency gains from inventory routing, the effect size and interrelations rather than looking at the differences between different case settings or industries. Controlled observations are enabled by holding particular factors (i.e. inventory strategy) constant and allowing other factors (i.e. demand and cost parameters) to vary as observed in the natural environment. Moreover, the use of quantitative data permits controlled logical deduction similar to that in natural science. Discrete event simulation being the underlying quantitative research method enables replicability of the study when using the same parameters, variables, and controls.

Normative empirical quantitative research is designed to test the validity of quantitative theoretical models with respect to real-life data. Thus, model driven empirical research takes advantage of axiomatic quantitative research, such as mathematical models, theorems and logical proofs (Meredith, 1998). Consequently the primary challenge is to make sure that there is a fit between the applied model and reality so that causal relationships between performance and control variables can be established (Betrand and Franscoo, 2002). Normative empirical quantitative research borrows from the logical positivist approach that isolates the phenomenon from the context for logical analysis, so to develop policies and strategies to improve the current situation. Consequently, verifiability comes from two different sources, namely empirical statements and analytic truth.

As a result, this dissertation follows a hypothetico-deductive research paradigm, where the starting point is a general theory of factors that affect an outcome and derives from it consequences that can be compared with observations and experimental results (see Table 2). If results agree with the prediction, the theory is inductively confirmed. Alternatively, if results disagree, the theory is refuted. Subsequently, the applied methodology forms a third way of scientific enquiry, neither strictly deductive nor strictly inductive, which seems typical for research in the context of supply chains (Hilmola, Hejazi and Ojala, 2005).

3.3. Research setting

This dissertation studies the inventory routing problem using context and data of the physical circulation of currency in cash supply chains. In particular, a network of ATMs is considered that allows illustrating and studying the properties of the underlying decision problem. The research setting was chosen mainly because of two reasons: (1) cash handling offers a highly standardized and structured environment for analysis, and (2) cash supply chains provide a new and potentially fruitful application for inventory routing.

In cash supply chains, currency is the physical product that is moved between different stages, incurring transaction and holding costs (see Figure 5).9 Cash management decisions at each stage, such as central bank, cash in transit (CIT) provider, bank vault, bank branch, off-premises and on-premises automated teller machine (ATM) aim to minimize total costs while ensuring the supply of currency.10

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9 From an inventory routing perspective, banknotes are very similar to classic applications of inventory routing (e.g. industrial gases and chemicals) in terms of value per unit supplied and other properties.
10 A discussion of cash supply chains form a central bank perspective is offered in Rajamani et al. (2006).
Actors in the cash supply chain face a trade-off between cost of inventory and cost of distribution, namely cost of funds and replenishment cost. Cost trade-offs originate from the coordination problem of simultaneous, non-concurrent goals in distribution and inventory management. The underlying set-dependent cost structure exhibits subadditive transaction costs in combining and coordinating multiple replenishments. In other words, integrating inventory and routing decisions into a joint decision model avoids sub-optimization and leads to cost-efficiency gains in form of lower total replenishment costs in the cash supply chain. Subsequently, providing cash management as a sharable service lowers total costs across the cash supply chain and increases efficiency of banking systems.

![Figure 5. Framework to analyze the physical circulation of currency in cash supply chains](image)

Adapted from: Rajamani, Geismar and Sriskandarajah (2006).

The approach is contrasted as follows. In the traditional distribution-inventory system, the distributor receives orders from the retail channel and then solves the routing problem only for these retailers. Consequently, inventory decision and delivery decision are taken sequentially. The distributor is forced to make the routing decision based on the individual inventory decision taken by each retailer. In practice, the retail channel orders banknotes from the CIT provider or bank vault. This practice limits the possibility to coordinate multiple replenishments causing sub-optimization.

In an inventory routing system, the distributor takes full control of replenishments of inventory at the retailer. Thus, the distributor takes both the inventory decision and distribution decision. In practice, this allows the CIT provider or bank to coordinate multiple replenishments and subsequently reduce replenishment costs. In other words, integrating inventory and routing decisions into a joint decision model avoids sub-optimization and leads to cost-efficiency gains in form of lower total replenishment costs in the cash supply chain. Hence, the distributor can provide cash management as a sharable service and outsourcing solution that increases the efficiency of banking systems. The CIT provider can act hereby either as provider of the outsourcing solution or as subcontractor and transporter for a bank.
A point of reference for understanding the scale of the operation in cash supply chains provides the number of banknotes in circulation, central bank branches, commercial bank branches and ATMs in a banking system (see Table 3).\textsuperscript{11} The number of banknotes in circulation of all major currencies continues to increase (Rajamani et al., 2006). For example, statistics provided by the European Central Bank reveal that the number of banknotes with denominations in EUR continues to increase year on year (see Figure 6 and Figure 7).\textsuperscript{12} This effect is partly attributed to economic growth and inflation among other factors. In the specific case of the euro, the enlargement of the euro area with new member states adopting the euro currency further contributes to the increase of currency in circulation. Finally, it is noted that, in contrast to other payment instruments, cash remains popular not least because it allows users to act anonymous and without trace or record (Hoffmann, Wörlen, Friedrich and Kanust, 2009).

Table 3. Cash supply chain overview in the euro area

<table>
<thead>
<tr>
<th>Country</th>
<th>ECB branches</th>
<th>Commercial bank branches</th>
<th>ATMs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>3</td>
<td>5,126</td>
<td>7,654</td>
</tr>
<tr>
<td>Belgium</td>
<td>6</td>
<td>5,864</td>
<td>7,256</td>
</tr>
<tr>
<td>Cyprus</td>
<td>0</td>
<td>921</td>
<td>556</td>
</tr>
<tr>
<td>Finland</td>
<td>4</td>
<td>1,575</td>
<td>1,669</td>
</tr>
<tr>
<td>France</td>
<td>83</td>
<td>26,162</td>
<td>43,700</td>
</tr>
<tr>
<td>Germany</td>
<td>49</td>
<td>42,110</td>
<td>50,307</td>
</tr>
<tr>
<td>Greece</td>
<td>23</td>
<td>3,492</td>
<td>6,258</td>
</tr>
<tr>
<td>Ireland</td>
<td>1</td>
<td>1158</td>
<td>3,306</td>
</tr>
<tr>
<td>Italy</td>
<td>88</td>
<td>33,568</td>
<td>43,840</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>1</td>
<td>396</td>
<td>404</td>
</tr>
<tr>
<td>Malta</td>
<td>1</td>
<td>120</td>
<td>156</td>
</tr>
<tr>
<td>Netherlands</td>
<td>1</td>
<td>2,851</td>
<td>7,556</td>
</tr>
<tr>
<td>Portugal</td>
<td>13</td>
<td>7,094</td>
<td>13,275</td>
</tr>
<tr>
<td>Slovenia</td>
<td>1</td>
<td>676</td>
<td>1,670</td>
</tr>
<tr>
<td>Spain</td>
<td>18</td>
<td>45,707</td>
<td>62,098</td>
</tr>
<tr>
<td>Total</td>
<td>292</td>
<td>176,820</td>
<td>249,705</td>
</tr>
</tbody>
</table>


\textsuperscript{11} The MasterCard network includes more than 1 million ATMs worldwide (MasterCard, 2009).

\textsuperscript{12} As of December 2010, euro banknotes in circulation amount 14.171 billion with a nominal value of EUR 821 billion (ECB, 2011).
Figure 6. Low denomination banknotes in circulation (EUR)


Figure 7. High denomination banknotes in circulation (EUR)

In contrast, the literature addressing the economic environment that cash supply chains operate within is comparatively limited. The only reliable data publically available (e.g. industry panels and white papers) is primarily limited to the banking system in the USA and concerns the economic environment of operating and maintaining a network of ATMs. D’Ambrosio, Fox & Hayes (2006) have analyzed 161 deployers from across the USA representing 134,110 of 396,000 national ATMs including deployers of all types and sizes. It is the most recent and comprehensive study found. With the US market accounting for more than one quarter of all ATMs deployed worldwide, this data provides yet a good indicator of the overall state of the industry.

Today, ATM deployers face intense pressure to reduce costs after years of rapid growth fueled by ATM surcharging. The expansion of ATM networks is exceeding transactions growth. The installed base of ATMs worldwide has grown from 640 thousand machines in 1996 to about 1.56 million machines in 2006 averaging an annual growth rate of about 9 percent (Harper, 2007). In the future, the number of ATMs installed is expected to grow at a more modest rate of about 4 percent annually and is estimated to reach 2.4 million machines by 2017. On the contrary, the growth rate of ATM transactions has slowed and is expected to remain at about 2 percent per year (Hayes, Ip and Lewis, 2004). The decline in average transactions per ATM continues and imposes even greater losses for most financial institutions in the future. Thus, the industry is reconsidering the way it assesses the value of ATMs. The focus is again on ATMs as a distinct customer touch point serving the needs and preferences of customers rather than ATMs as an independent profit center (D’Ambrosio et al., 2006). Thus, the industry is coming full circle with many returning to ATMs as a full service channel (Hayes et al., 2004). The business of operating a network of ATMs is described in more detail in Appendix B.

Historically, cash management has received widespread attention from academics and practitioners alike (for reviews see Gentry, 1988; Gregory, 1976; Srinivasan and Kim, 1986). A good deal of research effort has been devoted to developing inventory cash management models that match various cash balance requirements and hypothesized cash flow patterns. More recent studies have focused on randomly varying environments (Hinderer and Waldmann, 2001) and stochastic programming (Castro, 2009). However, all cash management models implicitly assume additivity in transaction costs, which, viewed through the lens of set-dependent costs structures, provides limited insight into the overall economies of cash supply chains.

Although, research in cash management and inventory management have traditionally taken a similar path, recent developments in cash management have failed to consider an integrated supply chain perspective that has led to advances in modeling set-dependent cost structures in inventory management and logistics. Particularly, the inventory routing problem is a prominent example. In essence, the model is an attempt to gain additional cost efficiency over sequential planning models and simplified cost structures by exploiting the subadditive nature of the underlying cost structure through an integrated decision model combining inventory and distribution. Subsequently, the chosen research setting provides a new and potentially fruitful application for inventory routing, yet benefits from a highly standardized and structured environment for analysis.13

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13 The inventory routing model has an advantage over many other earlier inventory models since it imposes neither fixed replenishment intervals nor fixed delivery routes, which may underpin security measures in the context of cash supply chains.
4 SUMMARY OF RESEARCH PAPERS


This research paper analyzes cost structures of inventory routing and investigates efficiency gains that result from combining vehicle routing and inventory management. Integrating routing and inventory decisions enables efficiency gains and cost benefits. As such the potential of inventory routing is readily and intuitively supported by academics and practitioners. However, the conditions under which the introduction of inventory routing systems is most beneficial are not well understood and empirical evidence on the magnitude of the effect and its drivers is limited. The aim of this paper is to investigate cost trade-offs governing inventory routing problems by isolating the effects of the underlying cost structure and by accounting for the impact of factor levels and factor interactions.

Mixed-integer models are applied to determine the optimal replenishment schedule. Total costs of a sequential approach are contrasted with an integrated approach in order to capture the impact of the underlying cost structure. The proposed methodology applies simulation and a factorial design to analyze the role of set-dependent cost structures as well as the impact of demand, cost factors, factor levels and interaction effects. Cost benefits are evaluated in a deterministic environment using nominal range sensitivity analysis and repeated measure analysis of variance (ANOVA). The approach is illustrated for a local network of Automated Teller Machines (ATMs) using empirical data of an international commercial bank. The data contains cash dispense records and replenishment schedules of a region with eight off-premises ATMs covering a period of 200 days.

The study identifies four statistically significant factors: fixed replenishment costs, routing costs, holding costs and demand. Results show that cost benefits of the integrated approach vary substantially with factor levels (0.48 percent to 10.98 percent) and are primarily determined by fixed replenishment costs and routing costs. Somewhat surprising is that the effect size of holding costs and demand is substantially smaller indicating no clear trend or higher order powers, despite differences in relative cost savings being statistically significant. Moreover, comparing the computational results with the original replenishment schedule suggests that cost savings attributed to the uncertainty-based coordination problem are by several orders of magnitude larger than those cost savings attributed to the objective-based coordination problem.

The originality value is the development of a methodology and its application to cash supply chains for identifying the drivers of cost efficiency gains derived from inventory routing, verifying cause-and-effect relationships through statistical analysis and testing the hypothesis that set-dependent cost structures and economies of scope yield substantial efficiency gains not captured by existing cash management models involving simple fixed, linear or affine cost structures. In particular, the paper provides answers to the following questions: How can the optimal replenishment strategy for a cash supply chain be derived conceptually and operationally from a strategic management accounting perspective? Specifically, how can the effects of set-dependent cost structures and economies of scope be quantified within the supply chain context, how large is the effect of set-dependent cost structures and economies of scope on performance, and what are the drivers of cost efficiency?

This research paper analyzes forecasting accuracy under information sharing by considering co-variability of daily demand series, inter-temporal correlation and spatial correlation within cash supply chains in addition to seasonality and calendar effects. Previous studies focus on explaining the long run determinants of currency demand offering limited insight into the short-run determinants and co-variability of daily demand in cash supply chains. Moreover, it is argued that independent forecasts isolate individual demand series and potentially amplify the uncertainty-based coordination problem in inventory routing. One commonly suggested way to improve forecasting accuracy of demand in supply chains is the use of central information for joint forecasting. However, empirical evidence regarding the forecasting accuracy under information sharing is to be presented. The aim of this paper is to evaluate the overall forecasting accuracy of daily cash demand and the potential for joint forecasting in cash supply chains.

This research paper contrasts competing techniques of forecasting daily demand in cash supply chains in order to determine the overall performance and the potential of joint forecasting for integrated planning. A joint forecasting approach is compared with well-established causal forecasting techniques, namely, a vector time series model and a seasonal ARIMA model using simple methods as benchmarks. The vector time series model captures the dynamics and co-variability that characterizes a multi-stage supply chain. From a theoretical perspective, such a model is expected to yield more accurate forecasts, thereby addressing the uncertainty-based coordination problem and improving the efficiency within the supply chain. The data is obtained from a mid-size European bank and contains cash dispense records of a randomly selected region with 20 ATMs serving approximately 30000 people. Each time series covers a period of 759 days. Evaluation is based on forecasting horizons of up to 28 days. Forecasting accuracy is measured using the mean absolute percentage error.

Results show that the seasonal ARIMA model yields a higher forecasting accuracy compared to the vector time series model. Variability in demand was mainly attributed to the day-of-the-week effect. In particular, co-variability is captured by seasonality and calendar effects limiting the potential of joint forecasting. Moreover, results show that cumulative forecasts for periods of 14 days are very robust with mean percentage errors of approximately two percent. The research paper confirms the benefit of advanced forecasting techniques for daily forecasts. However, the results also suggest that the role of information sharing is limited to coordination of replenishments across the cash supply chain and that information sharing does not yield more accurate forecasts based on joint forecasting. In other words, there is very little unique in the information that each demand series provides in order to improve overall forecasting accuracy of all demand series.

The originality value is to test the premises of information sharing, particularly the application to cash supply chains. Specifically, the paper sheds light on claims of the supply chain literature regarding the benefits of information sharing. The paper points out that the implicit conjecture of the supply chain management literature is that demand in supply chains is correlated across space and time and that external variables possess additional forecasting ability. The paper concludes that for joint forecasting to be valuable, supply chain partners are required to provide some unique forecasting ability rather than to engage in information sharing in the strict sense.

The research paper analyzes cost structures of inventory routing and investigates efficiency gains that result from combining vehicle routing and inventory management under stochastic demand. The major complication arises from the stochastic demand, which may exceed current inventory in any given period during the planning horizon. Alternatively, treating point forecasts as deterministic leads to more tractable models compared to the stochastic counterpart, yet implies a rather strong limitation for practical applications of inventory routing. In particular, deviations from expected demand cause stockouts or excess inventories that radically affect inventory routing decisions, and consequently impact service levels and costs. The aim of this paper is to identify the conditions under which the introduction of inventory routing is most beneficial, particularly the impact of cost structures, variability of cost parameters, stochastic demand, forecasting accuracy and service levels.

This paper presents a stochastic inventory routing model, where the stockout cost is replaced by a minimal service level constrain that requires the probability of stockout in every period to be less than a defined threshold. The approach differs further from previous studies by formulating the stochastic inventory routing problem as a mixed integer program. The proposed model rests on mainly two ideas. First, stockouts are not modeled as a cost, but rather as a predefined or required target service level, which implies that demand is satisfied from current inventory with a required minimum probability. Second, the stochastic nature of demand is not captured by a Markov process, but rather by modeling forecasting errors, which are assumed to follow a Gaussian distribution. Consequently, forecasting accuracy can be expressed as a constant ratio, where the standard error varies with the level of demand and is a multiple of the expected demand. The approach complements existing models in order to better understand cost trade-offs, in particular with respect to forecasting accuracy and service levels.

