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Contents

Foreword

In February 2002, the Industrial and Systems Engineering (ISE) Department at the University of Florida hosted a *National Science Foundation Workshop on Collaboration and Negotiation in Supply Chain Management and E-Commerce.* This workshop focused on characterizing the challenges facing leading-edge firms in supply chain management and electronic commerce, and identifying research opportunities for developing new technological and decision support capabilities sought by industry. The audience included practitioners in the areas of supply chain management and E-Commerce, as well as academic researchers working in these areas. The workshop provided a unique setting that has facilitated ongoing dialog between academic researchers and industry practitioners.

This book codifies many of the important themes and issues around which the workshop discussions centered. The editors of this book, all faculty members in the ISE Department at the University of Florida, also served as the workshop's coordinators. In addition to workshop participants, we also invited contributions from leading academics and practitioners who were not able to attend. As a result, the chapters herein represent a collection of research contributions, monographs, and case studies from a variety of disciplines and viewpoints. On the academic side alone, chapter authors include faculty members in supply chain and operations management, marketing, industrial engineering, economics, computer science, civil and environmental engineering, and building construction departments. Thus, throughout the book we see a range of perspectives on supply chain management and electronic commerce, both of which often mean different things to different disciplines. The subjects of the chapters range from operations research based models of supply chain planning problems to statements and perspectives on research and practice in the field. Three main themes serve to divide the book into three separate parts.

Part I of the book contains six chapters broadly focused on operations and logistics planning issues and problems. The first chapter, *Coordi-*

nation of Inventory and Shipment Consolidation Decisions: A Review of Premises, Models, and Justification, by Sıla Çentinkaya, provides a detailed and insightful look into the interaction between outbound logistics consolidation policies and inventory costs. This work focuses on providing both insights and guidance on effective policies for coordinating inventory and logistics decisions. Yalçin Akçay and Susan Xu study the component allocation problem in an assemble-to-order manufacturing environment in Chapter 2, *A Near-Optimal Order-Based Inventory Allocation Rule in an Assemble-to-Order System and its Applications to Resource Allocation Problems.* The problem is modeled as a multidimensional knapsack problem, and they develop an efficient heuristic for finding high-quality solutions to this problem. Their results provide insights on how to effectively manage assemble-to-order systems.

In Chapter 3, *Improving Supply Chain Performance through Buyer Collaboration*, Paul M. Griffin, Pınar Keskinocak, and Seçil Savaşaneril take a look at how different buyers can leverage collective purchase volumes to reduce procurement costs through collaboration. In addition to discussing recent trends in electronic markets and systems for procurement, the authors provide some very interesting results on the value of collaboration in procurement, both internally (across different divisions in the same organization) and externally (among different firms). In Chapter 4 *The Impact of New Supply Chain Management Practices on the Decision Tools Required by the Trucking Industry*, Jacques Roy provides an overview of the recent advances in supply chain management and information technologies, and discusses how the emerging information technologies can be used to support decision making to improve the efficiency of the freight transportation industry.

Chapter 5, *Managing the Supply-Side Risks in Supply Chains: Taxonomies, Processes, and Examples of Decision-Making Modeling*, by Amy Zeng, Paul Berger, and Arthur Gerstenfeld, analyzes the risks associated with suppliers and the supply market from a quantitative point of view. Two optimization-based decision tree models are proposed in order to answer questions of how many suppliers should be used and whether to use standby suppliers. In Chapter 6, *Demand Propagation in ERP Integrated Assembly Supply Chains: Theoretical Models and Empirical Results*, David Wu and Mary Meixell study supply chain demand propagation in an ERP-integrated manufacturing environment. They examine key factors that influence demand variance in the assembly supply chain, assess their effects, and develop insight into the underlying supply process.

Part II contains four chapters on electronic markets and E-Commerce technologies and their role in facilitating supply chain coordination.

Chapter 7, *Bridging the Trust Gap in Electronic Markets: A Strategic Framework for Empirical Study*, by Gary Bolton, Elena Katok, and Axel Ockenfels, describes a strategic framework for evaluating automated *reputation systems* for electronic markets, and provides suggestions on how to improve automated reputation system performance. In Chapter 8 *Strategies and Challenges of Internet Grocery Retailing Logistics*, Tom Hays, Pınar Keskinocak, and Virginia Malcome de López provide a detailed and thorough look at the practice of the Internet grocery retailing, focusing on alternative business models, order fulfillment and delivery methods. They offer a discussion of the lessons learned from failure and success stories of e-grocers, a summary of current trends, and future opportunities and directions.

Chapter 9, entitled *Enabling Supply-Chain Coordination: Leveraging Legacy Sources for Rich Decision Support*, by Joachim Hammer and William O'Brien, describes how firms with different legacy systems can use new technologies to not only reduce the cost of establishing inter-system communication and information sharing, but also to provide coordinated decision support in supply chains. The focus on information technologies for supporting effective supply chain management continues in Chapter 10, *Collaboration Technologies for Supporting E-supply Chain Management* (by Stanley Su, Herman Lam, Rakesh Lodha, Sherman Bai, and Max Shen). This chapter describes an e-supply chain management information infrastructure model to manage and respond to important supply chain "events" and to automate negotiation between channel members.

Part III provides a link between research and practice, beginning with three chapters that provide different frameworks, viewpoints, and paradigms on research and practice perspectives on supply chain management. The last two chapters illustrate industrial examples of effective application of supply chain management research in practice.

In Chapter 11, *The State of Practice in Supply-Chain Management: A Research Perspective*, Leroy Schwarz develops a new paradigm for managing supply chains, providing insight into the evolution of supply chain practice to date. From this perspective, he describes examples of current state-of-the-art practice in supply chain management, and forecasts future practice. In Chapter 12 *Myths and Reality of Supply Chain Management: Implications for Industry-University Relationships*, André Kuper and Sarbani Bublu Thakur-Weigold from Hewlett-Packard (HP) first present some recent trends that challenge companies in the area of supply chain management and then discuss how academic research might respond to these challenges. Drawing upon HPs successful collaboration with academic institutions in the area of supply chain management, they outline a number of factors for effective interaction between industry and academia. Chapter 13, *Supply Chain Management: Interlinking Multiple Research Streams*, by James Hershauer, Kenneth Walsh, and Iris Tommelein, provides a view of the evolution of the supply chain literature that emphasizes the influence of industry, and also takes a broad view beyond a traditional operations focus.

