574 LECTURE NOTES IN ECONOMICS AND MATHEMATICAL SYSTEMS

Rainer Kleber

Dynamic Inventory Management in Reverse Logistics

Springer

Lecture Notes in Economics and Mathematical Systems 574

Rainer Kleber

Dynamic Inventory Management in Reverse Logistics

With 55 Figures
and 20 Tables

Springer

Dr. Rainer Kleber

Otto-von-Guericke-University Magdeburg
Faculty of Economics and Management
Universitätsplatz 2
39106 Magdeburg, Germany
E-mail: rainer.kleber@ww.uni-magdeburg.de

ISBN-10 3-540-33229-4 Springer Berlin Heidelberg New York
ISBN-13 978-3-540-33229-9 Springer Berlin Heidelberg New York

Springer is a part of Springer Science+Business Media
springer.com

Printed in Germany

Typesetting: Camera ready by author
Cover: Erich Kirchner, Heidelberg
Production: LE-TEX, Jelonek, Schmidt & Vöckler GbR, Leipzig

SPIN 11731641 Printed on acid-free paper – 88/3100/YL – 5 4 3 2 1 0

Lecture Notes in Economics and Mathematical Systems

For information about Vols. 1–483
please contact your bookseller or Springer-Verlag

Vol. 484: D. D. Gatti, M. Gallegati, A. Kirman, Interaction and Market Structure. VI, 298 pages. 2000.

Vol. 485: A. Garnaev, Search Games and Other Applications of Game Theory. VIII, 145 pages. 2000.

Vol. 486: M. Neugart, Nonlinear Labor Market Dynamics. X, 175 pages. 2000.

Vol. 487: Y. Y. Haimes, R. E. Steuer (Eds.), Research and Practice in Multiple Criteria Decision Making. XVII, 553 pages. 2000.

Vol. 488: B. Schmolck, Ommitted Variable Tests and Dynamic Specification. X, 144 pages. 2000.

Vol. 489: T. Steger, Transitional Dynamics and Economic Growth in Developing Countries. VIII, 151 pages. 2000.

Vol. 490: S. Minner, Strategic Safety Stocks in Supply Chains. XI, 214 pages. 2000.

Vol. 491: M. Ehrgott, Multicriteria Optimization. VIII, 242 pages. 2000.

Vol. 492: T. Phan Huy, Constraint Propagation in Flexible Manufacturing. IX, 258 pages. 2000.

Vol. 493: J. Zhu, Modular Pricing of Options. X, 170 pages. 2000.

Vol. 494: D. Franzen, Design of Master Agreements for OTC Derivatives. VIII, 175 pages. 2001.

Vol. 495: I. Konnov, Combined Relaxation Methods for Variational Inequalities. XI, 181 pages. 2001.

Vol. 496: P. Weiß, Unemployment in Open Economies. XII, 226 pages. 2001.

Vol. 497: J. Inkmann, Conditional Moment Estimation of Nonlinear Equation Systems. VIII, 214 pages. 2001.

Vol. 498: M. Reutter, A Macroeconomic Model of West German Unemployment. X, 125 pages. 2001.

Vol. 499: A. Casajus, Focal Points in Framed Games. XI, 131 pages. 2001.

Vol. 500: F. Nardini, Technical Progress and Economic Growth. XVII, 191 pages. 2001.

Vol. 501: M. Fleischmann, Quantitative Models for Reverse Logistics. XI, 181 pages. 2001.

Vol. 502: N. Hadjisavvas, J. E. Martínez-Legaz, J.-P. Penot (Eds.), Generalized Convexity and Generalized Monotonicity. IX, 410 pages. 2001.

Vol. 503: A. Kirman, J.-B. Zimmermann (Eds.), Economics with Heterogenous Interacting Agents. VII, 343 pages. 2001.

Vol. 504: P.-Y. Moix (Ed.), The Measurement of Market Risk. XI, 272 pages. 2001.

Vol. 505: S. Voß, J. R. Daduna (Eds.), Computer-Aided Scheduling of Public Transport. XI, 466 pages. 2001.

Vol. 506: B. P. Kellerhals, Financial Pricing Models in Con-tinuous Time and Kalman Filtering. XIV, 247 pages. 2001.