A three-phase heuristic solution strategy and framework to evaluate efficiency gains from inventory routing is given. The impact of set-dependent cost structures on efficiency gains is demonstrated through cost savings by an interchange procedure that merges inventory and transportation decisions originally determined separately. The computational study illustrates the approach for a network of ATMs. The proposed methodology applies simulation and factorial design to analyze the role of set-dependent cost structures as well as the impact of demand, forecasting accuracy, length of rolling horizon, service level, vehicle capacity, cost factors, factor levels and interaction effects. Cost savings are evaluated through nominal range sensitivity analysis and repeated measure ANOVA using empirical data of an international financial institution. The data contains cash dispense records of a region with 107 ATMs comprising locations, such as shopping malls, hotels, hospitals and airports, and covering a period of 200 days.

The study identified six out of the eight proposed factors as statistically significant: fixed replenishment costs, holding costs, routing costs, vehicle capacity, demand, and length of the rolling horizon. Results show that the interchange procedure yields expected cost saving of approximately 18 percent and imply that cost savings between six to ten percent, as suggested by prior literature, could in practice be too conservative for large-scale stochastic inventory routing problems. Effect size was largest for fixed replenishment costs, routing costs, and length of rolling horizon. Not surprising is that
longer rolling horizons result in increased cost savings. However, the computational study also shows that the relevant range for the rolling horizon in cash supply chains is three to seven days. A rolling horizon of more than seven days did not result in additional cost savings. Similarly, expanding the vehicle capacity to serve more than eight ATMs on a single replenishment route does not yield additional cost savings.

Somewhat surprising is that the factors minimal service level and forecasting accuracy are not statistically significant and no linear or quadratic trend is observed. Further, an important result is that the effect size of holding cost and demand is substantially smaller indicating no clear trend or higher order powers, despite differences in cost savings being statistically significant.

The originality value is the development of a novel formulation of stochastic inventory routing, a solution strategy and its application to cash supply chains in order to gain an understanding of the conditions under which the introduction of inventory routing is most beneficial. Novel aspects account for minimal service level and forecasting accuracy in stochastic inventory routing. In particular, the research paper provides answers to the following questions: How can the optimal replenishment schedule be determined conceptually and operationally under stochastic demand? How can decision makers determine efficiency gains of inventory routing and determine the effect size? Specifically, how can decision makers assess the impact of stochastic demand, forecasting accuracy and service levels, and gain knowledge of the impact of the underlying cost structure, cost trade-offs, particularly with respect to forecasting accuracy and service levels. Moreover, how can decision makers be informed to make smart design choices with respect to capacity constraints of the replenishment system?
5 CONCLUDING REMARKS

This dissertation contributes towards an understanding of the conditions under which the introduction of inventory routing is most beneficial. In particular, the thesis argues for a strategic management accounting perspective of inventory routing that is informed by supply chain management, economics and operations research to guide the strategy formulation process of integrated logistics. The line of reasoning draws on the assumption that defining competitive strategies requires an understanding of the underlying cost structure and drivers of efficiency. The dissertation highlights the potential of strategic management accounting for informing the decision to introduce inventory routing by providing a methodology and investigating the cause-and-effect relationship of cost structures and drivers of efficiency.

5.1. Contributions to prior literature

Research paper 1 (Wagner, 2010a) shows that performance gains from supply chain collaboration requires a common cost component and cannot be explained by simple linear or affine cost structures. In other words, inventory management and distribution decisions become separable in the absence of a set-dependent cost structure, and neither economies of scope nor coordination problems are present in this case. Subsequently, the cost structure determines the need for collaboration and information sharing in supply chains.

Research paper 2 (Wagner, 2010b) contributes to prior literature by analyzing whether information sharing improves the overall forecasting accuracy in a two-stage supply chain. In contrast to claims in the supply chain literature, the analysis suggests that the potential for information sharing is limited to coordination of replenishments and that central information do not yield more accurate forecasts based on joint forecasting. The research paper concludes that for joint forecasting to be valuable, supply chain partners are required to provide some unique forecasting ability rather than to engage in information sharing in the strict sense. Further, the research paper contributes to prior literature in providing new empirical evidence to support this claim.

Research paper 3 (Wagner, 2010c) contributes to prior literature by providing a novel formulation of the stochastic inventory routing model that accounts for minimal service levels and forecasting accuracy. This allows to explicitly study the interaction of minimal service levels and forecasting accuracy with the underlying cost structure in inventory routing. Interestingly, results show that the factors minimal service level and forecasting accuracy are not statistically significant, and subsequently not relevant for the strategic decision problem to introduce inventory routing, or in other words, to effectively internalize inventory management and distribution decisions at the supplier. Consequently the main contribution of this thesis is the result that cost benefits of inventory routing are derived from the joint decision model that accounts for the underlying set-dependent cost structure rather than the level of information sharing. This result suggests that the value of information sharing of demand and inventory data is likely to be overstated in prior literature. In other words, cost benefits of inventory routing are primarily determined by the cost structure (i.e. level of fixed costs and transportation costs) rather than the level of information sharing, joint forecasting, forecasting accuracy or service levels.
5.2. Originality value

The originality value of the dissertation is in creating a new synthesis of inventory routing by advancing a strategic management accounting perspective. In developing a strategic management accounting perspective on inventory routing, the dissertation integrates ideas, practices and approaches of established, but largely independent fields enabling a new interpretation and level of analysis. As the literature review in Section 2 suggests, quantitative empirical studies enabling a detailed level of analysis are scarce. The dissertation attempts to overcome these shortfalls by engaging in a broad scale computational study to provide a rigorous investigation of the conditions under which the introduction of inventory routing is most beneficial or when it leads only to marginal improvements. The work is interdisciplinary in its nature and challenges the dominant view, which appears largely detached from strategy formulation, structural cost management, and competitive analysis. Subsequently, the thesis addresses an area that has been neglected due to a lack of interdisciplinary research and the dominance of qualitative studies (Barratt, 2004; Claasen et al., 2008).

The thesis applies quantitative methodologies and adopts techniques typically associated with operations research, supply chain management and economics, which add to knowledge in a way that has not been done before. The dissertation benefits from the quantitative approach by gaining knowledge of the strategic situations that favor the implementation of inventory routing systems, understanding cause-and-effect relationships, linkages and by gaining a holistic view of the value proposition of inventory routing on a cost structure level. Robustness of the results is assured by a factorial design that allows isolating individual effects and enables testing and refining the inventory routing strategy through statistical analysis of cause-and-effect relationships. The research setting is a practical application of inventory routing. Approach and methodology proposed in this dissertation are applied to cash supply chains and illustrated for networks of ATMs. It grounds the research in a real-life context providing a novel and potentially fruitful application area for inventory routing. In particular, the context of cash supply chains allows to isolate the phenomena under study and to provide scarce quantitative and reliable empirical evidence.

5.3. Conclusions

Inventory routing is a strategic choice. Overall, the thesis demonstrates the interdependency of management accounting and strategic decision making by highlighting the role of the underlying cost structure. In particular, when designing and implementing a costing system one should consider that the implications of the inherent cost structure extend beyond monitoring the effective implementation of a given strategy and impact strategic choice itself.

The value of inventory routing is not derived from decreasing inventories and de-amplification of demand oscillation. In effect, inventory holdings in inventory routing systems do not decrease dramatically compared to a traditional distribution-inventory system. Subsequently, one of the main differences of inventory routing compared to other supply chain initiatives is that inventory holdings under no circumstances will decrease (not radically and not even slightly) compared to a traditional distribution-inventory system, in fact inventory holdings tend to increase modestly, since inventory savings can be independently realized from routing (Wagner, 2010a, c).
The explanation is that inventory replenishments are shifted to a common time period in order to realize savings on the routing. This is beneficial because the savings on the routing outweigh the additional inventory cost. In other words, integrating inventory and routing decisions into a joint decision model avoids sub-optimization and leads to cost-efficiency gains in form of lower total replenishment costs.

The inventory routing model addresses cost trade-offs that originate from the coordination problem of simultaneous, non-concurrent goals in distribution and inventory management between a supplier and multiple retailers; rather than time delays in a planning loop of more than two stages. In fact, the inventory routing problem exists independent of time delays, and even as information becomes available instantly and lead time for deliveries becomes zero. However, this does not imply that we may abandon all Forrester Effect advice (see Forrester, 1958). In fact, the opposite is the case; this dissertation suggests that even an incrementally small delay in the decision rate in a planning loop, such as solving the inventory routing problem sequentially, leads to substantial inefficiencies in form of higher total costs of the distribution-inventory system. This, however, constitutes the core of inventory routing, its motivation and reason for its existence.

Further, the results of this dissertation have broader implications for explaining the varying success of supply chain initiatives aimed to provide coordination mechanisms that enable tightly coupled and responsive supply chain operations. The findings suggest that a strategic management accounting perspective is able to provide explanations that go beyond amorphous constructs such as collaboration, trust and information sharing. In particular, findings emphasize that timely information sharing and (joint) forecasting are not synonymous. The first is addressing a time delay in the flow of information, whereas the second is about making predictions about an uncertain future state of the world.

5.4. Limitations and directions for future research

The research context in this dissertation being cash supply chains allows to isolate the phenomena under study from further complicating factors such as non-homogenous products, varying quality or value of the product and perishable inventory. However, focusing on a single application of inventory routing is a limitation for generalizing the results to settings other than cash supply chains or networks of ATMs in particular. Most studies focusing on one application bear this trade-off. The chosen research setting is an example of a downstream application. However, this does not impose a limitation per se. In fact, the supplier-retailer relationship could occur at any stage in the supply chain.

The inventory routing model is a standard and highly relevant model in its own right, in fact defining a problem class, and cash supply chains, in particular networks of ATMs, provide a highly standardized and structured environment for analysis; but they do not in any way exhaust the possibilities of millions of other models and problem settings in supply chains (see Appendix C). Subsequently, the dissertation does at no point make or intends to draw inference from the findings on inventory routing beyond the subject of the dissertation. In that, the contribution of this dissertation complements rather than contradicts dynamic supply chain theories like the Forrester Effect.
The inventory routing model comprise three costs: (1) handling (ordering and packing), (2) holding (rent and waiting), and (3) transportation costs (capacity, distance mode). Thus costs are primarily decomposed in costs overcoming distances (i.e. handling and transportation) and costs overcoming time (i.e. holding). In this study it is assumed that costs vary with the number of replenishments, amount of inventory as well as the distance traveled. However, there may exist other costs that fall outside this cost structure or which are not truly “variable” in nature.

Topics that have not been addressed in this dissertation include demand pooling, product variants and product life-cycle. The square root law of inventory as originally formulated by Maister (1976) describes the effects of the concept of demand pooling and inventory centralization. The law provides and approximation of the benefits from consolidating the number of stocking locations. The inventory routing problem is defined as a single-supplier-multiple–retailer system. Hence, there are potentially two levels of consolidation: at the distribution warehouse (supplier) and at the level of retailers. Further reduction in the number of distribution warehouses would imply abandoning the level of distribution warehouses and eliminating the supplier from the inventory routing model. On the other hand, consolidation of retailers would simplify the routing problem. In the extreme case of abandoning retailers and introducing direct shipments, the single-supplier-multiple–retailer system would be substituted by a single-supplier-multiple–customer system, or in fact an inventory routing system where the number of retailers is replaced by an even larger number of end-customers, which dramatically increases the complexity of the inventory routing problem rather than reduces it. The topic of consolidating retailers could further be expanded to models establishing the optimal location of distribution warehouses and retailers. The option of direct shipments may be explored under the assumption that there is a large number of product variants (i.e. books) and short product life cycles (i.e. newspaper), but again this describes an entire different problem class. By definition inventory routing is not a system of multiple products, product variants or perishable goods.

The product life cycle concerns cash flows, sales revenue and profit in different maturity stages of a product requiring adjustments in the marketing mix, in particular regarding price and promotion, ultimately reflected in demand (forecasts). The computational study applying a factorial design addressed the impact of demand scaling using a demand multiplier. Considering an extreme scenario with low or even zero demand is not a technical violation of the inventory routing model and still leads to the optimal solution of the inventory-distribution system. The dissertation acknowledges that shorter rather than longer product life cycles would require a refinement of the time base unit. In this particular case the length of the product cycle would need to drop below the length of a single period (i.e. 1 day) or the length of the rolling horizon (i.e. 7 days). However, this would imply that the product is in fact a perishable good. Alternatively, looking at the life cycle of a product introduces again an entire new problem class, namely reverse logistics.

Further, the inventory routing model accounts for fluctuating demand between periods and is technically a dynamic model, both under stochastic and deterministic demand. Limitations arise from other static type assumptions. The inventory routing model uses parameters that explicitly capture changing assumptions regarding cost parameters, forecasting accuracy, service level, vehicle capacity and rolling planning horizon. While these parameters do not necessarily change constantly and can easily be updated, the underlying assumption is essentially of a static type for a particular planning period.

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14 The product life cycle can be distinguished in (1) introduction, (2) growth, (3) maturity, and (4) decline.
Realizing fully well that the inventory routing model with a focus on the cost structure and total replenishment costs may only capture a subset of management objectives, then analysis of the strategic management accounting perspective is contingent on many auxiliary assumptions. The set of management objective from a stakeholder perspective is likely to be different and certainly not limited to a focus on cost only.

Limitations offer amply opportunities for research. Future research would need to verify the results in another context or industry, potentially incorporating additional complicating factors. In addition, the impact of multiple product portfolios, the size of the distribution region, geographical dispersion and number of retailers may be studies in more detail. The analysis could further be extended from inventory-distribution systems to production-inventory-distribution systems advancing a strategic management accounting perspective that captures the logistics value chain as well as production. This is certainly a non-trivial task that offers numerous opportunities for research.

5.5. Managerial implications

The conclusions of this dissertation have important managerial implications since the focus is on “how”, rather than “whether”, inventory routing increases the cost efficiency compared to a traditional inventory-distribution system. Performance outcomes of inventory routing implementations range from substantial to marginal cost efficiency gains. Counter to conventional wisdom, the drivers of efficiency gains from integrated planning are not forecasting accuracy, service level, demand, and capacity constraints. In fact, it is shown that forecasting accuracy and service level are not relevant for the strategic decision to implement inventory routing. Instead, managers should focus their attention on the cost structure, primarily the level of fixed replenishment cost and routing cost, as well as the length of the planning horizon. Ceteris paribus, cost efficiency gains derived from inventory routing increase as routing costs increase or fixed replenishment costs decrease. Not surprising is that longer planning horizons result in increased cost efficiency gains. However, incremental cost savings diminish rapidly. In the context of this study, increasing the length of the planning horizon to more than seven days did not yield additional cost savings. Hence, managers are not expected to implement particularly long planning horizons in order to maximize the benefits of inventory routing. Similarly, results hold for expanding the capacity of each vehicle in the fleet. Other factors, such as holding costs and demand, play a subordinate role for the performance outcome and the expected benefits of the implementation of inventory routing and are therefore not of primary concern for strategic decision.

The strategic implications of the inventory routing model are clearly not contingent on the decision of outsourcing inventory management and distribution to a third party provider. Inventory routing is a decision model, whereby it is irrespective who carries out the operation, in other words, the economic feasibility from a management accounting perspective is solely determined by the cost structure and decision model, not whether the decision maker is physically controlling the operation or the subcontractor. However, outsourcing one or both of the activities in inventory routing to a third party may not be favorable where the loss of control results in agency problems or adversely affects other capabilities and subsequently the competitive position.

15 Phases in the life cycle of a product include (1) raw material extraction, (2) manufacturing and production, (3) transportation, (4) utilization and re-use, and (5) disposal and recycling.
Finally, although not explicitly discussed in the research papers, implications are derived regarding the value of the product being supplied. From an inventory routing perspective, banknotes are very similar to classic applications of inventory routing (e.g. industrial gases and chemicals) in terms of money variants per unit supplied and other properties.

The situation is similar in retailing, considering for example consumables, such as deodorants and detergents, or chocolates; in practice virtually almost all items in a supermarket. However, high value items, such as electronics carry larger holding cost per unit compared to low value item counterparts. The impact on relative cost savings is captured through holding cost. Consequently, increasing the value of a product has essentially the same effect as increasing the interest rate or holding costs.