Chapter 14, *PROFIT: Decision Technology for Supply Chain Management at IBM Microelectronics Division*, by Ken Fordyce and Gary Sullivan, provides a case history of the ongoing evolution of a major supply chain management effort in support of IBM's Technology Group. They also characterize the scope and scale of such an application, identify potential opportunities for improvement and set these within a logical evolutionary pattern, and identify research opportunities to develop new decision support capabilities. Staying with the theme of actual case studies, Young Lee and Jack Chen, in Chapter 15, *Case Studies: Supply Chain Optimization Models in a Chemical Company*, give an overview of the supply chain models that have recently been used in a large international chemical company. They describe three supply chain optimization models in detail, and discuss the lessons learned from these studies regarding issues that are especially relevant to the chemical industry.

As the foregoing descriptions indicate, the chapters in this book address a broad range of supply chain management and electronic commerce issues. The common underlying theme throughout involves the application of research to real industry contexts. The chapters are self-contained and all chapters in this book went through a thorough review process by anonymous referees. We would like to thank the chapter authors for their contributions, along with the referees, for their help in providing valuable suggestions for improvement. We would also like to thank the National Science Foundation for supporting the workshop that provided the impetus for this work (NSF Grant #DMI-0131527).

JOSEPH GEUNES, ELIF AKÇALI, PANOS PARDALOS, EDWIN ROMEIJN, AND MAX SHEN

I

SUPPLY CHAIN OPERATIONS

Chapter 1

COORDINATION OF INVENTORY AND SHIPMENT CONSOLIDATION DECISIONS: A REVIEW OF PREMISES, MODELS, AND JUSTIFICATION

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Abstract This chapter takes into account the latest industrial trends in integrated logistical management and focuses on recent supply-chain initiatives that enable the integration of inventory and transportation decisions. The specific initiatives of interest include Vendor Managed Inventory (VMI), Third Party Warehousing/Distribution (3PW/D), and Time Definite Delivery (TDD) applications. Under these initiatives, substantial savings can be realized by carefully incorporating an *outbound* shipment strategy with inventory replenishment decisions. The impact is particularly tangible when the shipment strategy calls for a *consolidation* program where several smaller deliveries are dispatched as a single combined load, thereby realizing the scale economies inherent in transportation. Recognizing a need for analytical research in the field, this chapter concentrates on two central areas in shipment consolidation: i) analysis of pure consolidation policies where a shipment consolidation program is implemented on its own without coordination, and ii) analysis of integrated policies where outbound consolidation and inventory control decisions are coordinated under recent supply-chain initiatives. The chapter presents a research agenda, as well as a review of the related literature, in these two areas. Some of the recent findings of the methodological research are summarized, and current and future research endeavors are discussed. By offering a theoretical framework for modeling recent supply-chain initiatives, the chapter highlights some of the many challenging practical problems in this emerging field.

1. Introduction

1.1 Background and Terminology

This chapter concentrates on the cost saving opportunities available in *outbound* transportation. These savings are easily realizable when outbound dispatch decisions include a strategy for *shipment consolidation*, the policy under which several small loads are dispatched as a single, larger, and more economical load on the same vehicle (Brennan (1981); Hall (1987); Higginson and Bookbinder (1995)). Development of a shipment consolidation program requires strategic and operational decision-making that involves the location of consolidation terminals, development of feasible delivery routes, vehicle allocations, etc. Once higher level decisions are made, the next step is to choose an operating routine, e.g., a consolidation policy for day-to-day problems. The focus of the chapter is on analytical models for such operational decisions.

Shipment consolidation may be implemented on its own without coordination. Such a practice is called a *pure* consolidation policy. Alternatively, in choosing an operating routine, it may be useful to consider the impact of shipment consolidation on other operational decisions, such as inventory decisions. Hence, another approach is to coordinate/integrate shipment consolidation with inventory decisions. This practice is called an *integrated* inventory/shipment consolidation policy. Research on pure consolidation policies provides a foundation for the analysis of integrated models. This chapter presents a review of both of these practices, and it introduces some future research avenues in the area.

i) Pure Consolidation Policies The "operating routine" for a pure consolidation policy specifies a selected dispatching rule to be employed each time an order is received (Abdelwahab and Sargious (1990)). The relevant criteria for selecting an operating routine include customer satisfaction as well as cost minimization. Some operational issues in managing pure consolidation systems are similar to those encountered in inventory control. Two fundamental questions that must be answered are i) when to dispatch a vehicle so that service requirements are met, and ii) how large the dispatch quantity should be so that scale economies are realized. It is worth noting that these two questions relate to consolidation across time since a consolidated load accumulates by holding shipments over one or more periods. This practice is also known as temporal consolidation.

The literature on pure consolidation policies is abundant. Recent research in the area concentrates on the development of analytical models as an aid to obtaining "suitable" operating routines for temporal consolidation practices (Bookbinder and Higginson (2002); Çetinkaya and Bookbinder (2002)). However, several challenging stochastic problems remain unresolved. There is a need for additional research on identifying the structural properties of optimal pure consolidation routines and analyzing the impact of these routines on total system cost and on the timely delivery requirements of the customers.

ii) Integrated Inventory/Shipment Consolidation Policies Interest in supply-chain management arises from the recognition that an integrated plan for the chain as a whole requires coordinated decisions between different functional specialties (e.g., procurement, manufacturing, marketing, distribution). In recent years, increased emphasis has been placed on coordination issues in supply-chain research (Arntzen, Brown, Harrison, and Trafton (1995); Blumenfeld, Burns, Daganzo, Frick, and Hall (1987); Boyaci and Gallego (2002); Davis (1993); Lee and Billington (1992); Lee, Padmanabban, and Whang (1997); Stevens (1989); Tayur, Ganeshan, and Magazine (1999)). In keeping with this trend, this chapter discusses a new class of coordination problems applicable in a variety of supply-chain initiatives relying on the integration of inventory and outbound transportation decisions. Examples of these initiatives include Vendor Managed Inventory (VMI), Third Party Warehousing/Distribution (3PW/D), and Time Definite Delivery (TDD) agreements.

