REVERSE LOGISTICS AND ENVIRONMENTAL CONSIDERATIONS IN EQUIPMENT LEASING AND ASSET MANAGEMENT

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REVERSE LOGISTICS AND ENVIRONMENTAL CONSIDERATIONS IN EQUIPMENT LEASING AND ASSET MANAGEMENT

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

Today many business enterprises employ capital assets in the form of electronic equipment (*e.g.*, personal computers, workstations and peripherals) in large quantities. As a result of rapid technological progress, these products have a very short life cycle, typically not much more than three or four years. Unfortunately, the disposal of electronic equipment (which contains hazardous materials) presents an environmental problem.

In the face of rapid equipment changes, current tax laws and disposal challenges, leasing or procurement contracts with take-back considerations are attractive. For a large electronic equipment leasing company, optimal management of assets supported by good logistics decisions is crucial and may provide a significant competitive advantage. The leasing company tries to maximize operating profits through key decisions associated with the length of leases, efficient utilization of logistics facilities for material flow to and from customer sites, and equipment reuse, refurbishment and disposal actions.

In this research, a mixed integer linear programming (MILP) model is developed to facilitate better decisions from the perspective of an electronic equipment leasing company. The model reduces to a linear program (LP) under certain cost assumptions. A case study with representative industry data validates the approach and demonstrates the utility of the model in answering key research questions. Since the aforementioned cost assumptions are industry representative, all computational results are based on the LP version of the model.

Next, important problem uncertainties are identified and prioritized. The effects of these key uncertainties on optimal lease length and product flow decisions are examined in detail via an extended case study. It is also shown how the leasing company can make near-robust leasing decisions in the face of these uncertainties.

The computational research results also have implications for policy formulation on electronic waste. The important insights include an understanding of the potential impacts and expected effectiveness of alternative environmental legislation in different geographic areas, and the imposition of negative externalities on other policy realms as a result of this non-uniform approach. Therefore, this research contributes new models and understanding to the intersection of the fields of reverse logistics and equipment replacement, and provides valuable insights to both business asset managers and environmental policy makers.

CHAPTER 1

INTRODUCTION

1.1 Problem background

In 2002, the Equipment Leasing Association estimated that of the total investment in business equipment by companies, nearly one-third, or \$204 billion, would be financed through leasing [32]. A key portion of the logistics cost for the leasing industry, the transportation costs, is approximately 1.5% of total costs [94], or approximately \$3 billion for 2002. Clearly, logistics decisions greatly impact asset management problems faced by equipment leasing companies.

This research addresses the special asset management problem faced by electronic equipment leasing companies. An estimated value of the sales of computers and electronic products (excluding semiconductors) in 2002 is \$140 billion [95]. Even though many of these computers would have been sold to individual consumers, the extension of general leasing trends to electronic products makes it clear that electronic equipment leasing companies can realize substantial benefits by making efficient logistics decisions.

Today, business enterprises use capital assets in the form of electronic equipment (*e.g.*, personal computers and workstations) in large quantities. The estimate for average computers per employee in 2001 was 0.56, with the ratio being as high as 0.99 in certain industries [99]. However, as a result of rapid technological progress, these products have a very short lifecycle. Typically, due to ever-increasing computing needs that arise out of growing business data, new software and new operating systems, their useful life is not much more than three or four years. After this time, some of the equipment can be redeployed to other suitable applications within the same organization. Some of it may be refurbished or cannibalized for parts and the remainder resold or discarded.

In light of increasing environmental consciousness and stricter legislation, disposal of electronic equipment, which contains hazardous materials, presents another problem. Employees in the organization may not have incentives, or even enough relevant knowledge, to make economically and ecologically optimal decisions for the overall useful lifecycle of these electronic products. Therefore, leasing or procurement contracts with take-back considerations become attractive options.

Introduction of environmental legislation with regard to electronic waste, combined with the short lifecycle of electronic equipment like computers, is expected to change the business strategies of firms in fundamental ways. The methodology developed in this research must therefore take these factors into account. The next section formally defines the problem that will be addressed in this dissertation.