5.6. Reflections on the debate of a means-centered versus a problem-centered approach to the defining of science

“To program is to understand.” This lesson is commonly attributed to Kristen Nygaard, who observed that translating a real-world problem into a model that could be understood and executed by a computer enhances the understanding of the problem domain. I agree. “Fingerübungen” 16 of this sort, such as formulating a mathematical program or designing a computational simulation reflects and enhances the understanding of the problem itself.

Mental shortcuts and jumping to conclusions using mathematical programming results very likely in an error message and yields a much better chance of being discovered than by relying on qualitative methodologies. The process of describing the application domain provides a valuable insight into the modeled application domain itself. Hence, mathematical programming and operations research should not just be considered a low-level technical discipline and a mean of getting around the problem, but rather a mean to enhance understanding of the problem domain through their application.

16 German "Fingerübung" (exercise in skill).
APPENDIX A.

THEORY OF CONSTRAINTS AND THROUGHPUT ACCOUNTING

A.1. Theory of constraints

The theory of constraints is a continuous improvement methodology and builds on the idea that organizations can be measured and controlled by variations on three measures: throughput, operational expense, and inventory (Goldratt, 1990a, b; Goldratt and Cox, 1984, 1986; Goldratt and Fox, 1986). The theory rests mainly on a working principle or a philosophy that consist of five focusing steps: (1) identify the system constraint, (2) decide how to exploit the system's constraint, (3) subordinate all the other processes to the decision, (4) elevate the system constraint, and (5) if in any of the previous steps a constraint is broken, go back to step 1 (Goldratt, 1990b).

The five focusing steps aim to ensure continuous improvement efforts are centered around the organization's constraints (Corbett, 1998; Rahman, 1998; Watson, Blackstone and Gardiner, 2007). The theory of constraints has been discussed and compared with activity-based costing (Corbett, 2000; Holmen, 1995), MRP (Aggarwal, 1985), linear programming (Balakrishnan and Cheng, 2000; Luebbe and Byron, 1992), labor-based management accounting (Patterson, 1992), JIT (Cook, 1994; Everdell, 1984; Ptak, 1991), MRP I/MRP II (Everdell, 1984; Ptak, 1991; Reimer, 1991), total productivity (Hilmola, 2001b); and applied in the context of evaluating new product alternatives (Lee and Plenert, 1993), make-or-buy and outsourcing decisions (Balakrishnan and Cheng, 2005; Gardiner and Blackstone, 1991; Hilmola, 2001a, b), product-mix decisions (Patterson, 1992), and total productivity. Limitations for applications arise when the constraint moves outside the boundaries of the organization, such as when demand becomes the limiting factor (Rahman, 1998).

A.2. Throughput accounting

The theory of constraints has evolved a new management accounting technique referred to as throughput accounting (TA) (Corbett, 1998; Noreen, Smith and Mackey, 1995). Throughput accounting is essentially a way of maximizing throughput contribution margin (defined as revenue minus super-variable costs) and addressing the problem of capacity utilization (Dugdale and Jones, 1998; Waldron and Galloway, 1988a, b, 1989a, b). Throughput accounting typically addresses the problem of a multi-stage production system, where a bottleneck in one stage leads to capacity underutilization in other stages. This radically limits the applicability of throughput accounting to the inventory routing model studied in this dissertation. The inventory routing model is not a production or production-distribution system, where a bottleneck leads to costly capacity underutilization. In fact, inventory routing is a cost minimization problem, not a profit maximization problem. Further, at no point does the inventory routing model include revenues and profits, which would allow the calculation of throughput contribution margin.
APPENDIX B.

EVOLUTION AND OPERATION OF CASH SUPPLY MANAGEMENT

B.1. Evolution of the ATM industry

Cash supply chains have evolved and undergone major changes since the first ATMs were introduced in 1969. The evolution of the industry distinguishes three phases (see Figure 8).

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>ATMs emerge as a distinct and viable channel.</td>
<td>Deployment growth booms; ATMs become P&amp;Ls.</td>
<td>Financial Institution deployers split along strategic dimensions.</td>
</tr>
<tr>
<td>- Proprietary ATMs</td>
<td>- New revenue sources</td>
<td>- Role of the ATM</td>
</tr>
<tr>
<td>- Emergence of shared EFT networks</td>
<td>- New entrants</td>
<td>- Cash dispenser</td>
</tr>
<tr>
<td>- Deployment and usage growth</td>
<td>- Surge in deployments</td>
<td>- Full service channel</td>
</tr>
<tr>
<td>- Focus on customer service and convenience</td>
<td>- Profitability declines.</td>
<td>- Surcharge-free access</td>
</tr>
<tr>
<td></td>
<td>- Declining per-ATM transaction</td>
<td>- Shared access</td>
</tr>
<tr>
<td></td>
<td>- Declining revenue</td>
<td>- Owned/branded access</td>
</tr>
<tr>
<td></td>
<td>- Rising costs</td>
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Figure 8. Evolution of the ATM industry

Adapted from: D’Ambrosio et al. (2006).

B.2. Operations and costs

Operating a network of ATMs involves numerous disparate functions. These include purchasing and installing of ATMs, processing transactions, clearing paper jams, repairing broken parts, picking up and processing deposits as well as replenishing cash (D’Ambrosio et al., 2006). How well deployers manage these functions determines operating expenses and operational efficiency.

Operating expenses fall mainly in two categories. Cash-Related expenses such as cash replenishment, costs of funds, and back office operations account for almost one third of the total expenses (Figure 9). Similar numbers are stated by All (2003) and Cappelli and Lewis (2006) reporting 31 percent and 33 percent. The replenishment of ATMs comprises typically a fixed cost for swapping and refilling cassettes inside ATMs and a variable cost for the distance traveled.

Non-Cash-Related expenses such as first line maintenance, second line maintenance, telecommunications, terminal driving, corporate overhead, rent, depreciation, and other expenses account for the remaining two thirds of the total expenses (D’Ambrosio et al., 2006). The biggest single expense is the depreciation of the machines installed. First Line Maintenance (FLM), which involves no tools or service parts (e.g. clearing journal or currency jams) and Second Line Maintenance (SLM) involving remedial maintenance or replacement of parts are the second and third biggest expense. Terminal driving refers to transaction authorization/settlement and EFT network routing, which is completely scale driven. Thus greater transaction volume implies lower costs per transaction.
Non-cash-related expenses are rather fixed in nature and independent of the cash deployment strategy. On the contrary, cash-related expenses solely depend on the cash deployment strategy and are subject to the day-to-day operation.

Operational efficiency has become key in a maturing market. Outsourcing selected or all of functions to third party providers with greater scale and scope potentially enables deployers to reduce operating complexity and expenses (D'Ambrosio et al., 2006). Nevertheless, many have preferred to keep these functions in-house to maintain greater control and to ensure quality.

Financial institutions may exclusively rely on third party providers or supplement their in-house capabilities to service their ATM networks. Figure 10 depicts financial institutions' service infrastructure for cash replenishment, deposit pick up, first line maintenance, and second line maintenance. The majority of off-premises ATMs (88%) involve servicing by third party providers. On the contrary, half of the on-premises ATMs (50%) are serviced entirely in-house.

Consequently, there exists a strong tension between accessibility and costs for ATM networks, which is unlikely to disappear over the next few years. ATM deployers are confronted with the trade-off between reducing costs and maximizing cardholder access. Financial institution deployers currently strive for low-cost cash deployment strategies to provide fee-free ATM access for their cardholders (D'Ambrosio et al., 2006).

Table 4. Industry data on average monthly revenues and expenses of ATMs, USA (USD)

<table>
<thead>
<tr>
<th></th>
<th>On-Premise ATMs</th>
<th>Off-Premise ATMs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surcharge Income</td>
<td>865 676 706</td>
<td>675 611 709</td>
</tr>
<tr>
<td>Interchange Income</td>
<td>413 375 398</td>
<td>400 341 304</td>
</tr>
<tr>
<td>Advertising Income</td>
<td>0 3 0</td>
<td>0 0 0</td>
</tr>
<tr>
<td><strong>Total Revenue</strong></td>
<td><strong>1278 1054 1104</strong></td>
<td><strong>1075 952 1013</strong></td>
</tr>
<tr>
<td>Depreciation</td>
<td>(375) (421) (417)</td>
<td>(254) (220) (260)</td>
</tr>
<tr>
<td>First Line Maintenance</td>
<td>(126) (124) (125)</td>
<td>(117) (105) (109)</td>
</tr>
<tr>
<td>Cash Replenishment</td>
<td>(70) (100) (185)</td>
<td>(180) (152) (221)</td>
</tr>
<tr>
<td>Second Line Maintenance</td>
<td>(199) (187) (200)</td>
<td>(150) (139) (150)</td>
</tr>
<tr>
<td>Costs of Funds</td>
<td>(90) (90) (100)</td>
<td>(90) (75) (100)</td>
</tr>
<tr>
<td>Telecommunications</td>
<td>(119) (125) (58)</td>
<td>(105) (100) (100)</td>
</tr>
<tr>
<td>Terminal Driving / Processing</td>
<td>(115) (95) (100)</td>
<td>(75) (55) (69)</td>
</tr>
<tr>
<td>Back Office Operations</td>
<td>(101) (100) (179)</td>
<td>(95) (68) (100)</td>
</tr>
<tr>
<td>Corporate Overhead</td>
<td>(0) (23) (80)</td>
<td>(0) (0) (70)</td>
</tr>
<tr>
<td>Rent</td>
<td>(0) (0) (0)</td>
<td>(187) (250) (271)</td>
</tr>
<tr>
<td>Other</td>
<td>(60) (50) (0)</td>
<td>(45) (30) (0)</td>
</tr>
<tr>
<td><strong>Total Expense</strong></td>
<td><strong>1255 1315 1444</strong></td>
<td><strong>1298 1194 1450</strong></td>
</tr>
<tr>
<td><strong>Profit</strong></td>
<td><strong>23 261 340</strong></td>
<td><strong>223 242 437</strong></td>
</tr>
</tbody>
</table>

Source: (D’Ambrosio et al., 2006; Hayes et al., 2004).
Figure 9. Cash-related and non-cash-related expenses in operating ATM networks, USA

Sources: D'Ambrosio et al. (2006), and Hayes et al. (2004).

Figure 10. Operating and service agreements of ATM networks, USA

Source: D'Ambrosio et al. (2006).
APPENDIX C.

CLASSIFICATION OF INVENTORY MODELS AND SYSTEMS

Figure 11. Classification of inventory models and systems

Source: Prasad (1994).
REFERENCES


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PART II:
RESEARCH PAPERS
Analyzing Cost Structures of Inventory Routing: Application to Cash Supply Chains

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Abstract

This paper analyzes cost structures of inventory routing and investigates efficiency gains that result from combining vehicle routing and inventory management. Mixed-integer models are applied to determine the optimal replenishment schedule. Total costs of a sequential approach are contrasted with an integrated approach in order to capture the impact of the underlying set-dependent cost structure. The proposed methodology applies simulation and a factorial design to analyze the role of set-dependent cost structures as well as the impact of demand, cost factors, factor levels and interaction effects. Cost benefits are evaluated in a deterministic environment using nominal range sensitivity analysis and repeated measure analysis of variance (ANOVA). The approach is illustrated for a local network of Automated Teller Machines (ATMs) using empirical data of an international commercial bank. Results of the case study show that cost benefits of the integrated approach vary with factor levels and are primarily determined by routing costs with remaining factors having only limited impact.

Keywords: Inventory, Routing, Sensitivity, ANOVA, ATM

1 Introduction

Inventory and transportation costs have a significant impact on the operating cost of the firm. Hence, researchers and practitioners alike seek ever new and better ways to gain competitive advantages in distribution networks over competitors. Integration and coordination of various aspects of distribution has become critical to lower costs and increase efficiency. Inventory routing is one model that has been adopted by the oil and gas, retail, textile and automotive industry (Campbell and Savelsbergh, 2004). The
approach integrates inventory allocation and vehicle routing that have been initially regarded separately. Hence, the objective is to minimize costs based on three joint distribution decisions: (1) when to deliver to a customer, (2) how much to deliver to a customer, and (3) how to route deliveries to customers.

Inventory routing models make various assumptions about planning horizon, demand, service levels, vehicle fleet and related working constraints. The reader is referred to Moin and Salhi (2006), Kleywegt, Nori and Savelbergh (2002) and Campbell and Savelbergh (2004) for topic overview, applications and developments in solving inventory routing problems. Clearly, integrating routing and inventory allocation enables efficiency gains and cost savings. As such, the potential of inventory routing is readily and intuitively supported by academics and practitioners alike. However, empirical evidence on the size of the effect and the underlying set-dependent cost structure is limited. Earlier literature suggests cost reductions to fall between six and ten percent (Bell et al., 1983, Federgruen and Zipkin, 1984, Golden et al., 1984) offering no insight into the impact of factor levels and interaction effects. In a more recent study, Raa and Aghezzaf (2009) pioneer the analysis of cost trade-offs governing inventory routing problems, but the study does not extend the analysis to an evaluation of the effect of set-dependent cost structures and subadditive transaction costs. As such, the present study considers the impact of factor levels and factor interactions by isolating the effect of set-dependent cost-structures.

Following the rational outline above, this study investigates set-dependent cost structures of inventory routing problems and evaluates potential efficiency gains from optimization, particularly comparing a sequential approach and an integrated approach where replenishments and routing are considered jointly. The approach combines mixed-integer inventory and routing models to derive the optimal replenishment schedule. The methodology and analysis are applied to cash supply chains and illustrated for a local network of ATMs, where cash has properties of both, currency and product. Effects are evaluated in a time-discrete, deterministic framework based on total replenishment costs using simulation and empirical data of an international commercial bank. Detailed analysis of the case study provides insight into the role of set-dependent cost structures.

The paper is organized as follows. §2 motivates and describes the background to the case study that illustrates the proposed methodology. §3 presents the research design including the basic framework, mathematical formulation, data and design of experiments. The problem formulation is stated as a mixed-integer inventory routing problem, contrasting an integrated and a sequential approach. §4 presents the results of the nominal range sensitivity analysis and statistical analysis, followed by the discussion and conclusion in §5.
2 Background to the Case Study

Cash supply chains provide a new and potentially fruitful area for inventory routing. Currency is moved between different stages, incurring transaction and holding costs (Rajamani et al., 2006). Cash management decisions at each stage, such as central bank, cash in transit (CIT) provider, bank branch, off-premises and on-premises ATM aim to minimize total costs while ensuring the supply of currency. Integrating cash management decisions at various stages of the cash supply chain allows to balance cost trade-offs and to increase the efficiency of banking systems. Hence, providing cash management as a sharable service increases efficiency and lowers total costs across the cash supply chain. The underlying set-dependent cost structure is captured by subadditive transaction costs in combining and coordinating multiple replenishments.

Historically, cash management has received widespread attention from academics and practitioners alike (for reviews see Gentry, 1988, Gregory, 1976, Srinivasan and Kim, 1986). A good deal of research effort has been devoted to developing inventory cash management models that match various cash balance requirements and hypothesized cash flow patterns. More recent studies have focused on randomly varying environments (Hinderer and Waldmann, 2001) and stochastic programming (Castro, 2009). However, all cash management models implicitly assume additivity in transaction costs, which, viewed through the lens of set-dependent costs structures, provides limited insight into the overall economies of cash supply chains.

Although research in cash management and inventory management have traditionally taken a similar path, recent developments in cash management have failed to consider an integrated supply chain perspective that has led to advances in modeling set-dependent cost structures in inventory management and logistics. Particularly, the inventory routing problem (IRP) is a prominent example. In essence, the model is an attempt to gain additional cost efficiency over simplified cost structures and sequential planning models by exploiting the subadditive nature of the integrated model characterized by set-dependent cost structures.

This paper considers the properties of the complex decision problem arising from an integrated cash replenishment approach by investigating the effect of set-dependent cost structures in cash supply chains. The goal is to assess set-dependent cost structures exhibiting subadditive transaction costs not captured by simple fixed, linear or affine cost functions. In particular, a network of ATMs is considered that illustrates the effect of set-dependent cost structures and provides a new application for inventory routing.
3 Research Design and Data

The study is based on normative empirical quantitative research and discrete event simulation to determine the effects of set-dependent cost structures. Borrowing from the logical positivist approach, the phenomenon of set-dependent cost structures is isolated from the context for logical analysis, so to assess the impact of factor levels (i.e. cost parameters and demand). The formulated mixed-integer model is based on prior axiomatic quantitative research in the area of supply chain management and inventory management outlined earlier. However, the inventory routing model considered in this study focuses on the properties of set-dependent cost structures. Consequently, complicating capacity and working constraints in inventory routing are not considered (for example see Chandra, 1993).