Revolutionized by Wal-Mart, VMI is an important coordination initiative in supply-chain management (Aviv and Federgruen (1998); Bourland, Powell, and Pyke (1996); Çetinkaya, Tekin, and Lee (2000); Kleywegt, Nori, and Savelsberg (1998); Schenck and McInerney (1998); Stalk, Evans, and Shulman (1992)). In VMI, the supplier is empowered to manage inventories of agreed-upon items at retailer locations. As a result, VMI offers ample opportunity for synchronizing outbound transportation (in particular, shipment consolidation) and inventory decisions. Similarly, 3PW/D and TDD agreements are contract based arrangements engaged in for the purpose of load optimization as well as timely delivery. The main goal of these initiatives is to design an effective distribution system.

Realization of the opportunities offered by VMI, 3PW/D, and TDD agreements, however, requires balancing the tradeoff between timely delivery and economizing on dispatch size and inventory holding costs. The integrated models discussed herein investigate these tradeoffs, and, hence, they are useful for justifying and analyzing the impact of VMI, 3PW/D, and TDD arrangements. This research has been identified through a partnership with computer and semiconductor industry members in Texas. It concentrates on identifying the properties of integrated policies and analyzing the impact of integration on cost and delivery requirements (Çetinkaya and Lee (2000); Çetinkaya and Lee (2002); Çetinkaya, Mutlu, and Lee (2002); Çetinkaya, Tekin, and Lee (2000)).

1.2 Overview

The remainder of this chapter is organized as follows. Sections 2 and 3 explain the premises and challenges of coordinating inventory and shipment consolidation decisions. While the majority of the chapter focuses on stochastic models, Section 4 provides a review of previous literature on both deterministic and stochastic models and relates it to current research endeavors in the area. Section 5 illustrates the models and methodology for some specific problems of interest. In particular, Section 5.1 concentrates on pure consolidation policies whereas Section 5.2 discusses integrated policies. The development and analysis in these sections rely on renewal theory. However, more general problems requiring the implementation of other methodologies, such as dynamic programming and stochastic programming, are also mentioned. Section 5.2 provides an introduction to the integrated models. Again, although the focus is on stochastic models, Section 5.3 presents an integrated model for the case of deterministic stationary demand. Section 5.4 focuses on integrated stochastic policies of practical interest and emphasizes the need for research on computing exact optimal policies and other extensions. Finally, Section 6 concludes the chapter.

2. Premises and Motivation

In the last few years, several competitive firms have focused on effective supply-chain practices via the new initiatives of interest in this chapter. Applied Materials, Hewlett-Packard, Compaq, and General Motors are a few examples, along with the pioneers of successful VMI practice, Wal-Mart and Procter and Gamble. As a result, the theory of coordinated inventory and transportation decisions has enjoyed a renewed interest in practical applications and academia (Bramel and Simchi-Levi (1997)). Nevertheless, most of the existing literature in the area is methodologically oriented (e.g., large scale mixed integer programs). This literature is of great value for decision making and cost optimization in a deterministic setting. However, by nature, it does not render general managerial insights into operational decisions under conditions of uncertainty or related system design issues. The research problems summarized here place an emphasis on providing insightful tools for operational decision-making and distribution system design under uncertainty. Although these problems have gained academic attention recently, there is still a need for research to meet the following objectives:

- To develop a modeling framework and theoretical understanding of inventory and transportation decisions in the context of new initiatives in supply-chain management.
- To identify optimal pure and integrated policies for general demand processes and cost structures and to develop computational procedures that simplify practical implementation.
- To analyze the cost and timely delivery implications of pure and integrated policies.
- To provide analytical tools for a comparison of different practices such as an immediate delivery policy, a pure consolidation policy, and an integrated policy.
- To render insights into effective distribution system/policy design and operational level decision-making.

The broader objective here is to explore the interaction between inventory and transportation decisions and address the question of under what conditions integration works.

Concern over the interaction between inventory and transportation costs has long been discussed in the JIT literature (Arcelus and Rowcroft (1991); Arcelus and Rowcroft (1993); Gupta and Bagchi (1987)). For illustrative purposes, let us revisit an example from Çetinkaya and Bookbinder (2002). Consider the case in Figure 1.1 where a number of small shipments arriving at origin A are to be delivered to destination B. These shipments may consist of components, or sub-assemblies, collected from various suppliers; for example, B might be a car assembly plant and A a warehouse that enables the staging JIT deliveries to B.

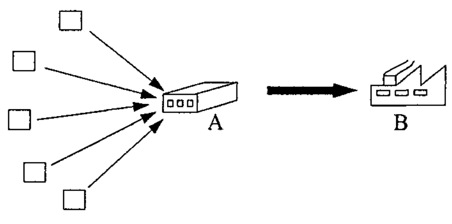

Figure 1.1. Consolidation in JIT deliveries.

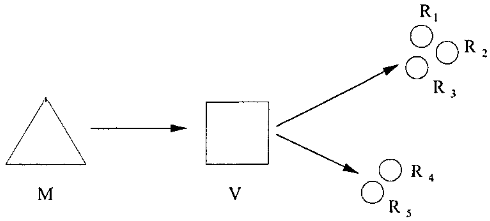

Figure 1.2. Consolidation in distribution.

On the other hand, in the context of VMI, shipment consolidation is a new area. The benefits of VMI are well recognized by successful retail businesses such as Wal-Mart. In VMI, distortion of demand information (known as the bullwhip effect) transferred from the downstream supply-chain member (e.g., retailer) to the upstream member (e.g., vendor) is minimized, stockout situations are less frequent, and system-wide inventory carrying costs are reduced. Furthermore, a VMI vendor has the liberty of controlling the downstream re-supply decisions rather than filling orders as they are placed. Thus, the approach offers a framework for coordinating inventory and *outbound* transportation decisions. The goal here is to present a class of coordination problems within this framework.