1.2 Problem definition

This research considers the problem from the perspective of a leasing company that offers operating leases on electronic equipment and may therefore be required to take back these products at the end of their useful life. Due to the intense competition, overhead costs, and the fact that equipment may be available on the market at very moderate prices, it is quite difficult to sustain profitable business operations just by varying the prices offered to customers. Therefore, effective management of these assets, supplemented by good logistics decisions, is crucial for such a business enterprise and may provide a significant competitive advantage. In fact, there have been reports that by turning assets over multiple times and by refurbishing between lease cycles, leasing companies are able to offer operating leases that do not recover the initial purchase price of the equipment in the first leasing cycle [18]. In order to maximize operating profits, the key decisions to be made are:

- Length of leases on a given set of assets,
- Efficient utilization of logistics facilities for material flow to and from customer sites, and
- Disposition actions after take-back; *e.g.*, resale (reuse), refurbishment, metal/glass/plastics recycling and landfilling.

These decisions are clearly interdependent. For example, the time lag between the lease and return of the products significantly affects the feasibility and cost of post take-back options; *e.g.*, the resale value of the latest configuration of a computer (newest technology) after five years will be much lower than that after two years. In fact, after five years, it may not be possible to resell the computer at all. Similarly, it may be more economical to maintain an inventory of older assets (which may be leased to users with lower requirements) rather than buying new assets for every order and disposing of all used assets that are returned at the end of the lease. In addition, the existence of alternative environmental legislation on electronic waste in different geographical regions (nationally and internationally) must be taken into account to ensure the legality of post take-back disposition actions and to reduce disposal costs. Therefore, in order to improve profitability, it is essential that these decisions be made simultaneously. In summary, the problem statement can be written as:

> "*In the presence of short product life cycles and increasingly strict environmental legislation for electronic products, how can efficient reverse logistics and equipment replacement* (*leasing*) *decisions be made simultaneously so as to maximize profitability?*"

However, due to the interdisciplinary nature of this problem, a detailed examination of the nature of key decisions and how they are affected by changes in problem parameters spanning across the various related disciplines has the potential to provide novel insight not only to business managers, but also to environmental policy makers. For example, by observing the changes in behavior of firms with state-sponsored environmental legislation in place, it is possible to obtain insight into the expected effectiveness of the formulated legislation. In addition, legislative effects that may not be immediately apparent at the time of formulation could be revealed. Therefore, other important questions that this research hopes to answer include the following.

- What effects do state-sponsored environmental initiatives (*e.g.*, landfill bans, advance recycling fees (ARFs), recycling disposal fees, etc.) have on the key decisions made by the leasing company?
- Do differences between environmental legislation in different locations (globally and nationally - such as between the European Union and the U.S., and even between different states within the U.S.) change the key decisions? If they do, what are the possible implications of the observed changes?

This research studies this important practical problem using an analytical approach, which is the formulation of a mixed integer linear program (MILP) to model and solve the problem. The model reduces to a linear program (LP) under certain realistic cost assumptions, and all computational results are derived using the LP version of the model.

The research results are expected to provide valuable insights to business asset managers and environmental policy makers. The next section briefly discusses the organization of this dissertation.

1.3 Organization of the dissertation

Before a detailed discussion of the research approach, it is essential to review the relevant literature published so far, and to show that the problem described in this proposal has not been addressed so far in published literature. Chapter 2 presents a literature review covering the various aspects of this problem, and shows how this research bridges some of the gaps in existing literature.

As mentioned in Section 1.2, the analytical research approach of this dissertation is the formulation of a MILP to model the problem. Chapter 3 describes the mathematical model that has been formulated for this problem and discusses its main characteristics, including strengths and limitations. Subsequently, a case study with representative industry data is presented in order to validate the model and to demonstrate its utility in answering the key research questions.

Chapter 4 considers a more realistic situation, where uncertainty is present in problem parameters. Various uncertainties are considered, following which they are prioritized and the effects of key uncertainties on optimal decisions made by the leasing company are examined in detail. The chapter also includes a discussion about how the leasing company can make near-robust decisions in the face of uncertainty.