Vol. 507: M. Koksalan, S. Zionts, Multiple Criteria Decision Making in the New Millenium. XII, 481 pages. 2001.

Vol. 508: K. Neumann, C. Schwindt, J. Zimmermann, Project Scheduling with Time Windows and Scarce Resources. XI, 335 pages. 2002.

Vol. 509: D. Hornung, Investment, R&D, and Long-Run Growth. XVI, 194 pages. 2002.

Vol. 510: A. S. Tangian, Constructing and Applying Objective Functions. XII, 582 pages. 2002.

Vol. 511: M. Külpmann, Stock Market Overreaction and Fundamental Valuation. IX, 198 pages. 2002.

Vol. 512: W.-B. Zhang, An Economic Theory of Cities.XI, 220 pages. 2002.

Vol. 513: K. Marti, Stochastic Optimization Techniques. VIII, 364 pages. 2002.

Vol. 514: S. Wang, Y. Xia, Portfolio and Asset Pricing. XII, 200 pages. 2002.

Vol. 515: G. Heisig, Planning Stability in Material Requirements Planning System. XII, 264 pages. 2002.

Vol. 516: B. Schmid, Pricing Credit Linked Financial Instruments. X, 246 pages. 2002.

Vol. 517: H. I. Meinhardt, Cooperative Decision Making in Common Pool Situations. VIII, 205 pages. 2002.

Vol. 518: S. Napel, Bilateral Bargaining. VIII, 188 pages. 2002.

Vol. 519: A. Klose, G. Speranza, L. N. Van Wassenhove (Eds.), Quantitative Approaches to Distribution Logistics and Supply Chain Management. XIII, 421 pages. 2002.

Vol. 520: B. Glaser, Efficiency versus Sustainability in Dynamic Decision Making. IX, 252 pages. 2002.

Vol. 521: R. Cowan, N. Jonard (Eds.), Heterogenous Agents, Interactions and Economic Performance. XIV, 339 pages. 2003.

Vol. 523: W.-B. Zhang, A Theory of Interregional Dynamics. XI, 231 pages. 2003.

Vol. 524: M. Frölich, Programme Evaluation and Treatment Choise. VIII, 191 pages. 2003.

Vol. 525: S. Spinler, Capacity Reservation for Capital-Intensive Technologies. XVI, 139 pages. 2003.

Vol. 526: C. F. Daganzo, A Theory of Supply Chains. VIII, 123 pages. 2003.

Vol. 527: C. E. Metz, Information Dissemination in Currency Crises. XI, 231 pages. 2003.

Vol. 528: R. Stolletz, Performance Analysis and Optimization of Inbound Call Centers. X, 219 pages. 2003.

Vol. 529: W. Krabs, S. W. Pickl, Analysis, Controllability and Optimization of Time-Discrete Systems and Dynamical Games. XII, 187 pages. 2003.

Vol. 530: R. Wapler, Unemployment, Market Structure and Growth. XXVII, 207 pages. 2003.

Vol. 531: M. Gallegati, A. Kirman, M. Marsili (Eds.), The Complex Dynamics of Economic Interaction. XV, 402 pages, 2004.

Vol. 532: K. Marti, Y. Ermoliev, G. Pflug (Eds.), Dynamic Stochastic Optimization. VIII, 336 pages. 2004.

Vol. 533: G. Dudek, Collaborative Planning in Supply Chains. X, 234 pages. 2004.

Vol. 534: M. Runkel, Environmental and Resource Policy for Consumer Durables. X, 197 pages. 2004.

Vol. 535: X. Gandibleux, M. Sevaux, K. Sörensen, V. T'kindt (Eds.), Metaheuristics for Multiobjective Optimisation. IX, 249 pages. 2004.

Vol. 536: R. Brüggemann, Model Reduction Methods for Vector Autoregressive Processes. X, 218 pages. 2004.

Vol. 537: A. Esser, Pricing in (In)Complete Markets. XI, 122 pages, 2004.

Vol. 538: S. Kokot, The Econometrics of Sequential Trade Models. XI, 193 pages. 2004.

Vol. 539: N. Hautsch, Modelling Irregularly Spaced Financial Data. XII, 291 pages. 2004.

Vol. 540: H. Kraft, Optimal Portfolios with Stochastic Interest Rates and Defaultable Assets. X, 173 pages. 2004.