In a VMI partnership, inventory and demand information at the retailer are accessible to the vendor by using advanced on-line messaging and data retrieval systems (Cottrill (1997); Parker (1996)). By reviewing the retailers' inventory levels, the vendor makes decisions regarding the quantity and timing of re-supply. Application of VMI calls for integrating supply and outbound transportation operations through information sharing. Hence, the approach is gaining more attention as Electronic Data Interchange (EDI) technology improves and the cost of information sharing decreases.

As an example, consider the case illustrated in Figure 1.2 where M is a manufacturer; V is a vendor/distributor; and $R_i, i = 1, 2, \ldots$ is a retailer or customer. Suppose that a group of retailers (R_1, R_2, etc.) located in a given geographical region has random demands, and these can be consolidated in a larger load before a delivery is made to the region. That is, demands are not satisfied immediately, but, rather, are shipped in batches of consolidated loads. As a result, the actual inventory requirements at V are specified by the dispatching policy in use, and consolidation and inventory decisions at V should not be made in isolation from each other. In this example, the total cost for the vendor includes procurement and inventory carrying costs at V, the cost of waiting associated with ordered-but-not-yet-delivered demand items to the retailers, and the outbound transportation cost for shipments from V to the region. Also, note that while V is not the final destination in the supply-chain, it may be logical for various orders to be shipped together from M to V, since they will be delivered closely in time. This would be the situation if an *inbound* consolidation policy was in place. The focus of the integrated models here, however, is on outbound consolidation.

3. Modeling Challenges

Although the determination of practical decision rules for shipment consolidation has received attention in the literature, the computation of optimal policies for shipment release timing still remains an area requiring further research. In the existing literature, there are only a few guidelines for computing optimal consolidation policy parameters (Bookbinder and Higginson (2002); Çetinkaya and Bookbinder (2002); Higginson and Bookbinder (1995)). This is a challenging problem for the following reasons.

Customer Service The first complicating factor pertains to *customer service* (Çetinkaya and Bookbinder (2002)). If a temporal consolidation program is in place, then the first order received at V (see Figure 1.2) is from that customer who ends up waiting the longest for the goods. Thus, acceptable customer service should be assured by imposing a maximum holding time (i.e., a time-window) for the first (or any) order. Unfortunately, even after the delays of early orders are accounted for, we cannot guarantee that the subsequent order arrivals (a stochastic process) will be sufficient to achieve the low total cost sought by the consolidation strategy. Hence, research in the area should analyze cost versus the delivery time implications of different customer service levels.

Inventory Holding and Waiting Costs The second complicating factor pertains to *holding costs* and *waiting costs* (Çetinkaya and Bookbinder (2002)). Under any shipment consolidation program, some period of time elapses between the staging of a number of orders and the departure of a consolidated load. That is, shipment consolidation is implemented at the expense of customer waiting costs as well as inventory carrying costs. Holding costs represent the actual warehousing expenses during a shipment-consolidation-cycle as well as the opportunity cost in advanced payment for materials or investment in inventory. Waiting costs represent an opportunity loss in delayed receipt of revenue as well as a loss in the form of a goodwill penalty. The optimal policy, thus, should minimize the sum of the transportation, holding, and waiting costs and address the issue of balancing the three.

Interdependence of Inventory and Shipment Release Decisions If an outbound consolidation policy is in place, then *the actual inventory requirements at the vendor are partly dictated by the shipment release schedules.* Hence, coordination of inventory replenishment decisions and shipment release timings may help to reduce system-wide costs. In fact, if consolidation efforts are ignored in the optimization of inventory, the cost saving opportunities that might be realized through coordination may be overlooked. This issue is important in the context of VMI, 3PW/D, and TDD agreements where inventory decisions at the vendor account for consolidated shipments to downstream supply-chain members. Naturally, however, integrating production/inventory and shipment release timing decisions increases the problem size and complexity.

Structure of Transportation Costs Another complicating factor relates to *the structure of the transportation costs* which depend on several factors such as transportation mode, routing policies, and carriage-type. Concentrating on the case of highway transportation and ignoring the routing-related costs, let us consider the major shipping cost patterns that arise in consolidation (Hall and Racer (1995); Higginson and Bookbinder (1995); Çetinkaya and Bookbinder (2002)).

- For the case of a private-carriage, the shipping cost is primarily a function of the distance between the origin and the destination; thus, it is a fixed cost per cargo/truck for each origin-destination pair.

- When a common-carriage is used, the total shipment cost is based on the shipment quantity (total cwt.) In this case, a prototype tariff function has the form

$$c(u) = \begin{cases} d_1 u, & 0 \leq u < U_1, \\ d_{j-1} u, & U_{j-2} \leq u < U_{j-1}, j = 2, .., J \\ d_J u, & U_{J-1} \leq u, \end{cases}$$

  where $d_1 > \ldots > d_J$ denote per unit-weight freight rates, and $0 < U_1 < \ldots < U_{J-1}$ denote the break-points for shipping larger quantities.

The cost structure given by $c(u)$ implies that if $d_2 U_1 / d_1 \leq u < U_1$, then $c(u) \geq c(z)$ for all z such that $U_1 \leq z < d_1 U_1 / d_2$. However, it is unreasonable to pay more for transporting a smaller weight than a larger weight. To avoid this situation, shippers are legally allowed to over-declare the actual shipment weight. That is, the shipper has the opportunity to decrease total common-carrier charges by artificially inflating the actual shipping weight to the closest break-point (Carter, Ferrin, and Carter (1995); Higginson and Bookbinder (1995); Russell and Krajewski (1991)). The strategy of declaring "a phantom weight" is known as a *bumping clause.* Under this strategy, observe that, for example, if there is a single price-break at U_1, the *effective* common-carriage tariff function, denoted $\tilde{c}(u)$, can be represented by

$$\tilde{c}(u) = \begin{cases} d_1 u, & 0 \le u < \hat{U}_1, \\ d_2 U_1, & \hat{U}_1 \le u < U_1, \\ d_2 u, & U_1 \le u. \end{cases}$$

where $\hat{U}_1 = d_2 U_1 / d_1$.