The impact of set-dependent cost structures is determined by comparing total costs of an integrated approach with total costs of a sequential approach. Relative cost savings are measured using simulation and empirical data from an international commercial bank. Nominal range sensitivity analysis is conducted to determine the impact of factor levels on cost savings. The factorial design and simulation enable statistical analysis of cost savings. Discrete probability distributions of cash demand are obtained from historic data of the case company. Repeated measure analysis of variance (i.e. One-Way RM ANOVA, Two-Way RM ANOVA) is conducted to test for differences in the impact of factor levels and interaction effects.

3.1 Basic Framework

For simplicity and illustration purpose, the effect of set-dependent cost structures in inventory routing is captured by a one-warehouse multi-retailer system in a multi-period, finite horizon framework. The case study contains a central vault supplying cash in form of a single currency to several cash dispensers. Demand for cash is assumed to be time-varying, ATM specific, deterministic, and time-discrete. No cash shortages and backlogs are permitted. Cash is routed from the central vault to ATMs via a single uncapacitated vehicle at the beginning of each period. Routing costs are represented by an undirected graph, where each arc is associated with a known weight capturing the distance between two ATMs.

The following notation is used in formulating the mathematical models:

**Sets**

\[ \mathcal{N} = \{ \text{atm}_i | i = 0, 1, \ldots, N \} \]

Set of \( N \) cash dispensers, \( \text{atm}_0 \) is the central vault

\[ \mathcal{T} = \{ \text{day}_t | t = 1, \ldots, T \} \]

Set of \( T \) days


Parameters

- $C_f$: fixed replenishment cost coefficient
- $C_r$: routing cost coefficient
- $D_{i,j}$: arc weight (atmi, atmj)
- $I$: holding cost coefficient
- $L$: large number
- $N$: number of ATMs
- $T$: number of periods
- $W_{i,t}$: cash amount dispensed by ATM $i$ in period $t$

Decision Variables

- $d_t$: set-dependent routing in period $t$
- $s_{i,t}$: cash amount held by cash ATM $i$ in period $t$
- $u_{i,t}, u_{j,t}$: arbitrary real numbers
- $x_{i,t}$: amount of cash supplied to ATM $i$ in period $t$
- $\omega_{i,j,t}$: binary indicator of traversing from ATM $i$ to ATM $j$ in period $t$
- $\omega_{i,t}$: binary indicator for replenishing ATM $i$ in period $t$

Total costs of inventory routing, as stated in Equation (1), are comprised of three cost components: linear holding costs, fixed replenishment costs and set-dependent routing costs. Holding costs are a linear function of the aggregated amount of undispensed cash, whereas replenishment costs represent a fixed amount incurred every time cash is supplied. Routing costs are dependent on the set of replenishment decisions in a given time period and are determined by the aggregated length of the respective optimal routes, scaled by a routing cost coefficient.

$$\text{Total Costs} = I \cdot \sum_{i \in N} \sum_{t \in T} s_{i,t} + C_f \cdot \sum_{i \in N} \sum_{t \in T} \omega_{i,t} + C_r \cdot \sum_{t \in T} d_t$$  \hspace{1cm} (1)

3.2 Integrated Approach

The here presented mathematical formulation of the integrated approach captures the effect of set-dependent cost structures by considering inventory and routing decisions jointly.

Minimize

$$1 \cdot \sum_{i \in N} \sum_{t \in T} s_{i,t} + C_f \cdot \sum_{i \in N} \sum_{t \in T} \omega_{i,t} + C_r \cdot \sum_{j \in N} \sum_{i \in N} \sum_{t \in T} D_{i,j} \cdot \omega_{i,j,t}$$  \hspace{1cm} (2)

Subject to

$$s_{i,t-1} + x_{i,t} - W_{i,t} = s_{i,t} \hspace{1cm} \forall i \in N; \forall t \in T$$  \hspace{1cm} (3)
Constraint (3) is required to balance inventory for each ATM. Constraints (4) and (5) set starting cash balances to zero and ensure the non-negativity of cash balance for each ATM. Replenishment indicator constraint (6) ensures that no cash is supplied without incurring fixed replenishment costs. Constraint (7) ensures that every route contains the central vault. Constraints (8) and (9) ensure that an optimal route that minimizes the objective (2) includes each ATM being replenished in a particular period. Constraint (10) is similar to the well-known sub-tour elimination constraint for the travelling salesman problem.

3.3 Sequential Approach

In order to isolate the effect of set-dependent cost structures a sequential approach is proposed, where replenishment decisions are determined independently (Subproblem 1) and to be accounted for in the subsequent routing problem (Subproblem 2).

**Subproblem 1 (Inventory):**

**Minimize** \[
I \cdot \sum_{i \in \mathbb{N}} \sum_{t \in T} s_{i,t} + C_f \cdot \sum_{i \in \mathbb{N}} \sum_{t \in T} \omega_{i,t}
\]

**Subject to** Constraints (3), (4), (5) and (6).

**Subproblem 2 (Routing):**

**Minimize** \[
C_r \cdot \sum_{i \in \mathbb{N}} \sum_{j \in \mathbb{N}} \sum_{t \in T} D_{i,j} \cdot \omega_{i,j,t}
\]

**Subject to** Constraints (7), (8), (9), and (10).
The integrated approach as well as the sequential approach are computationally non-trivial with both subproblems being NP-hard. In fact, the Subproblem 2 turns out to comprise $T$ distinct traveling salesman problems, each being NP-hard.

### 3.4 Data

The case study is based on data obtained from an international commercial bank covering a period of 200 days. The financial institution agreed to provide detailed cash dispense records for eight off-premises ATMs in one region, comprising locations such as shopping malls, hotels, hospitals and airports. The exact locations of all eight ATMs and the central vault were provided, which allowed the distance matrix to be derived. Summary statistics of daily-dispensed cash and the distance matrix are presented in Table 1 and Table 2.

**Table 1. Summary Statistics for Daily-Dispensed Cash**

<table>
<thead>
<tr>
<th>ATM</th>
<th>M</th>
<th>Mdn</th>
<th>Max</th>
<th>Min</th>
<th>SD</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16015.40</td>
<td>13920.00</td>
<td>54340.00</td>
<td>5370.00</td>
<td>7600.88</td>
<td>1.56</td>
<td>6.52</td>
</tr>
<tr>
<td>2</td>
<td>17734.10</td>
<td>14645.00</td>
<td>68920.00</td>
<td>5980.00</td>
<td>10082.44</td>
<td>2.32</td>
<td>9.95</td>
</tr>
<tr>
<td>3</td>
<td>3888.60</td>
<td>3840.00</td>
<td>13350.00</td>
<td>930.00</td>
<td>1970.98</td>
<td>1.67</td>
<td>7.13</td>
</tr>
<tr>
<td>4</td>
<td>4707.80</td>
<td>4810.00</td>
<td>15320.00</td>
<td>1320.00</td>
<td>1776.97</td>
<td>1.73</td>
<td>10.28</td>
</tr>
<tr>
<td>5</td>
<td>13068.80</td>
<td>11995.00</td>
<td>35490.00</td>
<td>1090.00</td>
<td>6542.32</td>
<td>0.78</td>
<td>3.40</td>
</tr>
<tr>
<td>6</td>
<td>16948.05</td>
<td>14350.00</td>
<td>47780.00</td>
<td>5240.00</td>
<td>7411.27</td>
<td>1.47</td>
<td>5.59</td>
</tr>
<tr>
<td>7</td>
<td>8292.90</td>
<td>7450.00</td>
<td>35590.00</td>
<td>2210.00</td>
<td>4260.71</td>
<td>2.55</td>
<td>13.72</td>
</tr>
<tr>
<td>8</td>
<td>2777.90</td>
<td>2370.00</td>
<td>8500.00</td>
<td>950.00</td>
<td>1419.16</td>
<td>2.05</td>
<td>6.82</td>
</tr>
</tbody>
</table>

*This table shows descriptive statistics for daily-dispensed cash for eight ATMs covering a period of 200 days.*

**Table 2. Distance Matrix**

<table>
<thead>
<tr>
<th>ATM</th>
<th>Vault</th>
<th>ATM-1</th>
<th>ATM-2</th>
<th>ATM-3</th>
<th>ATM-4</th>
<th>ATM-5</th>
<th>ATM-6</th>
<th>ATM-7</th>
<th>ATM-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vault</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>12</td>
<td>8</td>
<td>13</td>
<td>13</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>ATM-1</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>11</td>
<td>8</td>
<td>12</td>
<td>12</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>ATM-2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>11</td>
<td>6</td>
<td>11</td>
<td>12</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>ATM-3</td>
<td>12</td>
<td>11</td>
<td>11</td>
<td>0</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>ATM-4</td>
<td>8</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>0</td>
<td>7</td>
<td>7</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>ATM-5</td>
<td>13</td>
<td>12</td>
<td>11</td>
<td>7</td>
<td>7</td>
<td>0</td>
<td>3</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>ATM-6</td>
<td>13</td>
<td>12</td>
<td>12</td>
<td>6</td>
<td>7</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>ATM-7</td>
<td>11</td>
<td>10</td>
<td>10</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>4</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>ATM-8</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>9</td>
<td>7</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

*This table shows the distances between all ATMs and the central vault measured in kilometer and rounded to the nearest integer.*
3.5 Design of Experiments

In measuring the impact of set-dependent cost structures, four important design factors were identified: demand, fixed replenishment costs, holding costs, and routing costs. The factor demand is modeled as a multiplier that scales demand linearly and has quadratic impact on demand variance. The remaining three factors are cost coefficients. Factor levels resemble the situation faced by the bank and provide realistic upper and lower bounds. The full factorial design and respective factor levels are depicted in Table 3.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level I</th>
<th>Level II</th>
<th>Level III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand Multiplier</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Fixed Replenishment Cost Coefficient</td>
<td>10</td>
<td>30</td>
<td>90</td>
</tr>
<tr>
<td>Holding Cost Coefficient</td>
<td>0.00008</td>
<td>0.00016</td>
<td>0.00032</td>
</tr>
<tr>
<td>Routing Cost Coefficient</td>
<td>0.25</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

The factorial design assumes each factor to take one of three possible values, where the full design matrix is $3^4=81$ trials. Each trial contains 100 replications of simulated 200 days; each based on the observed discrete probability distribution of cash withdrawals per ATM. Hence, the computational complexity is $81 \times 100$ runs requiring $200 \times 8 \times 100$ daily cash withdrawals.

4 Tests and Results

This section presents the results of the nominal range sensitivity analysis and the statistical analysis regarding the impact of individual design factors, factor levels as well as interaction effects. The response variable is relative cost savings of the integrated approach compared to the sequential approach.

4.1 Nominal Range Sensitivity Analysis

Results presented in this subsection are based on the original factor level (Level II) and historic demand series faced by the international commercial bank. It is noted that the original replenishment schedule exercised by the bank resulted in 27.00% higher total costs compared to a sequential approach. The effect of the set-dependent cost structure is captured by the integrated approach and amounts to total cost saving of 3.02% compared to the sequential approach (see Table 4).

Investigation of individual cost components reveals the impact of set-dependent costs structures on total costs and shows how individual cost components are balanced using an integrated approach. Fixed replenishment costs were unaffected and cost savings entirely attributable to the sequential approach. In the case of routing costs, relative cost saving were attributable to the integrated approach. For holding costs, the
integrated approach resulted in relatively higher costs compared to the sequential approach, marking the trade-off in balancing individual cost components. Consequently, cost savings with respect to holding costs were attributable to the sequential approach.

<table>
<thead>
<tr>
<th>Component</th>
<th>Original</th>
<th>Integrated Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Replenishment Costs</td>
<td>-15.83%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Routing Costs</td>
<td>6.88%</td>
<td>22.05%</td>
</tr>
<tr>
<td>Holding Costs</td>
<td>-55.92%</td>
<td>-2.26%</td>
</tr>
<tr>
<td>Total Costs</td>
<td>-27.00%</td>
<td>3.02%</td>
</tr>
</tbody>
</table>

This table shows relative cost savings of the original cash deployment strategy and the integrated approach compared to the sequential approach for eight ATMs in the base line scenario with all factors being set to Level II and covering a period of 200 days.

In particular, analyzing the nominal range of each factor revealed differences in the impact of individual factor levels on relative cost savings (see Figure 1). The factor demand and the factor holding costs did not indicate trends or higher order powers contrary to the factor routing costs and the factor fixed replenishment costs. The importance measure, defined as the difference of cost savings within the variability range, indicated that the factor routing costs (10.98% - 0.48% = 10.50%) has the largest impact on cost savings, followed by the factor fixed replenishment costs (8.01% - 0.65% = 7.36%). Conversely, the importance measure suggested only limited impact on relative cost savings for the factor demand (3.19% - 1.72% = 1.47%) as well as for the factor holding costs (3.42% - 2.39% = 1.03%).

![Nominal range sensitivity analysis](image)

**Fig. 1.** Nominal range sensitivity analysis shows relative cost savings of each factor covering the variability range from Level I (0%) to Level III (100%). Relative cost savings are computed by varying one factor at a time with the remaining three factors being set to Level II.
4.2 Main Effects

One-way repeated measure ANOVA was performed to test the significance of factor levels for each of the four main factors: fixed replenishment costs, routing costs, holding costs, and demand. Normality of sampling distributions, relative cost savings, was met given the large sample size for each factor level (n=100), no outlying score (|z|>3.3) was detected. The assumption of homogeneity of variance was met, with the number of observations for each level being equal. The Huynh-Feldt adjustment corrected for the lack of sphericity in all four main factors detected by Mauchly’s test of sphericity (p<0.05).

Cost saving means for each factor level are tabulated together with standard errors, 95% confidence levels in Table 5. Results for one-way repeated measure ANOVA are presented in Table 6. Statistically significant effects included all four main factors. Interpretation, therefore, is focused on the differences in factor levels. Increase in cost savings as a function of an increasing routing cost coefficient was statistically significant, F(1, 1.12) = 13781.28, p<0.01, $\eta^2 = 0.99$. Similarly, an increase in the fixed replenishment cost coefficient was statistically significant, F(1, 1.12) = 8629.86, p<0.5, $\eta^2 = 0.99$. Both suggest a strong impact on cost savings. Although an increase in the holding cost coefficient F(1, 1.12) = 65.20, p<0.01, $\eta^2 = 0.40$, and an increase in the demand multiplier F(1, 1.12) = 309.75, p<0.01, $\eta^2 = 0.76$, were statistically significant, the effect sizes of the two factors were substantially smaller. Additionally, the Tukey HSD test for pairwise post-hoc comparison of level means was statistically significant (p<0.01) except the factor demand, where the pairwise comparison of Level I and Level II was not statistically significant.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level</th>
<th>M</th>
<th>SE</th>
<th>95% LCL</th>
<th>95% UCL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Replenishment Costs</td>
<td>Level I</td>
<td>0.08339</td>
<td>0.00065</td>
<td>0.08211</td>
<td>0.08468</td>
</tr>
<tr>
<td></td>
<td>Level II</td>
<td>0.03145</td>
<td>0.00034</td>
<td>0.03078</td>
<td>0.03212</td>
</tr>
<tr>
<td></td>
<td>Level III</td>
<td>0.00796</td>
<td>0.00016</td>
<td>0.00765</td>
<td>0.00826</td>
</tr>
<tr>
<td>Routing Costs</td>
<td>Level I</td>
<td>0.00391</td>
<td>0.00009</td>
<td>0.00374</td>
<td>0.00408</td>
</tr>
<tr>
<td></td>
<td>Level II</td>
<td>0.03145</td>
<td>0.00034</td>
<td>0.03078</td>
<td>0.03212</td>
</tr>
<tr>
<td></td>
<td>Level III</td>
<td>0.11281</td>
<td>0.00094</td>
<td>0.11095</td>
<td>0.11467</td>
</tr>
<tr>
<td>Holding Costs</td>
<td>Level I</td>
<td>0.03355</td>
<td>0.00071</td>
<td>0.03213</td>
<td>0.03497</td>
</tr>
<tr>
<td></td>
<td>Level II</td>
<td>0.03145</td>
<td>0.00034</td>
<td>0.03078</td>
<td>0.03212</td>
</tr>
<tr>
<td></td>
<td>Level III</td>
<td>0.02600</td>
<td>0.00029</td>
<td>0.02543</td>
<td>0.02657</td>
</tr>
<tr>
<td>Demand</td>
<td>Level I</td>
<td>0.03282</td>
<td>0.00044</td>
<td>0.03194</td>
<td>0.03370</td>
</tr>
<tr>
<td></td>
<td>Level II</td>
<td>0.03145</td>
<td>0.00034</td>
<td>0.03078</td>
<td>0.03212</td>
</tr>
<tr>
<td></td>
<td>Level III</td>
<td>0.04446</td>
<td>0.00054</td>
<td>0.04338</td>
<td>0.04554</td>
</tr>
</tbody>
</table>

This table shows descriptive statistics for each of the four main factors and the three factor levels.
Table 6. One-Way Repeated Measure ANOVA

<table>
<thead>
<tr>
<th>Factor</th>
<th>SS</th>
<th>DF</th>
<th>MS</th>
<th>F</th>
<th>(\eta^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Between-Subject Effects</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed Replenishment Costs</td>
<td>0.50261</td>
<td>1.0000</td>
<td>0.50261</td>
<td>23658.52546**</td>
<td>0.99584</td>
</tr>
<tr>
<td>Routing Costs</td>
<td>0.73177</td>
<td>1.0000</td>
<td>0.73177</td>
<td>13661.34053**</td>
<td>0.99281</td>
</tr>
<tr>
<td>Holding Costs</td>
<td>0.27601</td>
<td>1.0000</td>
<td>0.27601</td>
<td>11341.64507**</td>
<td>0.99134</td>
</tr>
<tr>
<td>Demand</td>
<td>0.39407</td>
<td>1.0000</td>
<td>0.39407</td>
<td>14288.43231**</td>
<td>0.99312</td>
</tr>
<tr>
<td><strong>Within-Subject Effects</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed Replenishment Costs</td>
<td>0.29802</td>
<td>1.50576</td>
<td>0.19792</td>
<td>8629.85847**</td>
<td>0.98865</td>
</tr>
<tr>
<td>Routing Costs</td>
<td>0.64126</td>
<td>1.12224</td>
<td>0.57141</td>
<td>13781.28117**</td>
<td>0.99286</td>
</tr>
<tr>
<td>Holding Costs</td>
<td>0.00303</td>
<td>1.57041</td>
<td>0.00193</td>
<td>65.19542**</td>
<td>0.39660</td>
</tr>
<tr>
<td>Demand</td>
<td>0.01023</td>
<td>1.88613</td>
<td>0.00542</td>
<td>309.74793**</td>
<td>0.75778</td>
</tr>
</tbody>
</table>

This table shows F-test and effect size for all four main factors: fixed replenishment costs, routing costs, holding costs and demand. Degrees of freedom are Huynh-Feldt adjusted for the averaged tests of significance. **p<0.01.