Vol. 541: G.-y. Chen, X. Huang, X. Yang, Vector Optimization. X, 306 pages. 2005.

Vol. 542: J. Lingens, Union Wage Bargaining and Economic Growth. XIII, 199 pages. 2004.

Vol. 543: C. Benkert, Default Risk in Bond and Credit Derivatives Markets. IX, 135 pages. 2004.

Vol. 544: B. Fleischmann, A. Klose, Distribution Logistics. X, 284 pages. 2004.

Vol. 545: R. Hafner, Stochastic Implied Volatility. XI, 229 pages. 2004.

Vol. 546: D. Quadt, Lot-Sizing and Scheduling for Flexible Flow Lines. XVIII, 227 pages. 2004.

Vol. 547: M. Wildi, Signal Extraction. XI, 279 pages. 2005.

Vol. 548: D. Kuhn, Generalized Bounds for Convex Multistage Stochastic Programs. XI, 190 pages. 2005.

Vol. 549: G. N. Krieg, Kanban-Controlled Manufacturing Systems. IX, 236 pages. 2005.

Vol. 550: T. Lux, S. Reitz, E. Samanidou, Nonlinear Dynamics and Heterogeneous Interacting Agents. XIII, 327 pages. 2005.

Vol. 551: J. Leskow, M. Puchet Anyul, L. F. Punzo, New Tools of Economic Dynamics. XIX, 392 pages. 2005.

Vol. 552: C. Suerie, Time Continuity in Discrete Time Models. XVIII, 229 pages. 2005.

Vol. 553: B. Mönch, Strategic Trading in Illiquid Markets. XIII, 116 pages. 2005.

Vol. 554: R. Foellmi, Consumption Structure and Macroeconomics. IX, 152 pages. 2005.

Vol. 555: J. Wenzelburger, Learning in Economic Systems with Expectations Feedback (planned) 2005.

Vol. 556: R. Branzei, D. Dimitrov, S. Tijs, Models in Cooperative Game Theory. VIII, 135 pages. 2005.

Vol. 557: S. Barbaro, Equity and Efficiency Considerations of Public Higer Education. XII, 128 pages. 2005.

Vol. 558: M. Faliva, M. G. Zoia, Topics in Dynamic Model Analysis. X, 144 pages. 2005.

Vol. 559: M. Schulmerich, Real Options Valuation. XVI, 357 pages. 2005.

Vol. 560: A. von Schemde, Index and Stability in Bimatrix Games. X, 151 pages. 2005.

Vol. 561: H. Bobzin, Principles of Network Economics. XX, 390 pages. 2006.

Vol. 562: T. Langenberg, Standardization and Expectations. IX, 132 pages. 2006.

Vol. 563: A. Seeger (Ed.), Recent Advances in Optimization. XI, 455 pages. 2006.

Vol. 564: P. Mathieu, B. Beaufils, O. Brandouy (Eds.), Artificial Economics. XIII, 237 pages. 2005.

Vol. 565: W. Lemke, Term Structure Modeling and Estimation in a State Space Framework. IX, 224 pages. 2006.

Vol. 566: M. Genser, A Structural Framework for the Pricing of Corporate Securities. XIX, 176 pages. 2006.

Vol. 567: A. Namatame, T. Kaizouji, Y. Aruga (Eds.), The Complex Networks of Economic Interactions. XI, 343 pages. 2006.

Vol. 568: M. Caliendo, Microeconometric Evaluation of Labour Market Policies. XVII, 258 pages. 2006.

Vol. 569: L. Neubecker, Strategic Competition in Oligopolies with Fluctuating Demand. IX, 233 pages. 2006.

Vol. 570: J. Woo, The Political Economy of Fiscal Policy. X, 169 pages. 2006.

Vol. 571: T. Herwig, Market-Conform Valuation of Options. VIII, 104 pages. 2006.

Vol. 572: M. F. Jäkel, Pensionomics. XII, 316 pages. 2006.

Vol. 573: J. Emami Namini, International Trade and Multinational Activity, X, 159 pages, 2006.

Vol. 574: R. Kleber, Dynamic Inventory Management in Reverse Logistics, XII, 181 pages, 2006.

Vol. 575: R. Hellermann, Capacity Options for Revenue Management, XV, 199 pages, 2006 (planned).