Incorporation of the bumping clause in optimization models may lead to a non-differentiable cost function. Hence, common-carrier transportation problems may be more demanding in terms of their computational requirements. With a few exceptions (Çetinkaya and Bookbinder (2002); Higginson and Bookbinder (1995); Russell and Krajewski (1991)), the concept of the bumping clause seems to be overlooked in most analytical models.

Cargo Capacity The fifth complicating factor is the effect of cargo capacity constraints. Typically, the volume of a consolidated load exceeds the cargo volume limit before an economical dispatch weight accumulates. Incorporation of cargo capacity in optimization models also leads to a non-differentiable total cost function, since, typically, cargo costs include fixed costs. Also, for stochastic problems, the weight or volume (or both) of a load accumulated during a fixed time interval is a random variable. In order to guarantee that this random variable does not exceed the existing cargo weight or volume limit, the capacity restrictions should be modeled as chance constraints, i.e., inequality constraints in the form of probabilities.

Multiple Market Areas and Products The last complication arises in coordinating shipment schedules to different market areas. The problem is particularly challenging when the demand and cost profiles for different market areas (as well as for individual customers within a given area) are different. A similar complication arises when there are multiple products. The focus in this chapter, however, is on single item, single market area problems.

It is worth noting that the above listed complications arise both in the context of pure consolidation policies and integrated policies.

4. Literature Review

4.1 Practice Oriented Literature and Applications

The principles of pure consolidation policies have traditionally been discussed in the logistics trade journals (Newbourne and Barrett (1972); Pollock (1978)). Different opportunities to realize shipment consolidation savings have also been described in fundamental logistics textbooks (Ballou (1999); Bowersox (1978); Daganzo (1996)). On the other hand, the economic justification of pure consolidation practices has received attention only in the last two decades (Blumenfeld, Burns, Diltz and Daganzo (1985); Burns, Hall, Blumenfeld and Daganzo (1985); Campbell (1990); Daganzo (1988); Gallego and Simchi-Levi (1990); Hall (1987); Higginson (1995); Pooley and Stenger (1992); Russell and Krajewski (1991); Sheffi, Eskandari, and Koutsopoulos (1988)). The early academic treatments are based on simulation models (Closs and Cook (1987); Cooper (1984); Jackson (1981); Masters (1980)). Several reasonable and easy-to-implement consolidation strategies can be identified in the previous literature. These include:

- time-based dispatch/consolidation policies, and
- quantity-based dispatch/consolidation policies.

A *time-based policy* ships accumulated loads (clears all outstanding orders) every T_c periods whereas a *quantity-based policy* ships an accumulated load when an economical dispatch quantity, say Q_c, is available. The literature also identifies a hybrid consolidation routine, called a *hybrid policy*, which is characterized by a dispatch frequency T_c and an economical dispatch quantity Q_c. Under a hybrid policy, a dispatch decision is made at $\min\{T(Q_c), T_c\}$ where $T(Q_c)$ denotes the arrival time of the Q_c^{th} demand.

Both time-based and quantity-based consolidation policies are popular in VMI, 3PW/D, and TDD applications where the interaction between inventory and shipment consolidation is considered for the purpose of cost and load optimization. Typically, time-based policies are used for A-class (lower volume/higher value) items such as commercial CPUs in the computer industry, and quantity-based policies are used for B-class and C-class (higher volume/lower value) items such as peripherals. Based on our experience, it seems that hybrid policies are not generally implemented explicitly; rather, they appear to be implicit, i.e, in managing day-to-day operations and in the troubleshooting associated with expedited orders.

Time-based and quantity-based policies are incorporated in supply contracts for the purposes of achieving timely delivery and load optimization, respectively. These contracts specify the rate schedules for TDD and full-truck-load (FTL) shipments which are also known as load-optimized deliveries. Naturally, time-based policies are suitable for TDD, whereas quantity-based policies are suitable for FTL shipments. For example, in a representative VMI application, the vendor provides warehousing and outbound transportation for finished goods and guarantees TDD and FTL shipments for outbound deliveries to the customers (i.e., a downstream supply-chain member). In this setting, since the actual inventory requirements at the vendor are dictated by the outbound shipment schedules, the inventory and outbound consolidation policies should be coordinated/integrated. We revisit this issue later in Section 5.2 where we also discuss a related modeling methodology.

4.2 Quantitative Literature

4.2.1 Simulation and Analytical Models for Pure Consolidation Policies. Higginson and Bookbinder (1994) compare time-based, quantity-based, and hybrid policies in a pure consolidation setting via a simulation model where most of the relevant parameters are varied. However, the *optimal* choices for Q_c and T_c may not be among the values tested for any of the policies. Although this limitation of simulation has been recognized in the early literature, there are only a few papers that provide analytical models for shipment release timing. Higginson and Bookbinder (1995) employ a Markovian Decision Process model to compute the optimal quantity policies *numerically.* Gupta and Bagchi (1987) adopt Stidham's (Stidham (1977)) results on stochastic clearing systems which are characterized by stochastic input (e.g., freight from M to V in Figure 1.2) and an output mechanism (e.g., dispatching a vehicle from V to the final destination in Figure 1.2) that clears the system (e.g., V in Figure 1.2). Brennan (1981) obtains structural results when consolidated loads are reviewed on a periodic basis for both deterministic and stochastic demand problems. Other analytical treatments of pure consolidation policies include those based on queueing theory in the setting of passenger transport and dynamic vehicle dispatch (Gans and van Ryzin (1999); Minkoff (1993); Powell (1985); Powell and Humblet (1986)). One common characteristic of the previous studies is that they focus mainly on quantity policies and do not consider compound demand processes. In a recent paper, Çetinkaya and Bookbinder (2002) model compound input processes and analyze both private-carriage and common-carriage problems. We revisit this work later in Section 5.1 where we also provide a list of future research issues in pure consolidation policies. Nevertheless, all of the papers mentioned so far in this section concentrate on pure consolidation policies, ignoring the following:

- the interaction between inventory and shipment consolidation decisions,
- cargo capacity constraints, and
- multiple market area distribution problems.