4.3 Interaction Effects

Two-way repeated measure ANOVA was performed to test the significance of the levels of interaction between the four factors: fixed replenishment costs, routing costs, holding costs, and demand. The assumptions of normality of sampling distributions and the assumption of homogeneity of variance were met, as with one-way repeated measure ANOVA. Likewise, degrees of freedom for the averaged tests of significance were Huynh-Feldt adjusted to account for the lack of sphericity indicated by Mauchly’s test of sphericity (p<0.05).

Table 7. Two-Way Repeated Measure ANOVA

<table>
<thead>
<tr>
<th>Factor</th>
<th>SS</th>
<th>DF</th>
<th>MS</th>
<th>F</th>
<th>(\eta^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand × Fixed</td>
<td>0.13732</td>
<td>2.69344</td>
<td>0.05098</td>
<td>945.04972**</td>
<td>0.90518</td>
</tr>
<tr>
<td>Demand × Routing</td>
<td>0.02902</td>
<td>1.76442</td>
<td>0.01645</td>
<td>518.17219**</td>
<td>0.83959</td>
</tr>
<tr>
<td>Demand × Routing × Fixed</td>
<td>0.02276</td>
<td>3.48458</td>
<td>0.00653</td>
<td>199.91124**</td>
<td>0.66880</td>
</tr>
<tr>
<td>Holding × Demand</td>
<td>0.12021</td>
<td>2.52555</td>
<td>0.04760</td>
<td>340.36967**</td>
<td>0.77468</td>
</tr>
<tr>
<td>Holding × Demand × Fixed</td>
<td>0.07047</td>
<td>4.35787</td>
<td>0.01617</td>
<td>100.91872**</td>
<td>0.50480</td>
</tr>
<tr>
<td>Holding × Demand × Routing</td>
<td>0.09215</td>
<td>3.07914</td>
<td>0.02993</td>
<td>349.96010**</td>
<td>0.77949</td>
</tr>
<tr>
<td>Holding × Fixed</td>
<td>0.14889</td>
<td>2.76272</td>
<td>0.05389</td>
<td>998.66307**</td>
<td>0.90981</td>
</tr>
<tr>
<td>Holding × Routing</td>
<td>0.03470</td>
<td>1.86480</td>
<td>0.01861</td>
<td>638.75881**</td>
<td>0.86581</td>
</tr>
<tr>
<td>Routing × Fixed</td>
<td>4.35216</td>
<td>2.31585</td>
<td>1.87930</td>
<td>23020.64386**</td>
<td>0.99572</td>
</tr>
<tr>
<td>Routing × Fixed × Holding</td>
<td>0.01921</td>
<td>3.24482</td>
<td>0.00592</td>
<td>173.04563**</td>
<td>0.63609</td>
</tr>
<tr>
<td>Routing × Fixed × Holding × Demand</td>
<td>0.05496</td>
<td>5.46237</td>
<td>0.01006</td>
<td>98.40961**</td>
<td>0.49850</td>
</tr>
</tbody>
</table>

This table shows F-test and effect size for the factor interactions: fixed replenishment costs, routing costs, holding costs and demand. The degrees of freedom are Huynh-Feldt adjusted for the averaged tests of significance. **p<0.01.
Results for two-way repeated measure ANOVA are presented in Table 7. Factor interactions, including two, three and four factor interactions, were statistically significant (p<0.01). Interpretation, therefore, is focused on the differences in effect size. The interaction of the factor routing costs and the factor fixed replenishment costs was statistically significant, $F(1, 2.32) = 23020.64$, $p<0.01$, $\eta^2_p = 0.99$, confirming a strong impact of routing costs and fixed replenishment costs on cost savings. Other two factor interactions were statistically significant, yet effect sizes were smaller. Three and four factor interactions were statistically significant, but the effect sizes were substantially smaller.

5 Conclusions

In this paper, a methodology for investigating set-dependent cost structures in inventory routing is presented. The set-dependent cost structure originated from coordinating multiple replenishments and was illustrated for a network of ATMs. The impact of set-dependent cost structures was demonstrated by contrasting total costs of an integrated approach with total costs of a sequential approach. In both, the nominal range sensitivity analysis and the statistical analysis, the integrated approach resulted in considerable lower total costs compared to the sequential approach.

Four statistically significant factors were identified: fixed replenishment costs, routing costs, holding costs and demand. Effect size was largest for fixed replenishment costs and routing costs. However, both factors had a contrary impact on cost savings. Larger fixed replenishment cost coefficients reduced cost savings, while larger routing cost coefficients increased cost savings. Somewhat surprising is that the effect size of holding cost coefficients and demand multipliers was substantially smaller indicating no clear trend or higher order powers, despite differences in cost savings being statistically significant.

Practical implications of this study concern the feasibility of inventory routing for cash supply chains. Results showed that set-dependent cost structures yield cost savings from coordinating multiple replenishments. However, the study also demonstrated that cost saving vary with factor levels and are primarily determined by routing costs with remaining factors having only limited impact. Hence, cost savings of more than six percent, as suggested by the literature, may in practice not be attainable, particularly for problem instances covering comparatively small networks.

Limitations of the case study are due to the single-case design. Nevertheless, using detailed empirical data distinguishes the study from exclusively normative quantitative research. The employed normative quantitative models allow for an assumptive generalizability, which a descriptive qualitative methodology does not provide (Eldabi et al., 2002). Moreover, simulation based results of inventory studies
tend to duplicate well in reality and thus reassure a certain generalizability which most single case settings otherwise would lack (Voss et al., 2002, Meredith, 1998).

Further research will have to address the design of set-dependent cost structures to reduce computational complexity for large-scale optimization problems. Time series analysis may allow the specification of scenarios and provide the link between a deterministic and stochastic setting. More advanced models may additionally take the likelihood of scenarios into account and establish the link to risk models.

References

Forecasting Daily Demand in Cash Supply Chains

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Abstract: Problem statement: Previous studies focused on explaining the long run determinants of currency demand offering limited insight into the short-run determinants and co-variability of daily demand in cash supply chains. Approach: This study contrasted competing techniques of forecasting daily demand in cash supply chains in order to determine the overall performance and the potential of joint forecasting for integrated planning. A joint forecasting approach was compared with well-established causal forecasting techniques, namely, a vector time series model and a seasonal ARIMA model using simple methods as benchmarks. Evaluation was based on multiple time series obtained from mid-size European bank with forecasting horizons of up to 28 days. Forecasting accuracy was measured using the mean absolute percentage error. Results: The seasonal ARIMA model resulted in a higher forecasting accuracy compared to the vector time series model. Variability in demand was mainly attributed to the day-of-the-week effect. Co-variability is captured by seasonality and calendar effects limiting the potential of joint forecasting. Cumulative forecasts for periods of 14 days are very robust with mean percentage errors of approximately two percent. Conclusion: The results confirmed the benefit of advanced forecasting techniques for daily forecasts. However, the study suggested that the role of information sharing is limited to coordination of replenishments across the cash supply chain and does not yield more accurate forecasts based on joint forecasting.

Key words: Cash supply chain, cash demand, forecasting, seasonal ARIMA, vector time series models

INTRODUCTION

Cash supply chains play a vital role for the efficiency of banking systems. This complex string of interrelations required to circulate currency from central banks to end users and back, is a special case of closed-loop supply chains. Currency circulates freely between different stages, such as central bank, Cash In Transit (CIT) providers, banks, Automated Teller Machines (ATM), corporate and private customers, incurring transaction and holding costs. Cash management decisions at each stage are interrelated, but mostly beyond the control of the central bank. Hence, currency in cash supply chains represents one of the largest autonomous liquidity factors in banking systems.

This study considers the co-variability of daily cash demand series within cash supply chains in addition to seasonality and calendar effects. The goal is to evaluate the overall forecasting accuracy of daily cash demand and the potential of joint forecasting in cash supply chains.

An analysis of forecasting daily currency demand in cash supply chains is interesting and important for mainly three reasons. From an economic perspective, it enhances the understanding of the demand for currency by considering seasonality and calendar effects in higher frequency data. Traditionally, data availability restricts studies to lower frequency data, such as monthly, quarterly and annual aggregates. From a supply chain perspective, it provides empirical evidence on the accuracy of forecasting demand in cash supply chains, which is essential for integrating autonomous cash management decisions across the cash supply chain, coordinating currency needs and increasing efficiency of banking systems. Similarly, from a business strategy perspective, the study provides further insights into the role of information sharing. In particular, the present study accounts for partnering, outsourcing and privatization that are currently transforming cash supply chains into a mature and optimized businesses (Rajamani et al., 2006).

Forecasting demand in cash supply chains requires an underlying theoretical framework that can reasonably explain the demand for currency. On theoretical grounds, the nature and structure of the demand for cash has been intensely debated by academics in the past (Serletis, 2007). Research has focused on the long run determinants of currency demand. Topics include estimation of income and interest rate elasticity, structural changes from currency
change over, influence of alternative payment systems, money hoarding and informal economic activity. Surprisingly little is known about the short run determinants of currency demand.

Recently, modeling and forecasting of daily cash demand in cash supply chains has gained prominence by two papers. Cabrero et al. (2009) consider the daily series of banknotes in circulation in the context of liquidity management of the European Central Bank (ECB). The authors analyze and compare the forecasting accuracy of a structural time series model based on the Root Mean Squared Forecast Error (RMSE) and the forecasting accuracy test by Diebold and Mariano (1995). Their empirical results suggest the two econometric models explain large parts of the variations in the daily series with the ARIMA model yielding a lower accuracy over forecasting horizons of up to 4 days and higher accuracy for forecasting horizons of more than 4 days compared to the structural time series model. Brentnall et al. (2008) take a different approach by studying the temporal process of cash withdrawals for individuals. The developed point process model describes the occurrence of individual cash withdrawals over time. Both studies provide strong evidence for seasonality and calendar effects in the series of daily demand for cash, but do not account for the potentially interrelated nature of demand in cash supply chains. The present study differs from previous work by (1) considering co-variability and (2) by focusing on points of cash withdrawal, not individual customers or macroeconomic aggregates.

Supply chain management is an approach to efficiently integrate the upstream and downstream relationships to provide goods in the right quantities, to the right locations, at the right time in order to minimize system wide costs while meeting service level requirements (Simchi-Levi et al., 2007). Hence, cash supply chain management adopts a system wide view by emphasizing the interrelated nature of currency demand on a macroeconomic level. Integration is rendered difficult by the variability in the supply chain due to the uncertainty of demand.

Clearly, independent forecasts isolate individual demand series and potentially amplify disturbances. One commonly suggested way to improve forecasting accuracy of demand in supply chains is the use of central information for joint forecasting (Aviv, 2002). However, empirical evidence regarding the benefits of this approach is to be presented. As such, the present study is the first to capture seasonality, calendar effects and cross-variable dynamics in daily cash demand series in cash supply chains.

Following the rationale outlined above, this study investigates forecasting accuracy and the potential of joint forecasting in cash supply chains by contrasting a vector time series model and a seasonal ARIMA model. Calendar effects are modeled using exogenous variables. The impact of co-variability is illustrated for a network of ATMs. Forecasting accuracy is evaluated using daily cash dispense records.

**MATERIALS AND METHODS**

**Data:** The data for this study is obtained from a mid-size European bank with total customer deposits in 2009 of approximately EUR 25 billion and contains cash dispense records of a randomly selected region with 20 ATMs serving approximately 30000 people. Each time series comprises 759 daily cash withdrawals covering the period March 21st 2007 to April 17th 2009. The size of the region provides a reasonable tradeoff between tractability and data requirements. In comparison, the same number of ATMs serves on average 15000 people in Spain, 29000 people in France, 32500 in Germany, 64000 people in Finland or 26000 people in the euro area (European Central Bank, 2009).

The data is analyzed first using a visual inspection of the time series plots. The data displays no long-run trend, but clearly a seasonal pattern and cyclical behavior in daily cash withdrawals. Most noticeable in all sample time series is that daily cash withdrawals seem to increase in December and drop in the months January and February. Daily, weekly and monthly patterns appear to be stable over time. However, each series seems to be affected by local events like festivals, promotions and technical failures of dispense devices, which may explain some of the unusual spikes and drops not related to calendar effects. These events alter the flow of people and consequently impact cash withdrawals. Figure 1 depicts daily cash withdrawals of one ATM in the data set and is exemplary for the other time series considered in this study.

Further evidence on seasonality and calendar effects in daily cash withdrawals is presented by a grouped box plot analysis. The box plot provides a graphical representation of summary statistics. The values are the minimum, 1st, 5th and 25th percentile, median, mean, 75th, 95th and 99th percentile and the maximum. Figure 2 shows day-of-the-week, month-of-the-year and holiday effects. The box plot displays larger daily cash withdrawals during the months March, October and December. Cash withdrawals are lower for the months January, February and April as well as on public holidays.
Fig. 1: Daily cash withdrawals. Notes: ATM cash dispense record contains daily cash withdrawals in the time March 21st, 2007-April 17th, 2009

Fig. 2: Day-of-the-week, month-of-the-year and holiday effect

Fig. 3: Day-of-the-month effect

In addition, the box plot reveals variations in daily cash withdrawals over the course of a week. Daily cash withdrawals tend to reach their peak on Thursdays and respective lows on Mondays with only small fluctuations occurring between Saturday and Tuesday. Furthermore, Figure 3 indicates a day-of-the-month effect with relatively more cash being dispensed towards the end of the month.

The findings seem to confirm earlier reports of seasonality and calendar effects with respect to daily demand for cash. Cabrero et al. (2009) identify weekly, monthly and annual seasonal patterns, which resemble a certain regularity in payments and behavior. Similarly, the trading day effect results in an increase in the amount of banknotes in circulation just before the weekend that reverses after the weekend. Likewise, the number of banknotes in circulation decreases before the middle of the month and increases towards the end of the month. The authors further report a strong impact of holidays on the demand for cash.

Brentnall et al. (2008) reach similar conclusions for the occurrence of cash withdrawals for individuals and report a weekly cyclical pattern as well as holiday effects. Although the occurrence rate of cash withdrawals seems to differ largely among individuals, the long-term rate is fairly constant. However, no information regarding the amounts per withdrawal is provided.

In order to forecast demand in cash supply chains, a framework is needed that captures seasonal and calendar effects of the individual time series as well as possible co-variability among the time series. Next, two approaches are contrasted and presented: a seasonal ARIMA model and a vector time series model.