Vol. 576: J. Zajac, Economics Dynamics, Information and Equilibrium, X, 284 pages, 2006 (planned).

Vol. 577: K. Rudolph, Bargaining Power Effects in Financial Contracting, XVIII, 330 pages, 2006 (planned).

to Kerstin, Lenny, and Lisa

Acknowledgements

I would like to acknowledge many people at the Faculty of Economics and Management at the Otto-von-Guericke University Magdeburg who have helped me during the course of this dissertation. First, I would like to express my sincere appreciation to my advisor, Karl Inderfurth, for his generous time and commitment. He offered me the chance to work with other researchers in an international network ‘Reverse Logistics and its Effects on Industry’, which was thankfully supported by the European Union. A substantial part of this work is a direct result of this opportunity.

I am also indebted to the readers of this thesis, Alfred Luhmer and Franz Wirl. During my graduate studies, Franz Wirl opened my eyes to the depths of Operations Research, more specifically that of dynamic optimization problems. I would like to thank Alfred Luhmer for his encouragement and interest in this subject as well as his valuable comments.

I have enjoyed the company of two co-authors in several research papers, namely Stefan Minner and Gudrun P. Kiesmüller. Stefan in particular was always an invaluable source of ideas and knowledge. I extend many thanks to my current and former colleagues for both their research-oriented focus and a nice working atmosphere. In particular, I am thankful to Gerald Heisig, Ian M. Langella, Ivo Neidlein, and the late Gerd Lindner for numerous scientific discussions and their friendship. Furthermore, Ian M. Langella and Dirk Matzner considerably improved readability of this work by enhancing my English.

Finally I would like to express my gratitude to my family and friends, for without their constant support this work would not have been possible. This is especially true for my Mother, who gave me the best start into a scientific career that could be imagined. To my wife and best friend, Kerstin, I wish to express my heartfelt gratitude for her understanding and patience, but also for our wonderful children, Leonard and Elisabeth, that keep our lives in balance.

Magdeburg, April 2006 *Rainer Kleber*

Preface

Reverse Logistics is an area that has attracted growing attention over the last years both from the industrial as well as from the scientific side. The proper management of reverse flows of products and materials is of considerable importance in many industries because of its influence on economic performance and environmental impact. The respective management tasks, however, are connected with new challenging planning and control problems. This especially holds for product recovery management concerning remanufacturing operations where used products, after being returned to the manufacturer, are reprocessed such that they are as good as new and can be re-integrated into the forward logistics stream.

A major issue in remanufacturing is how to optimally coordinate the potential activities directed at meeting customer demands for serviceable products and to deal with returns of products after end-of-use. The respective decisions refer to finding a proper mix of manufacturing original and remanufacturing used products as well as of stock-keeping and disposing of returned items. Hereby, relevant cost impacts and time patterns of demand and returns have to be taken into consideration.

Up to now, research contributions to this field of Reverse Logistics have addressed only two main aspects that result in high complexity of decision making in product recovery management. One aspect is that of capacity restrictions and fixed costs in manufacturing and remanufacturing systems that makes coordination of lot-sizing a challenging problem. The second aspect refers to uncertainty of demands and returns that leads to complicated stochastic interactions which have to be coped with by appropriate decision rules and safety stock policies. While these issues are highly relevant for operational and tactical decision making, a third aspect with mainly strategic importance has largely been ignored. This is the aspect of time-variability and dynamic change of major input parameters for product recovery decisions. On the one hand, this refers to the variability of product demand and return schemes that can be observed both due to seasonality and the classical life cycle pattern for many product categories. On the other hand, over larger time spans we also face specific cost dynamics caused by experience effects in manufacturing and remanufacturing processes.

It is the commendable contribution of this book that it sheds some light into this complicated field of how to respond most effectively to the dynamically changing environment in product recovery strategy. This response refers to choice of time-varying coordination strategies of manufacturing, remanufacturing and disposal activities as well as to the timing of investment decisions in product recovery technologies. Embedded in these considerations an analysis is developed of how and why to use different kinds of strategic inventories to enable best reactions to dynamic cost, demand and return processes. Based on advanced quantitative modeling and optimization techniques a deep analysis of the addressed complex dynamic decision problems is given.