4.2.2 Analytical Models for Integrated Policies. Although the literature on integrated inventory and transportation decisions is abundant, most of the existing work is methodologically oriented and concentrates on algorithmic procedures for large scale optimization models. Furthermore, with a few exceptions (e.g., Çetinkaya and Lee (2000)), the existing literature does not directly address the effects of temporal consolidation. Bramel and Simchi-Levi (1997) provide an excellent review of the literature on integrated models for inventory control and vehicle routing (also see, Anily and Federgruen (1990); Anily and Federgruen (1993); Chan, Muriel, Shen, Simchi-Levi, and Teo (2002); Federgruen and Simchi-Levi (1995); Hall (1991); Viswanathan and Mathur (1997)).

In general the multi-echelon inventory literature and, in particular, the problem of buyer-vendor coordination is closely related to the integrated problems considered here. For example, Axsäter (2000); Banerjee (1986); Banerjee (1986); Banerjee and Burton (1994); Goyal (1976); Goyal (1987); Goyal and Gupta (1989); Joglekar (1988); Joglekar and Tharthare (1990); Lee and Rosenblatt (1986) and Schwarz (1973) present meritorious results in this area. However, the previous work in buyer-vendor coordination neglects the complicating factors of shipment consolidation addressed in Section 2 and throughout this chapter.

Inventory lot-sizing models in which transportation costs are considered explicitly are more distantly related to the topic of interest in this chapter. In recent years, joint quantity and freight discount problems have received significant attention in logistics research (Aucamp (1982); Baumol and Vinod (1970); Carter and Ferrin (1996); Constable and Whybark, (1978); Diaby and Martel (1993); Gupta (1992); Hahm and Yano (1992); Hahm and Yano (1995a); Hahm and Yano (1995b); Henig, Gerchak, Ernst, and Pyke (1997); Knowles and Pantumsinchai (1988); Lee (1986); Lee (1989); Popken (1994); Sethi (1984); Tersine and Barman (1991); Tyworth (1992)). The efforts in this field are mainly directed towards deterministic modeling with an emphasis on *inbound* transportation. These previous models do not address the outbound distribution issues that arise, particularly in the context of VMI, 3PW/D, and TDD arrangements.

4.2.3 Limitations. Although a large body of literature in the general area of integrated inventory and transportation decisions exists, the following research problems need attention:

- Computation of parameter values for *practical* pure consolidation policies (e.g., time, quantity, and hybrid policies) in a stochastic setting for general demand processes, for transportation by a private fleet and common-carriage trucking company under cargo capacity constraints, and for single and multiple market area problems.

- Characterization of *optimal* pure consolidation policies for general demand processes, for transportation by a private fleet and common-carriage trucking company under cargo capacity constraints, and for single and multiple market area problems.

- Computation of parameter values for *practical* integrated policies in a stochastic setting for general demand processes, for transportation by a private fleet and common-carriage trucking company under cargo capacity constraints, and for single and multiple market area problems.

- Characterization of *optimal* integrated policies and integrated policies which assure acceptable customer service, again, in a stochastic setting for general demand processes, for transportation by a private fleet and common-carriage trucking company under cargo capacity constraints, and for single and multiple market area problems.

- Analysis of time versus cost tradeoffs for pure and integrated policies and analysis of conditions under which integration works best.

- Development of analytical as well as sophisticated simulation tools for comparison of different practices and initiatives that render insights into distribution system/policy design and operational level decision making.

5. Models and Methodology

Some special cases of the problems itemized above have been modeled and solved in Çetinkaya and Bookbinder (2002); Çetinkaya and Lee

(2000); Çetinkaya and Lee (2002); Çetinkaya, Mutlu, and Lee (2002), and Çetinkaya, Tekin, and Lee (2000), and an overview of these results is presented next. Several important future research directions are also discussed.

5.1 Pure Consolidation Policies

5.1.1 Problem Setting. To set the stage for a mathematical formulation, we revisit the example illustrated in Figure 1.1 where a number of small shipments arriving at A are to be delivered to B. Consider the case where the arrival times, as well as the weights of the shipments, are random variables. The purpose is to find a consolidation policy that minimizes the expected long-run average cost of shipping plus holding shipments at A. The consolidation policy parameters specify i) when to dispatch a vehicle from A so that service requirements are met, and/or ii) how large the dispatch quantity should be so that scale economies are realized.

A similar pure consolidation problem is also encountered at V in Figure 1.2. Suppose that a group of customers (e.g., R_1, R_2, and R_3) located in a given market area places small orders of random size at random times, and suppose these can be consolidated in a larger load before a delivery truck is sent to the market area. Note that in this latter example, the objective function should include the cost of waiting associated with ordered, but not-yet-delivered, demand items.

If dispatch decisions (at A or V) are made on a recurring basis, under certain additional assumptions, we may utilize renewal theory. More specifically, provided that the underlying order arrival and dispatch processes satisfy certain conditions, we may compute the parameter values for time, quantity, and hybrid policies through renewal theoretic analysis. A simple example of such an analysis, based on the results in Çetinkaya and Bookbinder (2002), is presented in the following discussion.

Recall that a time-based dispatch policy ships each order (consolidated or not) by a predetermined shipping date. In turn, a stationary time-based policy is characterized by a single parameter, say T_c, which is called the *critical (maximum) holding time.* A second approach is to employ a quantity-based policy under which a dispatch decision is made when the accumulated load is more than a *minimum (critical) weight*, say Q_c. Finally, the third approach is a combination of the above two. A hybrid policy aims to dispatch all orders before a predetermined shipping date (during a time-window); but if a minimum consolidated load accumulates before that date, then all outstanding orders are dispatched immediately. On the other hand, if a minimum consolidated weight does not accumulate in time, all orders are dispatched on the prespecified date. Economies of scale associated with shipping a larger quantity may be sacrificed; however, customer service requirements are always met. Concentrating on single market area problems, Çetinkaya and Bookbinder (2002) report results on computing the parameters of optimal time and optimal quantity policies separately for the cases of *private-carriage* and *common-carriage*. These existing results make some specific assumptions about the underlying demand processes as we explain shortly.