Seasonal ARIMA model: The seasonal Box-Jenkins model considered in this study is generalizing the ARIMA model to time series containing stochastic seasonal periodic components (Box et al., 2008). The multiplicative seasonal ARIMA model is said to be of the type SARIMA (p,d,q)×(P,D,Q)s:

\[ \phi(B)\Phi(B^s)\nabla^d y_t = \theta(B)\Theta(B^s)a_t, \]  

(1)

Where:

- \( \phi(B) = \) The regular autoregressive polynomial of order p
- \( \Phi(B) = \) The seasonal autoregressive polynomial of order P
- \( \theta(B) = \) The regular moving average polynomial of order q
- \( \Theta(B) = \) The seasonal moving average polynomial of order Q

The differentiating operator \( \nabla^d \) and seasonal differentiating operator \( \nabla^s \) eliminate non-seasonal and seasonal non-stationarity. The term \( a_t \) follows a white noise process and s defines the seasonal period.
The joint data generation process may capture additionally variables determined outside the system, such as calendar effects. Respectively, the VAR(p) model with exogenous variables is referred to as VARX(p,q):

\[ Y_t = W_0 + \sum_{i=1}^{p} A_i Y_{t-i} + \sum_{j=1}^{q} B_j X_{t-j} + U_t \]  

(10)

Where:

- \( B_j = (K \times M) \) coefficient matrices
- \( X_t = M \)-dimensional vector of exogenous variables

The order of the VARX model concerning endogenous and exogenous variables is determined by the parameters \( p \) and \( q \).

Next, the steps involved in specifying, estimating and testing of the models outline above are described. Adequate models are identified using the first 731 observations \( t = \{1, \ldots, 731\} \) of each time series. Consequently, the holdout sample covers the last 28 observations of each time series preserving two full years of data for in-sample analysis and model estimation.

Seasonal ARIMA model specification: Specification of the SARIMA \((p.d.q) \times (P.D.Q)s\) model is based on enumerative search following the procedure presented in Wei (2005). The enumerative search in this study considers models of the type \( p \in \{0, 1, 2\}, q \in \{0, 1, 2\}, P \in \{0, 1, 2\}, Q \in \{0, 1, 2\}, d \in \{0, 1, 2\}, D \in \{0, 1, 2\} \) and the seasonal period \( s = 7 \). The order of integration is selected using non-seasonal and seasonal unit root tests (Ghysels and Osborn, 2001). The model choice among the class of adequate models for each time series is based on the 1-step ahead forecasting error using the Mean Absolute Percentage Error (MAPE).

Table 1 depicts the single best performing SARIMA model for each of the 20 ATMs for the in-sample period \( t = \{1, \ldots, 731\} \). All series, except ATM19, are seasonally integrated and require seasonal differencing of order one. In fact, the SARIMA \((0,0,0) \times (0,1,1)s\) model is the single best performing model for 14 out of 20 ATMs. The selected models for the remaining series include additionally non-seasonal differencing of order one and moving average and autoregressive polynomials. The SARIMA \((0,1,1) \times (0,1,1)s\) model, which resembles the well know airline model, is selected for ATM1 and ATM16.

Extensions of the SARIMA model include an intervention function and concern the impact of calendar effects on the demand for cash. Adequate models contain only parameters that are statistically significant (\( p \leq 0.05 \)).
Selection of the best performing model is again based on the MAPE. Exogenous variables for day of the week and month of the year allow to capture calendar effects that result from the change of the relative position from year to year, which otherwise would not be taken into account. Other calendar effects captured by exogenous variables identify public or bank holidays, the day before a public or bank holidays and end of the month.

**Vector time series model specification:** Specification of the vector time series model involves the selection of the VAR order. Obviously, the true order \( p \) of the observed data generation process is unknown. An intuitive choice of the VAR order \( p \) for the given empirical data with a weekly cyclical behavior is \( p = 7 \). The literature suggests a range of criteria to avoid fitting VAR models with unnecessarily large orders (Lütkepohl, 2005). The Hannan-Quinn Information Criterion (HQIC) and the Schwarz-Bayes Information Criterion (SBIC) provide consistent order selection criteria. Both, the HQIC and the SBIC suggest a VAR model of order \( p = 1 \). The Akaike Information Criterion (AIC) and the Final Prediction Error (FPE) criterion minimize the forecast MSE. However, the latter two suggest a VAR model of order \( p = 2 \). Both, AIC and FPE are known to asymptotically overestimate the true order. Hence, VAR models of order \( p = 1 \) are considered for further evaluation. The whiteness of the error terms is confirmed by a portmanteau test and LM test.

VARX models consider in addition the same calendar effects as specified for the SARIMA model with exogenous variables. Coupling effects, such as between the day before a public or bank holiday and the actual holiday are captured using separate calendar effects. Hence, a VARX\((p,q)\) model with order \( q = 0 \) is considered, which reduces to a VAR\((p)\) model with exogenous variables, sometimes referred to as VAR\((p)\) model.

Subject to exogenous variables, three alternative models are considered to gain further insight to the impact of calendar effects on forecasting accuracy. The first model represents a model with all calendar effects. The second model only considers the day-of-the-week and month-of-the-year effects, while the third model is restricted to the day-of-the-week effect.

**RESULTS**

Forecasting accuracy is measured using the mean absolute percentage error depicted in (11). Despite its criticism, the MAPE remains a popular and recommended error measure (Hyndman and Koehler, 2006). In this study, the applicability of the measure is not compromised by scale incompatibilities, negative or close to zero values. Hence, there is no compelling reason to apply alternative measures that aim at addressing potential shortcomings for these specific cases. It is however acknowledged that MAPE puts a heavier penalty on positive forecasting errors than on negative forecasting errors. The sometime suggested Symmetric Mean Percentage Error (SMAPE) has instead a heavier penalty on negative forecasting errors and therefore provides no considerable alternative:

\[
\text{MAPE} = \left( \frac{1}{T} \sum_{t=1}^{T} \left| \frac{Y_t - \hat{Y}_t}{Y_t} \right| \right) \times 100\%
\]  

Forecasting accuracy of the ARIMA model and the vector time series model are compared as well as contrasted with two simple models that were included as benchmark. One is the naive model, which is often considered for this type of comparison. Like a random walk model, it uses the most recent observation as a predictor. The other model, a seasonal naive model, uses the last observation of the same season as predictor. The accuracy of each model is measured and compared for the in-sample \( t = \{1,...,731\} \) and the holdout sample \( t = \{732,...,759\} \). In order to obtain more robust results, the holdout period of 28 days is split further in two periods of 14 days. In addition, the one-step ahead non-cumulative error is compared with the cumulative error for the holdout samples \( t = \{732,...,745\} \) and \( t = \{746,...,759\} \).

Results of the various models and sample periods are summarized in Table 2. Clearly, the vector time series models perform best for the in-sample period and outperform the SARIMA models.
Table 2: Forecasting errors (MAPE)

<table>
<thead>
<tr>
<th>Model</th>
<th>In-sample non-cumulative (%)</th>
<th>Holdout I non-cumulative (%)</th>
<th>Holdout II non-cumulative (%)</th>
<th>Holdout I cumulative (%)</th>
<th>Holdout II cumulative (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SARIMA</td>
<td>41.10</td>
<td>19.06</td>
<td>21.81</td>
<td>2.03</td>
<td>1.59</td>
</tr>
<tr>
<td>SARIMA + Day + Month + Other</td>
<td>30.74</td>
<td>19.23</td>
<td>20.72</td>
<td>4.59</td>
<td>3.92</td>
</tr>
<tr>
<td>VAR(1)</td>
<td>37.65</td>
<td>32.97</td>
<td>31.47</td>
<td>5.75</td>
<td>6.46</td>
</tr>
<tr>
<td>VAR(7)</td>
<td>25.73</td>
<td>20.32</td>
<td>29.77</td>
<td>4.05</td>
<td>5.12</td>
</tr>
<tr>
<td>VAR(1) + Day + Month + Other</td>
<td>26.10</td>
<td>21.65</td>
<td>23.88</td>
<td>7.60</td>
<td>8.63</td>
</tr>
<tr>
<td>VAR(1) + Day + Month</td>
<td>26.77</td>
<td>20.33</td>
<td>24.80</td>
<td>8.39</td>
<td>7.33</td>
</tr>
<tr>
<td>VAR(1) + Day</td>
<td>27.33</td>
<td>20.77</td>
<td>24.94</td>
<td>9.42</td>
<td>5.72</td>
</tr>
<tr>
<td>VAR(7) + Day + Month + Other</td>
<td>23.26</td>
<td>21.57</td>
<td>27.62</td>
<td>4.89</td>
<td>6.55</td>
</tr>
<tr>
<td>VAR(7) + Day + Month</td>
<td>23.90</td>
<td>20.49</td>
<td>28.80</td>
<td>4.31</td>
<td>5.79</td>
</tr>
<tr>
<td>VAR(7) + Day</td>
<td>24.23</td>
<td>20.23</td>
<td>29.10</td>
<td>4.11</td>
<td>4.82</td>
</tr>
<tr>
<td>Naive</td>
<td>50.12</td>
<td>50.94</td>
<td>51.35</td>
<td>1.66</td>
<td>1.83</td>
</tr>
<tr>
<td>Seasonal naive</td>
<td>34.88</td>
<td>18.22</td>
<td>32.51</td>
<td>2.73</td>
<td>5.54</td>
</tr>
</tbody>
</table>

Notes: Results depict the mean absolute percentage error for the network of 20 ATMs and compare the 12 models for time periods \( t = \{1, \ldots, 731\} \) (March 21st, 2007-March 20th, 2009), \( t = \{732, \ldots, 745\} \) (March 21st, 2009-April 3rd, 2009) and \( t = \{746, \ldots, 759\} \) (April 4th, 2009-April 17th, 2009).

Exogenous variables that capture calendar effects further reduce the errors of SARIMA models and vector time series models. Limiting the calendar effects under consideration to the day-of-the-week and month-of-the-year or simply the day-of-the-week results in larger MAPEs. Nevertheless, these models outperform their counterparts without exogenous variables. The VAR(7) model yields a higher accuracy during the in-sample period than the VAR(1) model. This effect diminishes and reverses for the models including exogenous variables during the holdout period.

However, the vector time series model VAR(7) without exogenous variables results in lower MAPEs than VAR(1) suggesting that an over-specified model can reduce forecasting errors.

The result for the non-cumulative holdout sample is not as unambiguous as for the in-sample period. MAPEs for the holdout period are generally lower, but increase during the second half. This indicates that holiday effects present in \( t = \{746, \ldots, 759\} \) are only partially accounted for and may in fact be determined by additional factors such as weather and festivals. In fact, the holiday effect is reversed during the holdout period with more cash being dispensed than on an average day or compared to the in-sample period.

The seasonal naive model outperforms the non-seasonal naive model in the in-sample as well as the holdout period. MAPEs of the seasonal naive model are in line with the SARIMA model and vector time series models suggesting that a large part of the variability in the demand series is attributed to seasonality in form of the day-of-the-week effect.

Moreover, cumulative forecasts result in exceptionally low MAPEs suggesting that most forecasting errors are offset over a period of 14 days. Cumulative 14 days forecasts using the naive method match the performance of the SARIMA model without exogenous variables despite the non-cumulative errors being more than twice as large. Joint forecasting and exogenous variables do not further reduce MAPEs for cumulative forecasts.

**DISCUSSION**

In this study, a framework for investigating the overall forecasting accuracy of cash demand and the potential of joint forecasting in cash supply chains is presented. The approach is motivated by advances in supply chain management. The applied methodology considers the potentially interrelated nature of individual daily cash demand series combined with seasonality and calendar effects. In particular, a vector time series model and a seasonal ARIMA model were compared using naive methods as benchmark.

The vector time series model captures the dynamics and co-variability that characterizes a multi-stage supply chain. From a theoretical perspective, such a model is expected to yield more accurate forecasts, thereby enabling integration of upstream and downstream relationships and improving the efficiency within the cash supply chain. The approach is illustrated for a network of ATMs.

Forecasting accuracy was measured and compared using MAPE. Both, the SARIMA model and the vector time series model resulted in lower MAPEs than the respective benchmark models. Results showed that overall forecasting accuracy is high with a mean absolute percentage error of approximately 20 percent. Particularly, cumulative forecasts for periods of 14 days are very robust with mean percentage errors of approximately two percent. Specification of models revealed strong and consistent seasonal patterns that led to the SARIMA \((0,0,0)\times(0,1,1)_7\) model being the single best performing SARIMA \((p,d,q)\times(P,D,Q)_s\) model. The vector time series model resulted in smaller MAPEs than the SARIMA model during the in-sample period. However, the joint forecasting approach did not yield a higher accuracy.
than the independent forecasting approach for the holdout sample. Exogenous variables capturing calendar effects accounted for part of the variability in daily cash demand series. Results suggest further that other factors such as weather and local events affect the demand for cash and may even dominate calendar effects.

Practical implications of this study concern the ability to forecast currency needs in order to manage cash supply chains more efficiently. More accurate forecasts enable cost savings by reducing excess cash holdings as well as by cutting the number of emergency replenishments needed to prevent cash outs. For example, a EUR 10000 reduction of the average stock held by a bank branch or ATM results in annual cost savings of EUR 400, given the cost of capital is four percent per annum. The potential economic impact is large considering the entire euro area with 190886 commercial bank branches and 249705 ATMs (European Central Bank, 2009) or the MasterCard network with more than 1 million ATMs worldwide (MasterCard, 2009).

CONCLUSION

Results confirm the potential of advanced forecasting techniques for cash supply chains and help explain variability in daily cash demand. Reduced forecasting errors result in lower demand uncertainty and enable supply chain partners to coordinate replenishments across the cash supply chain. However, the potential for information sharing seems to be limited to this role and does not necessarily translate into more accurate forecasts based on joint forecasting.

Limitations of this study arise from the simple two-stage supply chain framework and the relatively small amount of data available. Long-run time series contain more observations of calendar effects such as holidays and may provide further insights. In addition, cumulative forecasts are very robust, since forecasting errors are offset over a period of 14 days. Similar effects may explain, why the joint forecasting model does not yield substantially better forecasts. In fact, anomalies in one series may be passed on to all other series increasing forecasting errors system-wide. However, limitations linked to the applied error measure, the mean absolute percentage error, can be regarded minimal given the nature of the data.

Results of this study provide preliminary evidence and call for further investigation of joint forecasting in a multi-stage supply chain spanning more than two stages. Further research will have to address additional exogenous variables such as weather and festivals that may dominate certain calendar effects. Advanced forecasting models may additionally provide the link to scenarios and risk models in cash supply chain management.

REFERENCES

Analyzing Cost Efficiency Gains from Inventory Routing

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Abstract

Inventory routing problems involve determining the optimal replenishment schedule that integrates inventory management and vehicle routing. This paper presents a stochastic inventory routing model, where the stockout cost is replaced by a minimal service level constraint that requires the probability of stockout in every period to be less than a defined threshold. Moreover, a three-phase heuristic solution strategy and framework to evaluate efficiency gains from combining the two distinct problems is given. The impact of set-dependent cost structures on efficiency gains is demonstrated through cost savings by an interchange procedure that merges inventory and transportation decisions originally determined separately. The computational study illustrates the approach for a network of Automated Teller Machines (ATMs). Cost savings are evaluated through nominal range sensitivity analysis and repeated measure ANOVA using empirical data of an international financial institution. The results show that the interchange procedure yields expected cost savings of approximately 18 percent and imply that cost savings between six to ten percent, as suggested by prior literature, could in practice be too conservative for large-scale stochastic inventory routing problems.

Keywords: Stochastic Inventory Routing, Mixed Integer Programming, Service Level, Sensitivity.

1. Introduction

Inventory routing characterizes a rich class of planning models integrating vehicle routing and inventory management. The approach allows suppliers to coordinate the two components of the logistics value chain by jointly determining replenishment periods, replenishment quantities and delivery routes for a set of retailers. Practical applications are found in a wide range of industries including automotive, food and beverages, healthcare, oil and gas, retail and textile industry.

This study addresses the question of analyzing cost efficiency gains from inventory routing. The research question originated from a project with Giesecke & Devrient, a global supplier of currency processing and automation systems. The company was interested in developing and assessing a model for the integration of inventory management and vehicle routing in cash supply chains (see Rajamani et al., 2006). The aim was to build a tool that minimizes total costs of vehicle routing and inventory management, enables planning as well as scenario analysis. First, the tool should allow decision makers to determine the optimal replenishment schedule, to quantify efficiency gains and to determine the effect size. Second, the tool should enable decision makers to assess the impact of variability in cost parameters. Third, the tool should enable decision makers to assess the impact of stochastic demand, forecasting accuracy and service levels. Fourth, the tool should allow decision makers to make smart design choices with respect to capacity constraints of the replenishment system.
Following the rational outlined above, this paper presents a stochastic inventory model with minimal service level constraints, a three-phase heuristic solution strategy and a framework to evaluate potential efficiency gains from optimization, particularly identifying the effect set-dependent cost-structures. The study takes into consideration forecasting errors and service level constraints in analyzing efficiency gains, the effect of subadditive transaction costs, the role of factor levels and factor interactions. The proposed stochastic inventory routing model is illustrated for a network of ATMs, where banknotes share properties of both, currency and products.