Summarizing, this book presents major progress in scientifically investigating the field of complex problems of product recovery management induced by several types of dynamics in the planning environment. The underlying dynamic problem aspects are of enormous practical importance, but have not been addressed appropriately in research contributions before. By studying this book the reader will learn novel and interesting findings on how to respond strategically to ongoing changes of a product recovery environment by responsive recovery policies and dynamic inventory management.

Magdeburg, April 2006 *Karl Inderfurth*

Contents

1

Introduction

1.1 Objective and Motivation

The integration of product recovery into regular production processes has developed into a challenge for the manufacturing industry (Guide and Van Wassenhove (2002)). While in the past a firm's main concern was to sell its products leaving the burden of final disposal to society, it is now increasingly assigned responsibility for what happens with the product after use. Consequently, product recovery leads to additional restrictions firms must take into account, but it also enables new opportunities (Stock et al. (2002)).

There are many reasons for this development. An increasing environmental consciousness of the public and limited availability of natural resources to manufacture new products on one side and the necessity to find alternatives to landfilling and incineration of waste led to new regulations that aim at reducing the quantity and environmental impact of waste. Environmental legislation incorporates the prohibition of substances that aggravate material recovery, the enforcement of collection networks, and industry specific take back and recovery obligations. Some of the many examples are the German Recycling and Waste Control Act (Kreislaufwirtschafts- und Abfallgesetz, KrW-/AbfG) enacted in 1996 that extended product responsibility of manufacturers to the end of life phase and the EU Directive on Waste Electric and Electronic Equipment (WEEE) from 2003 which calls for the installment of collection networks. A recent overview on end-of-life legislation issues with examples from the US, Europe, and Japan can be found in Toffel (2003).

In addition, economic motives lead to a voluntary product take back of original equipment manufacturers (OEMs), as detailed and classified in Toffel (2004). First, recovering products allows us to reduce production cost by using recovered material and components in lieu of virgin material and newly produced components. Second, the fact that there is demand for leased products in the marketplace forces us to confront these products again at the end of the lease period. In this example, dealing with returns is part of the 'price we pay' to service the demand for these products. Third, customer behavior seemed to be influenced by the environmental image of firm, and therefore using recovered material in products or merely engaging in product recovery itself increases the demand from this market segment. Fourth, aftermarkets are often lucrative revenue generators, and therefore must be protected against third parties servicing demand for spare parts, etc. Finally, it is also viewed that taking environmentally friendly steps, for instance implementing a product recovery system before take-back laws exist, at times successfully preempts environmental legislation. On the other hand, Reinhardt (1999) also points out that encouraging environmental legislation can lead to an improved position of the firm, forcing competitors into compliance.

An increasing return of used products encourages OEMs to produce more environmental friendly yet recoverable products. A large number of examples for product recovery due to varying incentives are assembled by de Brito et al. (2005) and range from the reprocessing of chemicals in the pharmaceutical industry (see Teunter et al. (2005)) to the remanufacturing of Kodak single-use cameras or of complex products like engines in the car manufacturing industry (the latter two examples will be further detailed below as case studies). Thierry et al. (1995) put forth an overview on strategic product recovery issues and differentiate between product recovery options recycling, repair, cannibalization, refurbishing, and remanufacturing. Out of these options, remanufacturing seems especially appealing to OEMs since large parts of the added value can be recovered (Klausner and Hendrickson (2000)).

Product recovery management is charged with the coordinated planning and control of both production and recovery processes that serve the same demand for materials, parts, or final products. In the context of remanufacturing, both sources are assumed to be perfect substitutes, and recovered products are usually said to be as good as new. It should be noted that although we might choose other recovery options (e.g. repair or refurbishing) to be performed on the returns, we restrict our attention to remanufacturing as we presume substitutability.

When dealing with product returns, logistic processes are more complicated to control since both forward and backward flows must be coordinated. Production planning is more complex since there now exist two possible sources to serve the demand which need to be coordinated, therefore raising new operational questions. These problems receive growing interest from researchers and practitioners alike and are summarized in the field of *Reverse Logistics*. The European Working Group on Reverse Logistics (REVLOG) uses the following definition:

> The research area of Reverse Logistics covers "the process of planning, implementing and controlling backward flows of raw materials, in process inventory, packaging and finished goods, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal." (de Brito and Dekker (2004))

Quantitative approaches in reverse logistics have been surveyed by Fleischmann et al. (1997) and more recently by Dekker et al. (2004). According to the example of the latter work one can distinguish between three important domains of research within this field, namely: extended supply chain management dealing with relations between different partners inside a reverse logistics system, reverse distribution which includes collection and transportation aspects, and production and inventory management. Here, we focus on the last aspect and assume that an appropriate collection network exists which provides an OEM access to its own used products.