5.1.2 An Illustrative Model for Private-Carriage. Considering a single market area problem, an illustration for computing the critical holding time T_c under a *pure* time-based policy for the consolidation problem at V (Figure 1.2) is presented below. That is, we ignore the inventory replenishment and carrying costs at V and concentrate only on the outbound dispatch problem. Later, in Section 5.2, we discuss the integrated policy where inventory at V is modeled explicitly.

Suppose that orders from customers located in a given market area form a stochastic process with interarrival times $\{X_k : k = 1, 2, \ldots\}$. For the moment, assume that $X_k \geq 0, k = 1, 2, \ldots$ are independent and identically distributed (i.i.d.) according to distribution function $F(\cdot)$, where $F(0) < 1$, and density $f(\cdot)$. Letting $S_0 = 0$ and $S_k = \sum_{i=1}^{k} X_i$, we define $N_1(t) = \sup\{k : S_k \leq t\}$. It follows that $N_1(t)$ is a renewal process that registers the number of orders placed by time t. Also, let $\{W_k : k = 1, 2, \ldots\}$ represent another sequence of i.i.d. random variables with density $g(\cdot)$ and distribution $G(\cdot)$ where $G(0) < 1$. We shall interpret W_k as the weight of the k^{th} order. Thus, $\mathcal{N}(t) = \sum_{i=1}^{N_1(t)} W_i$ is the weight of the cumulative demand until time t. We define $D_0 = 0$, $D_k = \sum_{i=1}^{k} W_i$, and $N_2(q) = \sup\{k : D_k \leq q\}$. Likewise, $N_2(q)$ is a renewal process and registers the number of orders until the cumulative demand reaches q. Since a dispatch decision is taken every T_c days, the maximum holding time, T_c, correspondingly represents the length of a shipment-consolidation-cycle for the market area. A realization of the demand process under this scenario is depicted in Figure 1.3.

Let $L(t)$ represent the size of the consolidated load, i.e., the number of outstanding demands, at time epoch t. The consolidation system is cleared and a new shipment-consolidation-cycle begins every T_c time-units. In turn, $L(jT_c), j = 1, 2, \ldots$ is a sequence of random variables representing the dispatch quantities. Keeping this observation in mind, we define

$$\mathcal{N}_j(T_c) \equiv L(jT_c), \quad j = 1, 2, \ldots.$$

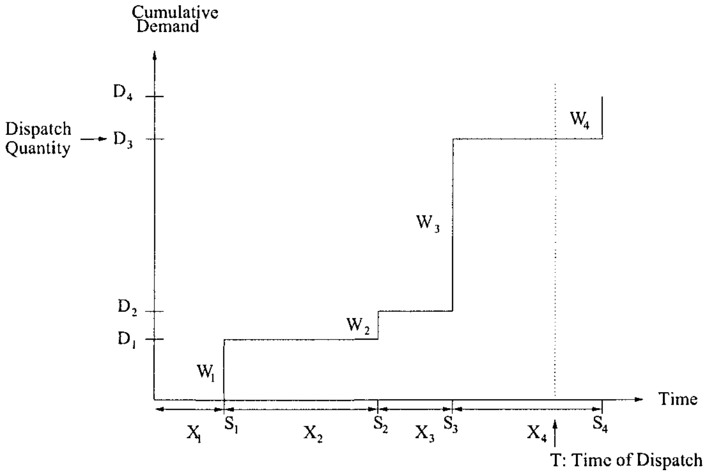

Figure 1.3. A realization under a time-based policy.

Observe that the sequence $\mathcal{N}_j(T_c), j = 1, 2, \ldots$ symbolizes the dispatch/shipment release weights under the time-based dispatching policy in use whereas the sequence $W_n, n = 1, 2, \ldots$ represents the actual order weights. The process $\mathcal{N}_j(T_c), j = 1, 2, \ldots$ is a function of T_c, and thus the dispatch quantities are random variables established by the parameter of the shipment-consolidation policy in use.

If $\mathcal{N}(t)$ is a compound Poisson process, then the random variables $\mathcal{N}_j(T_c), j = 1, 2, \ldots$ are i.i.d., each having the same distribution as the random variable $\mathcal{N}(T_c)$. It is worth noting that for other renewal processes, $\mathcal{N}_j(T_c), j = 1, 2, \ldots$ are not necessarily i.i.d., and this is a major source of difficulty for the problem of interest. Obtaining analytical results for general renewal processes seems to be rather challenging if not impossible, and it remains an open area for future investigation. Here, as in Çetinkaya and Bookbinder (2002), the focus is on the case of compound Poisson processes for analytical tractability.

The expected long-run average cost, denoted by $\mathcal{C}(T_c)$, is computed using the renewal reward theorem, i.e.,

$$\begin{aligned}\mathcal{C}(T_c) &= \frac{E[\text{Transportation cost per shipment-consolidation-cycle}]}{T_c} \\ &+ \frac{E[\text{Waiting cost per shipment-consolidation-cycle}]}{T_c}.\end{aligned}$$

If truck capacity constraints are ignored and only a fixed transportation cost, denoted by K_c, is associated with a dispatch decision, then

$$\mathcal{C}(T_c) = \frac{K_c + E[\text{Waiting cost per shipment-consolidation-cycle}]}{T_c}.$$

Figure 1.4 illustrates the accumulation of waiting costs in an arbitrary consolidation cycle. For the particular consolidation-cycle illustrated in Figure 1.3, $N_1(T_c) = 3$ so that the corresponding waiting cost is given by

$$w\left[(X_2 D_1 + X_3 D_2) + (T_c - S_3) D_3\right]$$

$$= w\left[X_2 W_1 + X_3 (W_1 + W_2) + (T_c - S_3)(W_1 + W_2 + W_3)\right],$$

where w denotes the cost of waiting for one unit of demand per unit-time. Using these illustrations and letting $A_1(T_c) = T_c - S_{N_1(T_c)}$ denote the age of $N_1(t)$ at T_c, it can be easily verified that

$$E[\text{Waiting cost per shipment-consolidation-cycle}] =$$

$$wE\left[\sum_{i=2}^{N_1(T_c)} X_i \sum_{j=1}^{i-1} W_j\right] + wE\left[A_1(T_c)\mathcal{N}(T_c)\right].$$