The paper is organized as follows. Section 2 summarizes related problems and research in the literature. Section 3 presents a detailed definition of stochastic inventory routing, assumptions and a mathematical formulation of the problem. Section 4 describes the proposed three-phase heuristic to solve the stochastic inventory routing model including service level constraints. Section 5 presents the computational study, data, design of experiments, and results of nominal range sensitivity analysis and statistical analysis, followed by the discussion and conclusion in Section 6 and 7.

2. Literature Review

Motivated by the wide range of existing and potential applications, there is now a sizeable literature on the topic, which extends the basic idea of inventory routing to account for various assumptions about planning horizons, demands, service levels, vehicle fleets and related working constraints. The reader is directed to Kleywegt, Nori and Savelsbergh (2002), Campbell and Savelsbergh (2004), Moin and Salhi (2007) and Andersson et al. (2010) for topic overview, applications and recent advances in solving inventory routing problems.

Clearly, integrating inventory allocation and vehicle routing enables efficiency gains and cost savings. As such, the potential of inventory routing is readily and intuitively supported by academics and practitioners. However, empirical evidence on the effect size cost trade-offs is limited. Most of the earlier work has focused on the deterministic case and suggests cost reductions between six and ten percent offering limited insight into the impact of factor levels and interaction effects (Bell et al., 1983, Federgruen and Zipkin, 1984, Golden et al., 1984). Gaur and Fisher (2004) present a randomized heuristic for a fixed partition policy with deterministic time varying demand and periodic deliveries for a supermarket chain, where they expect cost savings of up to 20 percent. However, their model is limited to transportation costs and does not account for inventory holding costs. In a more recent study, Raa and Aghezzaf (2009) study explicitly cost trade-offs governing inventory routing problems. The authors adopt a long-term cyclical approach with deterministic constant demand rates to identify three-way cost trade-offs among vehicle fleet size, distribution and inventory costs.

Complications arise from the stochastic nature of demand, which may exceed current inventory in any given period during the planning horizon. Treating point forecasts as deterministic leads to more tractable models compared with the stochastic counterpart, yet implies a rather strong limitation for practical applications of inventory routing. Deviations from expected demand cause stockouts or excess inventories that radically affect inventory and routing decisions, and consequently impact service levels and costs.

In recent years, researchers have increasingly addressed the stochastic nature of demand and modeled the stochastic inventory routing problem as a Markov decision process solved by approximate dynamic programming approaches, where stockouts are captured using penalty costs (Adelman, 2004, Schwartz et al., 2006, Hvattum and Løkketangen, 2009, Hvattum et al., 2009, Kleywegt et al., 2002).
This paper differs from previous studies by formulating the stochastic inventory routing problem as a mixed integer program. The approach rests on mainly two ideas. First, stockouts are not modeled as a cost, but rather as a predefined or required target service level (see Houtum and Zijm, 2000), which is typically specified in contracts among suppliers and retailers. The minimal service level constraint implies that demand is satisfied from current inventory with a required minimum probability. In contrast, a mean service level constraint concerns the average ability to satisfy demand from inventory across all periods (see Chen and Krass, 2001), which is often less of a concern for retailers. Second, the stochastic nature of demand is not captured by a Markov process, but rather by modeling forecasting errors, which are assumed to be independent and to follow a Gaussian distribution. Consequently, forecasting accuracy can be expressed as a constant ratio, where the standard error varies with the level of demand and is a multiple of the expected demand. The approach complements existing ideas to better understand cost trade-offs, in particular with respect to forecasting accuracy and service levels.

3. Detailed Problem Definition

This paper considers the case where the supplier minimizes replenishment and inventory costs given that a specific minimal service level is met in any given period. The stochastic inventory routing model considered in this study describes the problem of determining a replenishment schedule that minimizes inventory holding and replenishment costs in a two-level supply chain with a single supplier and multiple retailers. The problem involves three decisions: (1) determining the replenishment periods, (2) determining the replenishment quantities and (3) delivery routes for a set of retailers.

The model is based on the following assumptions:

(a) The supplier is a central decision maker that determines replenishment periods, replenishment quantities and delivery routes for a set of retailers.
(b) The planning horizon is finite. Replenishments can take place at the beginning of any period and are received instantly without lead time before the demand in that period occurs.
(c) A fixed cost is charged per retailer for every replenishment. A linear holding cost is incurred for end of period inventories that are carried over between periods.
(d) Demand is random (i.e. unknown to the supplier in advance) and may vary by retailer as well as from period to period. Forecasting errors are independent and follow a Gaussian distribution. Forecasting accuracy is given by a constant ratio \( F = \sigma / \mu \), (i.e. the standard error varies with the level of demand and is a multiple of the expected demand).
(e) The probability of demand not exceeding current inventory meets the minimum service level in every period.
(f) Vehicle fleet is homogenous and large enough to handle all replenishments. Routes are only restricted by the number of retailers that can be visited before each vehicle is required to return to the supplier.
(g) Transportation cost are variable and charged based on the total length of all routes.

The following notation is used in formulating the problem:
Sets
\[ N = \{ r | i = 0, 1, ..., N \} \] Set of \( N \) retailers with \( r_0 \) being the supplier’s distribution center
\[ T = \{ \text{day} | t = 1, ..., T \} \] Set of \( T \) periods

Parameters
\[ C_f \]: fixed replenishment cost coefficient
\[ C_r \]: routing cost coefficient
\[ D_{ij} \]: arc weight \((r_i, r_j)\)
\[ I \]: holding cost coefficient
\[ L \]: large number
\[ N \]: number of retailers
\[ T \]: number of periods
\[ P \]: maximum number of ATMs that a vehicle can visit before returning to the depot
\[ F \]: forecasting accuracy
\[ S \]: z-score for given minimal service level
\[ \Psi_{i,t} \]: demand at retailer \( i \) in period \( t \)
\[ \Omega_{i,j,t} \]: demand at retailer \( i \) between periods \( j \) and \( t \) not exceeding the one minus alpha percentile

Decision Variables
\[ \sigma_{i,t} \]: end of period inventory of retailer \( i \) in period \( t \)
\[ u_{i,t}, u_{j,t} \]: arbitrary real numbers
\[ \chi_{i,t} \]: amount of stock supplied to retailer \( i \) in period \( t \)
\[ \omega_{i,j,t} \]: binary indicator of traversing from retailer \( i \) to retailer \( j \) in period \( t \)
\[ \alpha_{i,t} \]: binary indicator for replenishing retailer \( i \) in period \( t \)
\[ \pi_{i,j,t} \]: binary indicator for most recent stock received period to period \( j \) by retailer \( i \) in period \( t \)

The stochastic inventory routing model is given below:

Minimize
\[
E_x \left( \sum_{i \in N} \sum_{t \in T} \left( \sigma_{i,t} + C_f \cdot \sum_{i \in N} \sum_{t \in T} \omega_{i,j,t} + C_r \cdot \sum_{i \in N} \sum_{j \in N} \sum_{t \in T} D_{i,j} \cdot \omega_{i,j,t} \right) \right) \] (1)

Subject to
\[
\sigma_{i,t} + \chi_{i,t} - \Psi_{i,t} = \sigma_{i,t} \quad \forall i \in N; \forall t \in T \] (2)
\[
\sigma_{i,0} = 0 \quad \forall i \in N \] (3)
\[
E_x \left( \sigma_{i,j} \right) \geq 0 \quad \forall i \in N; \forall t \in T \] (4)
\[
\omega_{i,j,t} - \frac{\sigma_{i,t}}{L} \geq 0 \quad \forall i \in N; \forall t \in T \] (5)
\[
\sum_{t \in T} \pi_{i,j,t} = 1 \quad \forall i \in N; \forall j \in T \] (6)
\[
\sum_{j \in T} \left( \Omega_{i,j,t} - \sum_{k \in \{j-1, 0\}} \Psi_{i,k} \right) \cdot \pi_{i,j,t} \leq \sigma_{i,t} \quad \forall i \in N; \forall t \in T \] (7)
\[
\omega_{i,j-t+1} - \sum_{k \in \{j-1, 2t\}} \omega_{i,k} \leq \pi_{i,t,j} \quad \forall i \in N; \forall t \in T; \forall j \in T \] (8)
\[
\sum_{i \in N} \omega_{i,j,t} = \omega_{f,t} \quad \forall t \in T; \forall j \in N - \{0\} \] (9)
\[
\sum_{j \in N, i = j} \omega_{i,j,t} = \omega_{i,t} \quad \forall t \in T; \forall i \in N - \{0\} \tag{10}
\]

\[
u_{i,t} - u_{j,t} + P \cdot \omega_{i,j,t} - P + 1 \leq 0 \quad \forall i, j \in N - \{0\}, i \neq j; \forall t \in T \tag{11}
\]

The objective (1) is to jointly minimize expected holding costs, fixed costs, and routing costs. Constraint (2) is required to balance inventory between periods for each retailer. Constraints (3) and (4) set the starting inventory to zero and ensure non-negativity of the expected end of period inventories for each retailer. Replenishment indicator (5) ensures that no stock is added without incurring fixed replenishment costs. Constraints (7) and (8) ensure that the minimal service level is met. In addition, equation (12) gives the expected demand at retailer \(i\) between two periods for a given forecasting accuracy and minimal service level required. Constraints (9) and (10) ensure that the optimal routes include all retailers that are replenished in a given period. Constraint (11) is the sub-tour elimination constraint and in addition restricts the number of retailer on a single delivery route to \(P\).

\[
\sum_{k \in [t - j + 1], t} \Psi_{i,k} \cdot S \cdot F \cdot \sqrt{\sum_{k \in [t - j + 1], t} (\Psi_{i,k})^2} = \Omega_{i,t,j} \quad \forall i \in N; \forall t \in T; \forall j \in \{1, t\} \tag{12}
\]

4. Solution Strategy

In this study a three-phase heuristic algorithm is developed to solve the stochastic inventory routing model including service level constraints. The first phase determines the replenishment amounts per retailer for each period. The second phase assigns individual replenishments to vehicle routes. The third phase uses an interchange procedure to further improve the replenishment schedule within a rolling time window.

4.1 Method for phase 1

The sub-problem solved in the first phase concerns the optimal replenishment amount \(x_{i,t}\) corresponding to demand forecasts \(\psi_{i,t}\) of retailer \(i\) for each period \(t\). Vehicle routing constraints are eliminated by relaxing the original stochastic model as follows.

Sub-problem 1 (Inventory): 

Minimize 
\[
I \cdot \sum_{i \in N} \sum_{t \in T} \sigma_{i,t} + C_f \cdot \sum_{i \in N} \sum_{t \in T} \omega_{i,t} \tag{13}
\]

Subject to 
Constraints (2),(3),(4),(5),(6),(7) and (8).

Eliminating vehicle routing constraints removes dependencies between individual retailers. Consequently, the inventory problem stated as Sub-problem 1 contains \(N\) independent problems, each corresponding to the stochastic dynamic lot sizing problem with fixed setup costs and linear inventory holding costs that can be separated and solved individually to obtain an optimal solution.
The deterministic counterpart to the stochastic dynamic lot-sizing problem is the well known Wagner-Whitin problem, which has been discussed intensively in the past (see Wagner and Whitin, 1958, Evans, 1985, Federgruen and Tzur, 1991, Wagelmans et al., 1992, Heady and Zhu, 1994). In contrast, the stochastic dynamic lot-sizing problem is less widely studied. Publications date back to a heuristic sequential procedure proposed by Silver (1978) and an alternative formulation by Askin (1981). The more recent stream of literature builds on the “static-dynamic uncertainty” strategy proposed by Bookbinder and Tan (1988). The basic idea is first to determine replenishment periods. Thereafter individual order-up-to levels are specified to account for the randomness of demand since the last replenishment period. Thus, order quantities are based on the difference of the order-up-to level of a given replenishment period and the closing inventory of the previous period.

Tarim and Kingsman (2004) proposed a mixed integer formulation that jointly optimizes replenishment periods and order-up-to levels. The work of Tempelmeier (2007) considers a fill rate (i.e. quota of demand that is regularly satisfied from current inventory) in addition to the minimal service level constraint (i.e. quota of periods where no stout occur). A variant of the problem with non-stationary costs is given by Sox (1997).

Sub-problem 1 is closely related to the mixed integer formulation of Tarim and Kingsman (2004) and resembles the “static-dynamic uncertainty” strategy. It allows the corresponding stochastic dynamic lot-sizing problem to be optimized for a given minimal service level constraints and a target forecasting accuracy.

4.2 Method for phase 2

The sub-problem solved in the second phase determines a transportation plan that implements the replenishment schedule obtained in the first phase. Inventory constraints are eliminated by relaxing the original stochastic model as follows.

**Sub-problem 2 (Transportation):**

\[
\text{Minimize} \quad C_v \cdot \sum_{i \in N} \sum_{j \in N} \sum_{t \in T} D_{i,j} \cdot \omega_{i,j,t}
\]

Subject to Constraints (9), (10) and (11).

Eliminating inventory constraints removes dependencies between periods. Consequently, the transportation problem stated as Sub-problem 2 contains \( T \) independent sub-problems, each corresponding to the multiple traveling salesman problem (mTSP) with a restriction on the maximum number of visits per route. The mTSP is a generalization of the well-known traveling salesman problem (TSP). The objective is to determine a set of routes that each start at and return to the depot, and visit all selected retailers exactly once per period, while minimizing the total distance of all routes. The reader is referred to Bektas (2006) for a recent review of mTSP formulations, variants, and exact as well as heuristic solutions strategies. An alternative approach is to transform the mTSP to a standard TSP, which allows the use of a wide range of solution methodologies and special purpose software (see Lodi and Punnen, 2002, Applegate et al., 2006).

The mixed integer formulation presented in Sub-problem 2 is a variant of the asymmetric mTSP. It resembles a vehicle routing problem, where the capacity restriction is eliminated or sufficiently large and a constraint on the number of visits per route imposed.
4.3 Method for phase 3

After determining replenishment amounts and vehicle routes an interchange procedure is applied to merge inventory and transportation decisions. The idea is to combine individual replenishments that are assigned initially to different periods in order to further reduce overall costs. Cost savings result from fewer replenishments and reduced total distance of all routes at the expense of increased inventory holding costs. Herer and Levy (1997) refer to the change in overall costs from combing two routes across periods as gain function. The basic idea of the interchange procedure is adopted and modified to merge individual replenishments to a common period. The gain function is maximized within a rolling horizon, since periods that are more distant have limited influence and are less likely to result in positive gains. The rolling horizon is shifted by one period from the end of planning horizon to the beginning in order to account for the finite number of periods. The algorithm can be described as follows:

1. Initialize solutions from Sub-problem 1 and Sub-problem 2
2. Set \( t \) equal zero
3. Fix all decision variables
4. Unfix decision variables in periods \( \{ T-p-t+1 ; T-t \} \)
5. Maximize the gain function
6. Join replenishments that yield the largest positive gain
7. Increment \( t \) by one period
8. Repeat Steps 3 to 7 until \( t \) equals \( T \)

5. Computational Study

The model and solution strategy are evaluated for a network of ATMs, where the cash in transit (CIT) company is the central decision maker coordinating cash replenishments and vehicle routing. The application provides a new and potentially fruitful area for stochastic inventory routing.

5.1 Data

The case study is based on data obtained from an international financial institution covering a period of 200 days. The firm agreed to provide detailed cash dispense records for 107 ATMs in a particular region, comprising locations such as shopping malls, hotels, hospitals and airports (see Fig.1). The exact locations of all 107 ATMs and the central vault were provided, which allowed the distance matrix to be derived.

![Fig.1. The network has 107 ATMs covering a region of approximately 625km².](image)
5.2 Design of Experiments

In evaluating potential efficiency gains of the stochastic inventory routing model and the effect of set-dependent cost structures the following eight factors were identified: fixed replenishment costs, holding costs, routing costs, demand, forecasting accuracy, length of the rolling horizon, minimal service level, maximum number of customers on a route before the vehicle is required to return to the supplier. The first three factors are cost parameters. The factor demand is modeled as a multiplier that scales demand linearly. Forecasting accuracy is captured by a constant ratio $F = \frac{\sigma_i}{\mu_i}$. The remaining three factors are essentially design choices.