1.2 Inventory Management in Reverse Logistics

There are several reasons to keep stock in traditional production settings, as discussed in Silver et al. (1998), Chapter 3, and inventories can be classified based on their economic motivation. Specifically, safety stock is used to buffer from short term uncertainty of demand and supply, cycle stock is used to account for trade-offs between e.g. fixed setup and holding costs, and anticipation stock is often used to smooth capacity utilization in a dynamic (e.g. seasonal) environment.

Managing inventory in the presence of returns leads to additional complexity. In the case of safety stock, we must now account (in addition to the traditional demand uncertainty) for the uncertainty surrounding the supply of returns, whereas in lot sizing we must coordinate lot sizes and setup times for both production and remanufacturing. Stocks have to be distributed among inventories for serviceables and recoverables (returns). These issues have received attention in research (for reviews on inventory management in reverse logistics see Dekker and van der Laan (2003), de Brito and Dekker (2003) and Fleischmann and Minner (2004)), but they hardly explain the large amount of returned used products held in stock at remanufacturing facilities, as is confirmed by Seitz and Peattie (2004). When adapting our treatment of anticipation stock, we find that the addition of the return stream yields entirely new situations in which we hold stock, which directly result from the dynamic environment firms operate in.

A closer look at the product recovery environment reveals many factors which fluctuate over time. Starting with an obvious one, the demand for the product will vary over time. However, this is no surprise. Frequently, life cycle patterns as well as seasonality will influence demand. In medium-range aggregate production planning (Silver et al. (1998), Chapter 14), we seek to smooth capacity utilization by using seasonal inventory. The resulting solution lies between two extremes of nearly constant production (level) and production which is synchronized with demand (chase). The amounts of returned products may likewise vary over time, as is documented in the following two cases:

Case 1.1. DaimlerChrysler engines (see Kiesmüller et al. (2004))
DaimlerChrysler operates several facilities for recovering parts from used cars, one of which remanufactures used engines for Mercedes Benz cars at the plant Berlin-Marienfelde (MTC). Annually, about 12,000 engines from 28 classes and 800 different model variants are remanufactured. An ABC-classification revealed that 60% of the returns are contributed by 3 classes.
Dynamic issues, i.e. time dependent demands and returns, have to be considered for two reasons. First, demands for an engine class follow the shape of a product life cycle, starting with a phase of increasing sales, followed by the maturing phase and finally declining sales towards the end of a product's life cycle. Returns follow demands in a similar pattern, delayed by the usual life time of an engine and reduced by the number of not returned engines. In the growth phase, demand for remanufactured engines is significantly higher than available returns and all returned cores are remanufactured. Later in the maturing phase, demand decreases and returns can exceed remanufacturing orders. This divides the product life cycle into two main phases, the first with insufficient cores and another one with excessive cores. Similar effects, i.e. dynamic fluctuations of both, demand for remanufactured items and supply of returns, leading to shortage and overage situations have also been reported for car part remanufacturing at Volkswagen (van der Laan et al. (2004)).

Case 1.2. Kodak single-use cameras (see Goldstein (1994) and Guide et al. (2003b))
Introduced by Fuji Photo Film Co. as 'film with lens' and originally designed to be thrown away after use, the single-use camera now is another example of successfully closing the loop on a higher level of product recovery. According to Kodak (2003), about 775 Million cameras have been processed since the start of the product recovery program in 1990 and currently a worldwide return rate of 75% has been achieved. The amount of reusable materials ranges between 77-90% (by weight) of the product. Most recovered parts are plastic bodies, which are reused up to six times and the circuit boards required in flash cameras, which are used up to 10 times.
An important issue that Kodak faces is to deal with dynamic demand and return streams. Goldstein (1994) stated that there is "a lot of seasonality and cyclical behavior" in the market for single-use cameras. This stems from peak selling periods that differ among the various models: Underwater cameras mostly are sold in summer and winter vacation season, while flash cameras sell best around winter holiday season, and peak season for single-use cameras is between March and early September. On the reverse flow side, batch shipments from smaller photofinisher labs to collection facilities can lead to a delay of a couple of months between development of film and shipment to Kodak. On average it took between three and five months for a camera to be returned after being (re)manufactured. Although these numbers have been reduced in recent years, a large number of used products return at the end of a peak season or during off-season.