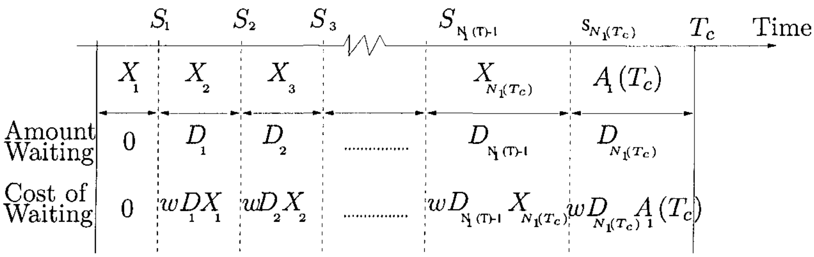

Figure 1.4. Amount waiting under a time-based policy.

Also,

$$E\left[\sum_{i=2}^{N_1(T_c)} X_i \sum_{j=1}^{i-1} W_j\right] = E[W_k] E\left[v(T, N_1(T_c))\right], \quad \text{and}$$

$$E\left[A_1(T_c)\mathcal{N}(T_c)\right] = Z(T_c),$$

where

$$
\begin{aligned}
v(t,k) &= \sum_{i=1}^{k-1} iE[X_{i+1}|N_1(t)=k], \\
Z(t) &= z(t) + \int_0^t Z(t-y)dF(y), \text{ and} \\
z(t) &= E[W_k]\int_0^t E[A_1(t-y)]dF(y).
\end{aligned}
$$

When demand is a compound Poisson process, then it is easy to obtain an analytical expression for T_c. The result, a variation of the EOQ formula, is not surprising. As we have mentioned earlier, for other compound processes, the optimal T_c cannot be computed using renewal theory; more general approaches such as Markov renewal theory, Markov decision processes, or stochastic dynamic programming are feasible. However, these approaches have not yet been investigated. The above approach can also be applied to obtain an optimal quantity-based policy for which similar results are applicable not only for compound Poisson processes but also for compound renewal processes. For those computations, $N_2(q)$ plays the role of $N_1(t)$ in computing a time-based policy. The following comparative results for compound Poisson processes are based on analysis of the private-carriage case in Çetinkaya and Bookbinder (2002).

PROPERTY 1.1

i) The expected dispatch quantity under the optimal time-based policy is larger than the optimal critical weight but smaller than the mean load dispatched under the optimal quantity-based policy.

ii) An optimal quantity-based policy has a mean shipment-consolidation-cycle length larger than that of the corresponding optimal time-based policy. Hence, the time-based policy offers superior service to customers, not only in the sense that a specific delivery time can be quoted, but also in the sense that delivery frequencies are higher.

5.1.3 An Illustrative Model for Common-Carriage. It is the cost structure and parameters that distinguish between the common and private carriage. However, as we illustrate next, this distinction leads to an important computational difficulty in obtaining an expression for expected transportation cost per shipment-consolidation-cycle so that insightful structural results cannot be presented even for the simpler case of compound Poisson demand processes.

Let us consider the case of a single price-break so that the effective common-carriage cost function is given by $\tilde{c}(u)$ in Section 3. For illustrative purposes, let us try to compute the optimal T_c for a common-carriage under the assumptions that X_k and W_k are exponentially distributed with respective parameters λ and α (or $1/E[X_k]$ and $1/E[W_k]$). The expected waiting cost per shipment-consolidation-cycle is computed as in the case of the private-carriage. For the specific example under consideration, $\mathcal{N}(t)$ is a compound Poisson process. Thus, it is straightforward to show that

$$\frac{E[\text{Waiting cost per shipment-consolidation-cycle}]}{T_c} = \frac{wE[W_k]\lambda T_c}{2}.$$

However, the remaining terms of $\mathcal{C}(T_c)$ require the density function of $\mathcal{N}(t)$, denoted by $\phi(t,x)$, for which a closed form expression does not exist in most cases. The expected transportation cost per shipment-consolidation-cycle is given by

$$E\left[\tilde{c}\left(\mathcal{N}\left(T_c\right)\right)\right] = \int_0^\infty E\left[\tilde{c}(x)\right]\phi\left(T_c,x\right)dx$$

$$= \int_0^{\hat{U}_1} d_1 x\phi\left(T_c,x\right)dx + \int_{\hat{U}_1}^{U_1} d_2 U_1\phi\left(T_c,x\right)dx + \int_{U_1}^\infty d_2 x\phi\left(T_c,x\right)dx,$$

Based on the result in Medhi (1994) (p. 176-7), the probability generating function (p.g.f.) of $\mathcal{N}(t)$, denoted $P_\phi(\cdot)$, is given by $P_\phi(s) = \exp\left[\lambda t\left(P_g(s)-1\right)\right]$, where $P_g(s)$ denotes the p.g.f. of W_k. However, this approach does not lead to a closed form expression for $\phi(t,x)$, except for the special case where W_k is geometric. The above expression for $P_\phi(s)$ can be used to evaluate $\phi(t,x)$ *numerically*, and then the outcome can be utilized for a numerical evaluation of $\mathcal{C}(T_c)$. This, in turn, requires the use of numerical integration procedures. Although such an approach is feasible, the corresponding computations may require some effort. Easier-to-compute approximations are presented in Çetinkaya and Bookbinder (2002). Nevertheless, even if we can numerically evaluate $\mathcal{C}(T_c)$, its optimization requires an enumeration approach. That is, there is no guarantee that the global optimum can be found in a reasonable amount of time because, depending on the model parameters, the cost function may not be convex.

Again, the above approach can also be applied to obtain an optimal quantity-based policy under a common-carriage tariff function. Although a closed form solution does not exist, the numerical computations may be easier. This is because, to obtain an optimal quantity-based policy, we do not need an expression for $\phi(t,x)$ but rather an expression for