Factor levels resemble the conditions faced by the financial institution including upper and lower bounds. With eight factors, there are 28 two-way factorial designs, where each of the respective two factors is assumed to take one of three possible levels with all other factors remaining at Level II. The full two-way factorial design contains 129 unique trials which is replicated 26 times using simulation. Each replication covers 200 days and is based on the discrete probability distribution of cash withdrawals observed for each ATM. Hence, the computational complexity is 129 trials $\times$ 26 replications requiring $200 \times 10^7 \times 26$ daily cash withdrawals. The factorial design and respective factor levels are presented in Table 1.

Table 1. Factorial Design

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level I</th>
<th>Level II</th>
<th>Level III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Replenishment Cost Coefficient</td>
<td>10</td>
<td>30</td>
<td>90</td>
</tr>
<tr>
<td>Holding Cost Coefficient</td>
<td>0.00008</td>
<td>0.00016</td>
<td>0.00032</td>
</tr>
<tr>
<td>Routing Cost Coefficient</td>
<td>0.25</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Demand Multiplier</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Forecasting Accuracy</td>
<td>1/10</td>
<td>1/3</td>
<td>1/2</td>
</tr>
<tr>
<td>Rolling Horizon</td>
<td>3</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Minimal Service Level</td>
<td>0.90</td>
<td>0.95</td>
<td>0.99</td>
</tr>
<tr>
<td>Vehicle Capacity</td>
<td>4</td>
<td>8</td>
<td>14</td>
</tr>
</tbody>
</table>

5.3 Tests and Results

This section presents the results of the computational study. The effect of set-dependent cost structures is captured through cost savings by the proposed interchange procedure that merges inventory and transportation decisions originally determined separately. Particularly, the impact of individual factors on relative cost savings is analyzed. First the nominal range sensitivity analysis is given followed by the statistical analysis of individual factors and factor interactions effects.

5.3.1 Nominal Range Sensitivity Analysis

The nominal range sensitivity analysis of the eight main factors shows relative cost savings of each factor covering the variability range from Level I (0%) to Level III (100%). The variability range is extended for the length of the rolling horizon to obtain a more detailed picture. Relative cost savings are computed by varying one factor at a time with the remaining factors being set to Level II. In particular, analyzing the nominal range of each factor revealed differences in the impact of individual factor levels on relative cost savings (see Fig. 2, Fig. 3, and Fig. 4).
Fig. 2. Nominal range sensitivity analysis of cost factors.

Fig. 3. Nominal range sensitivity analysis of non-cost factors.

Fig. 4. Nominal range sensitivity analysis of the length of the rolling horizon in days
The factors holding costs, forecasting accuracy, service level, and demand did not indicate trends or higher order powers contrary to the factors fixed replenishment costs, routing costs, vehicle capacity, and length of the rolling horizon. The importance measure depicted in Table 2 and defined as the difference of cost savings within the variability range, indicated that the factor routing costs (36.19% - 4.03% = 32.16%) has the largest impact on cost savings, followed by the factor fixed replenishment costs (31.74% - 2.76% = 28.98%). Conversely, the importance measure suggested only very limited impact on relative cost savings for the factor forecasting accuracy (19.07% - 14.59% = 4.48%) as well as for the factor minimal service level costs (19.14% - 14.20% = 4.94%).

Table 2. Importance Measures

<table>
<thead>
<tr>
<th>Factor</th>
<th>MIN</th>
<th>MAX</th>
<th>Range</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Costs</td>
<td>0.02761</td>
<td>0.31742</td>
<td>0.28981</td>
<td>2</td>
</tr>
<tr>
<td>Holding Costs</td>
<td>0.15077</td>
<td>0.22632</td>
<td>0.07555</td>
<td>5</td>
</tr>
<tr>
<td>Routing Costs</td>
<td>0.04026</td>
<td>0.36186</td>
<td>0.32160</td>
<td>1</td>
</tr>
<tr>
<td>Forecast Accuracy</td>
<td>0.14589</td>
<td>0.19070</td>
<td>0.04481</td>
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<td>Service Level</td>
<td>0.14202</td>
<td>0.19143</td>
<td>0.04941</td>
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<tr>
<td>Vehicle Capacity</td>
<td>0.08265</td>
<td>0.19052</td>
<td>0.10787</td>
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</tr>
<tr>
<td>Demand</td>
<td>0.16165</td>
<td>0.22345</td>
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<tr>
<td>Horizon a</td>
<td>0.00000</td>
<td>0.20990</td>
<td>0.20989</td>
<td>3</td>
</tr>
</tbody>
</table>

*Extended variability range of the length of rolling horizon (1 day to 11 days).

Note: The importance measure for the factor length of rolling horizon covering the variability range Level I (3 days) to Level III (7 days) is 20.99% - 6.28% = 14.71%.

5.3.2 Main Effects

One-way repeated measure ANOVA was performed to test the significance of factor levels for each of the eight main factors: fixed replenishment costs, holding costs, routing costs, forecasting accuracy, minimal service level, maximum number of customers on a route before the vehicle is required to return to the supplier, demand, and length of the rolling horizon.

Normality of sampling distribution was met given the sample size for each factor level (n=26) and 50 df for the error term. No outliers (|z|>3.3) were detected. The assumption of homogeneity of variance was met, with the number of observations for each level being equal. The Huynh-Feldt adjustment corrected for the lack of sphericity detected by Mauchly’s test of sphericity (p<0.05) in three cases: forecasting accuracy, vehicle capacity (i.e maximum number of customers on a route before the vehicle is required to return to the supplier), and length of the rolling horizon.

Mean values of efficiency gains for each factor level are tabulated together with standard errors and 95% confidence levels in Table 3. Results for one-way repeated measure ANOVA are presented in Table 4. Statistically significant effects included all main factors, except forecasting accuracy F(1,42,37.11) = 0.36, p = 0.263, and minimal service level F(2,50) = 0.12, p = 0.88. Pairwise comparison showed no statistical significant change in efficiency gains with respect to forecasting accuracy levels (Level I versus Level II: p = 0.59; Level I versus Level III: p = 0.81; Level II versus Level III: p = 0.99) and with respect to minimal service levels (Level I versus Level II: p = 0.99; Level I versus Level III: p = 0.99; Level II versus Level III: p = 0.99).
### Table 3. Descriptive Statistics of Cost Savings

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level</th>
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<th>SE</th>
<th>95% LCL</th>
<th>95% UCL</th>
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<tbody>
<tr>
<td>Fixed Costs</td>
<td>I</td>
<td>0.33288</td>
<td>0.00546</td>
<td>0.32164</td>
<td>0.34412</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>0.18749</td>
<td>0.00657</td>
<td>0.17396</td>
<td>0.20103</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>0.02942</td>
<td>0.00192</td>
<td>0.02546</td>
<td>0.03338</td>
</tr>
<tr>
<td>Holding Costs</td>
<td>I</td>
<td>0.12429</td>
<td>0.00771</td>
<td>0.10841</td>
<td>0.14016</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>0.18749</td>
<td>0.00657</td>
<td>0.17396</td>
<td>0.20103</td>
</tr>
<tr>
<td></td>
<td>III</td>
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<td>0.00405</td>
<td>0.16327</td>
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<tr>
<td>Routing Costs</td>
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<td>0.04591</td>
<td>0.00195</td>
<td>0.04189</td>
<td>0.04993</td>
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<tr>
<td></td>
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<td>0.17307</td>
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</tr>
<tr>
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<td>III</td>
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<td>0.00830</td>
<td>0.35718</td>
<td>0.39135</td>
</tr>
<tr>
<td>Forecast Accuracy</td>
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<td>0.01098</td>
<td>0.14658</td>
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<td>0.17499</td>
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<tr>
<td>Service Level</td>
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<tr>
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<td>III</td>
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<td>0.00577</td>
<td>0.18759</td>
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</tr>
<tr>
<td>Demand</td>
<td>I</td>
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<td>0.00708</td>
<td>0.11760</td>
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<tr>
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<td>0.00554</td>
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<td>0.22181</td>
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</table>

### Table 4. One-Way Repeated Measure ANOVA

<table>
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<th>Factor</th>
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<th>DF</th>
<th>MS</th>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Fixed Costs</td>
<td>2.61968</td>
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<td>2.61968</td>
<td>3627.55668**</td>
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<tr>
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<td>2.02519</td>
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<td>2.02519</td>
<td>1484.89849**</td>
<td>0.98344</td>
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<tr>
<td>Routing Costs</td>
<td>3.19145</td>
<td>1.00000</td>
<td>3.19145</td>
<td>1701.41403**</td>
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</tr>
<tr>
<td>Forecast Accuracy</td>
<td>2.50541</td>
<td>1.00000</td>
<td>2.50541</td>
<td>988.26144**</td>
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<tr>
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<td>2.75778</td>
<td>1276.55032**</td>
<td>0.98079</td>
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<td>Vehicle Capacity</td>
<td>2.14283</td>
<td>1.00000</td>
<td>2.14283</td>
<td>1250.94713**</td>
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<tr>
<td>Demand</td>
<td>2.09260</td>
<td>1.00000</td>
<td>2.09260</td>
<td>1599.20686**</td>
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<tr>
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<tr>
<td><strong>Within-Subject Effects</strong></td>
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<td></td>
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</tr>
<tr>
<td>Fixed Costs</td>
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<tr>
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<tr>
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<td>0.98013</td>
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<td>Forecast Accuracy</td>
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<tr>
<td>Demand</td>
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<td>0.02079</td>
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<tr>
<td>Horizon</td>
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<td>1.59156a</td>
<td>0.16842</td>
<td>385.03798**</td>
<td>0.93903</td>
</tr>
</tbody>
</table>

This table shows F-test and effect size for all eight main factors. * Degrees of freedom are Huynh-Feldt adjusted for the averaged tests of significance. **p<0.01.
Increase in cost savings as a function of an increasing fixed cost coefficient was statistically significant, $F(2, 50) = 942.53, p<0.01, \eta^2_p = 0.97$. Similarly, an increase in the routing cost coefficient $F(2, 50) = 1233.44, p<0.01, \eta^2_p = 0.98$, vehicle capacity $F(1.35; 33.85) = 166.89, p<0.01, \eta^2_p = 0.87$, and rolling horizon $F(1.59; 33.79) = 385.04, p<0.01, \eta^2_p = 0.94$ were statistically significant. All four suggest a strong impact on cost savings. Although an increase in the holding cost coefficient $F(2, 50) = 32.49.20, p<0.01, \eta^2_p = 0.57$, and an increase in the demand multiplier $F(2, 50) = 26.61, p<0.01, \eta^2_p = 0.52$, were statistically significant, the effect sizes of the two factors were substantially smaller. Additionally, the Tukey HSD test for pairwise post-hoc comparison of level means of these six factors were statistically significant ($p<0.01$) except the factor holding costs (Level II versus Level III: $p = 0.13$), vehicle capacity (Level II versus Level III: $p = 0.20$), and demand (Level II versus Level III: $p = 0.25$), where the pairwise comparison of Level II and Level III were not statistically significant.

5.3.3 Interaction Effects

Two-way repeated measure ANOVA was performed to test the significance of the levels of interaction between the eight main factors: fixed replenishment costs, holding costs, routing costs, forecasting accuracy, minimal service level, maximum number of customers on a route before the vehicle is required to return to the supplier, demand, and length of the rolling horizon.

The assumptions of normality of sampling distributions and the assumption of homogeneity of variance were met, as with one-way repeated measure ANOVA. Likewise, degrees of freedom for the averaged tests of significance were Huynh-Feldt adjusted to account for the lack of sphericity indicated by Mauchly’s test of sphericity ($p<0.05$) in 16 out of 28 cases. Results and Huynh-Feldt adjustments are shown in Table 5.

Two factor interactions, including fixed replenishment costs and forecasting accuracy, $F(1.96, 49.08) = 0.70, p = 0.50, \eta^2_p = 0.03$, routing costs and minimal service level, $F(4, 100) = 0.22, p = 0.93, \eta^2_p = 0.01$, forecasting accuracy and vehicle capacity, $F(4, 100) = 0.97, p = 0.43, \eta^2_p = 0.04$, and minimal service level and demand, $F(2.65, 49.08) = 1.78, p = 0.17, \eta^2_p = 0.07$, were statistically not significant. For these four two factor interactions no linear or quadratic trend can be inferred. The interaction between forecasting accuracy and minimal service level, $F(4, 100) = 2.56, p = 0.07, \eta^2_p = 0.08$, as well as between demand and minimal service level, $F(4, 100) = 2.03, p = 0.09, \eta^2_p = 0.08$, were only significant under the condition $p<.10$.

All other two factor interactions were statistically significant ($p<0.01$) showing linear and quadratic trends. Interpretation, therefore, is focused on the differences in effect size. The effect size was largest for the interaction of the factors fixed replenishment costs and routing costs, $F(3, 75) = 459.60 p<0.01, \eta^2_p = 0.95$, routing costs and length of the rolling horizon, $F(3, 75) = 459.60 p<0.01, \eta^2_p = 0.95$, routing costs and vehicle capacity, $F(3.11, 78.32) = 170.79 p<0.01, \eta^2_p = 0.87$, fixed replenishment costs and length of the rolling horizon, $F(2.83, 70.90) = 117.25 p<0.01, \eta^2_p = 0.82$, and fixed replenishment costs and holding costs, $F(4, 100) = 114.01 p<0.01, \eta^2_p = 0.82$. Other two factor interactions were statistically significant, yet effect sizes were smaller.
6. Concluding Remarks

In this study, a methodology is presented for investigating the drivers of efficiency gains in stochastic inventory routing. A two-stage supply chain was considered, where a single supplier takes the responsibility of managing inventory levels for a set of retailers and has access to the demand and inventory information. The set-dependent cost structures originated from jointly determining replenishment periods, replenishment quantities and delivery routes for the set of retailers. Efficiency gains are demonstrated through cost savings by an interchange procedure that merges inventory and transportation decisions originally determined separately.

In particular, a novel formulation of a stochastic inventory routing model is presented that accounts for stochastic demand, forecasting accuracy, rolling planning horizon, minimal service level requirements, as well as capacity constraints regarding the maximum number of customers on a single delivery route. The model allows making realistic assumptions regarding the operative environment, particularly accounting for practical aspects such as service levels and forecasting accuracy.
The stochastic inventory routing model was illustrated for a network of ATMs using empirical data of an international financial institution. In both, the nominal range sensitivity analysis and the statistical analysis, the described solution strategy resulted in considerable lower total costs. The computational study showed that the interchange procedure yields expected cost saving of approximately 18 percent. Analyzing the drivers of efficiency gains, six of the proposed eight factors were statistically significant. Interesting and somewhat surprising is that no linear or quadratic trend was observed for the factors minimal service level and forecasting accuracy. Effect size was largest for fixed replenishment costs, routing costs, and length of the rolling horizon. Larger fixed replenishment cost coefficients reduced cost savings, while larger routing cost coefficients increased cost savings. Not surprising is that longer rolling horizons result in increased cost savings. However, the computational study also showed that that incremental cost savings diminish at a given point. The relevant range for managing a network of ATMs is three to seven days. A rolling horizon of more than seven days did not result in additional cost saving. Similarly, expanding vehicle capacity resulted in increased cost savings, yet capacity expansion to more than eight customers on a single replenishment route did not yield additional cost savings. Further, an important result is that the effect size of holding costs and demand was substantially smaller indicating no clear trend or higher order powers, despite differences in cost savings being statistically significant.

This study contributes towards a better understanding of the determinants of cost efficiency gains from combining inventory management and vehicle routing. Previous research readily supports the benefits from inventory routing without providing a detailed investigation of the magnitude and the drivers of efficiency gains. In particular, supply chain coordination through information sharing is widely seen as a key source of efficiency gains. However, a more detailed investigation shows that forecasting accuracy is not a key driver, suggesting that benefits are related to the decision model rather than information sharing.

Practical implications of this study concern the feasibility of inventory routing for two-stage supply chains. Results show that set-dependent cost structures yield substantial cost savings from coordinating multiple replenishments. However, the computational study also demonstrates that cost savings vary substantially. In the case of a network of 107 ATMs cost savings vary between 9% and 23% depending on fixed replenishment costs, routing costs, and length of the rolling horizon. Nonetheless, cost savings between six and ten percent, as suggested by the earlier literature, could in practice be too conservative for large-scale stochastic inventory routing problems.

Research can be extended in several directions. The proposed model, despite several desirable properties, remains a sub-system of the overall supply chain and may be extended to include multiple products and stages. In addition, the size of the region, geographical dispersion and number of retailers may be studied in more detail. Moreover solution methodologies need to be developed to further reduce computational complexity of large-scale optimization problems.
References