As the two cases have shown, there will be periods where returns exceed demand (excess returns) and other moments where demand exceeds returns (excess demand). Since available returns can also be seen as a capacity to recover products, an inventory can be used to enlarge the capacity when needed. Fleischmann and Minner (2004) call such stocks 'opportunity stocks', because they enable additional recovery opportunities. From a more strategic point of view, cost parameters themselves can change over time caused not only by external influences (such as ever-increasing disposal fees) but also by internal impacts like learning (or experience) curve effects. Lastly, in the long run, available capacity for product recovery is also not fixed over time but can be changed through capacity expansion or reduction.

Most of product recovery and inventory management models are either restricted to stationary conditions or treat dynamic aspects only numerically, for recent overviews on stochastic inventory control see van der Laan et al. (2004) and for lot sizing issues Minner and Lindner (2004). As a consequence, Dekker et al. (2000) suggest more examination of the effects of non-stationary demand/return conditions on inventory control for joint manufacturing remanufacturing systems.

This thesis concerns itself with the incorporation of dynamic issues in medium and long-term product recovery management. In doing so, we expressly ignore more operative disassembly issues, which would complicate matters. We also restrict ourselves to time-varying deterministic environments, ignoring short term stochastic fluctuations as is common practice in other medium to long term models. We avoid more unnecessary complication by examining the simplest case of a single product or a single part/module. Decisions faced in this realm include (1) when to invest in remanufacturing capabilities (if at all), (2) when to start collecting, hold stock of, and dispose of returns. It specifically deals with use of anticipation inventories for smoothing both capacity supply (e.g. return availability) as well as capacity demand. Strategic implications are expressly considered, especially the decision of whether to engage in a higher level of recovery or not, including aspects such as knowledge acquisition (e.g. experience curve effects) and the additional operational and investment expenditures required to implement product recovery processes (Toffel (2004)). The consideration of more strategic issues in research has been recently demanded by Guide et al. (2003a) since it is seen to be of particular value for practitioners. Long term decisions involve significant sums of money and are often difficult (if not impossible) to change. Examining our problem specifically, we can see that the decision on when to invest if made erroneously could result in opportunity costs rising from either lost recovery cost advantage (if made late) or capital costs (if made early). Investment on product recovery capability is a decision made very carefully by managers, and one that they certainly do not want to get wrong. Likewise, deciding on the correct time to start keeping excess returns is also important and has far reaching effects. If we start too early, we sacrifice capital costs filling our inventory with unusable scrap. This error would be particularly painful if we could have reaped a salvage value by ‘disposing’ of the returns. Waiting too long, on the other hand, results in lost recovery cost advantage.

1.3 Methodology

An appropriate way to examine long term issues is to use a continuous time model, which avoids the discretization of time and the influence of the choice of time units on the model and results. Another advantage of this modeling is that parameters can be given by continuous time functions, eliminating the need to specify them for each time period. Dynamic modeling properties motivates the use of the theory of *Optimal Control* as a solution method. Starting with the pioneering work by Pontryagin et al. (1962) it has reached a wide range of applications in economics and management, see e.g. Seierstad and Sydsæter (1987), Kamien and Schwartz (1991), or Sethi and Thompson (2000). It can be compared with dynamic programming methods developed by Bellman (1957) at about the same time but, according to Feichtinger and Hartl (1986), a main advantage of optimal control is the possibility of gaining insights into the *general structure* of solutions for an *entire problem class*.

Although there are extensions to solve discrete time problems, optimal control literature mainly deals with continuous time systems. A system in this sense is characterized by one or more state variables (e.g. an inventory stock level) which are changed by external influences (demand) or by choosing control variables (production). The development of the states is characterized by a differential equation named *state (transition) equation*. Both, state as well as control variables, can be subject to constraints which have to be considered. An optimal solution is given by optimal trajectories (functions of time) of the state and control variables which maximize (or minimize) a given objective function.

Pontryagin's Maximum Principle provides a set of necessary conditions for an optimal solution, which is also sufficient under certain conditions. Using the Maximum Principle the dynamic problem is decomposed into an infinite sequence of interrelated static problems, one for each time instant. These are connected by introducing co-state (also called adjoint) variables, which can interpreted as the shadow price of changing the system state. A static objective function, called *Hamiltonian*, is constructed in a way that it measures the total effects of the decisions at a certain time point on the objective. These can be split into a direct and an indirect effect. The direct effect is given for instance by the costs of producing an item. The indirect effect arises since decisions also have an influence on future opportunities by changing the system's state, e.g. by decreasing or increasing the inventory level. It is measured by the rate of change of the state times the corresponding shadow price (given by the co-state). This yields another advantage of optimal control since the co-states can also be interpreted as the value of e.g. another returned item, a produced, or remanufactured product.

As in dynamic programming, where an optimal decision is taken at each stage (instant of time) assuming that up to that point all decisions have been taken optimally and the same will hold for future decisions, the Hamiltonian has to be maximized at each instant of time by appropriately choosing the controls for given optimal state and co-state values, subject to relevant constraints on control and state variables. This is applied by using standard methods of non-linear programming. Further necessary conditions contain the rate of change of the co-state variables. Thus, a system of differential equations including the state transitions, co-state transitions, and optimal control policies has to be solved.

For an overview on traditional continuous time production and inventory models see e.g. Feichtinger and Hartl (1986), Chapter 9 or Sethi and Thompson (2000), Chapter 6. Well known examples are variants of the HMMS-model (Holt et al. (1960), Thompson and Sethi (1980)) that uses a quadratic objective in order to retain goal levels for both inventory and production. Linear inventory and convex production costs are used in Arrow-Karlin type models (Arrow and Karlin (1958)). More recently, these models have been extended to cope with environmental issues. Wirl (1991) and Hartl (1995) analyzed effects of environmental constraints in the Arrow-Karlin model and Dobos (1998) used the HMMS approach. Product recovery systems including remanufacturing and disposal of returned products under non-linear cost regimes are covered e.g. by Kistner and Dobos (2000). In most practical situations, however, a linear cost regime is present and will be used throughout this work. Recent applications of optimal control in dynamic product recovery are reviewed by Kiesmüller et al. (2004).

1.4 Outline of the Thesis

The road-map followed in the succeeding chapters is given as follows.

In *Chapter 2*, a basic model for product recovery is presented. It aims to explain under which conditions returns should be kept in an anticipation stock. It extends the investigation of a single product/single stage product recovery system by Minner and Kleber (2001) by allowing for discounting. Some attention is paid to the valuation of inventories which in this case can be quite easily accomplished through exploiting the advantages of the solution methodology.

In traditional medium-term aggregate production planning an anticipation stock is used when capacity of the cheaper regular mode becomes binding in order to avoid high costs of overtime. However, the second supply source might also be limited. Therefore, *Chapter 3* discusses the implications of capacity constraints on both the cheaper source (remanufacturing) and the 'overtime' mode (production).

Chapter 4 relaxes the assumption of general preferability of remanufacturing over manufacturing. Knowledge acquisition during repeated remanufacturing operations can itself lead to profitable remanufacturing, even if there is no immediate cost advantage. The influence of learning in the remanufacturing process on stock-keeping decisions is analyzed, revealing that (under certain circumstances) another motive for holding recoverables is to postpone the start of remanufacturing.

Chapter 5 deals with the use of anticipation inventory in controlling remanufacturing capacity over the product life cycle in the most simple case, the choice of the investment time of a remanufacturing facility with unlimited capacity. More specifically, when introducing a new product, two related decisions have to be considered, namely product design and the choice of the recovery mode and a corresponding technology. This is accomplished by considering the influences of such decisions on direct production costs and initial investment expenditures. Taking into account the limited availability of used products in the beginning of a products life cycle and a decreasing time value of the required investment expenditures connected with the set-up of the remanufacturing process, the issues addressed here are when to initiate this process and how the use of a strategic recoverables inventory does affect this decision.

Some concluding remarks are given in *Chapter 6*, along with a recapitulation of the main results of the thesis, as well as a short discussion of related work.