The results obtained in Chapters 3 and 4 also have implications for the formulation of environmental policy. Therefore, a discussion of these policy implications and the insights provided by this research into aspects of policy formulation on electronic waste is the subject of Chapter 5. The chapter also includes short essays on policy issues that are indirectly related to this research, but not addressed herein. Finally, Chapter 6 presents conclusions and the expected contributions of this dissertation. Interesting directions for future research are also discussed.

CHAPTER 2

LITERATURE REVIEW

In this chapter, a review of published literature related to the various aspects of the research problem in this dissertation is presented. Section 2.1 discusses literature on parallel asset replacement, a popular research area for engineering economists. Section 2.2 discusses literature on asset replacement literature with uncertainty. The primary types of uncertainties examined in existing literature address changes in problem parameters (such as cash flows and discount rates) and technological change. Reverse logistics and environmental issues are integral parts of this research as well, and therefore, quantitative models for reverse logistics are the subject of Section 2.3. The status of environmental legislation on electronic waste is the subject of Section 2.4. Finally, a summary discussing the trends in published literature and the gaps in existing research directions is provided in Section 2.5.

2.1 Literature on parallel asset replacement

The leasing activity by itself (*i.e.*, how long to lease an order) is quite similar to a *parallel asset replacement problem*. Parallel asset replacement concerns the replacement of a multitude of economically interdependent assets that operate in parallel [77]. Issues such as demand, economies of scale and budget constraints may cause the interdependence. Customers replace assets when the costs of retaining them outweigh the benefits; similarly, leasing companies end leases (analogous to customers' replacement of assets) when the costs of leasing outweigh the benefits.

Vander Veen (1985) [102] provides the first known formulation of a parallel replacement problem. The formulation is a mixed integer linear program. Demand is considered to be deterministic, but non-stationary. The total number of machines is assumed constant over time, and therefore, demand fluctuations are addressed by allowing machine utilizations to be decision variables.

Jones, Zydiak and Hopp (1991) [55] introduce a different parallel machine replacement problem, assuming constant demand but including economies of scale (fixed asset purchase costs and variable operating costs). They formulate the problem using dynamic programming and solve it using linear programming. To facilitate solution, they first illustrate the *no splitting property*, which states that clusters of same aged assets would either be kept or replaced as a group in any period. They then prove the *older cluster replacement rule*, under mild cost assumptions, which states that older assets must be replaced before younger assets. Tang and Tang (1993) [89] extend the results, under slightly milder cost assumptions, to the *all-or-none replacement rule*, which states that in any period, it is optimal to either keep or replace all machines regardless of age. Hopp, Jones and Zydiak (1993) [47] relax the cost assumptions a little further and prove that the older cluster replacement rule still holds. Chen (1998) [22] and McClurg and Chand (2002) [65] provide algorithms for the parallel replacement problem introduced by Jones, Zydiak and Hopp. McClurg and Chand also prove the no splitting property and the older cluster replacement rule under different cost assumptions.

Rajagopalan (1998) [79] expands the problem to include arbitrary demand patterns, and provides an alternate formulation of the problem, which allows for more efficient dual-based solution procedures. Hartman and Lohmann (1997) [46] formulate an integer program to minimize the purchase, operating and maintenance (O&M) and salvage costs for a fleet of assets of a large railroad company where multiple replacement options such as purchases, leases and rebuilds are allowed. “Salvage” of an asset means that it is disposed of at a fixed cost (or revenue). Additional constraints such as meeting the demand and not exceeding capital or expense budgets are taken into account. Assets are also allowed to vary in their utilization and capacity. Chand, McClurg and Ward (2000) [20] present a special case of these two problems, but use a different model and solution procedures. Non-declining demand is assumed.

Karabakal, Lohmann and Bean (1994, 2000) [57][56] address a parallel asset replacement problem where economic interdependence between assets is caused by capital rationing and budget constraints. The problem is formulated as a 0-1 integer program. In their first paper (1994), they use a branch-and-bound algorithm to solve moderately sized vehicle fleet replacement problems optimally. Their second paper (2000) extends this line of research by developing a heuristic Multiplier Adjustment Method (MAM) for solving large, realistically sized problems. Their results suggest that the effectiveness of their approach increases with the problem size.

Hartman (2000) [43] provides an integer programming formulation of the general parallel replacement problem, which includes economies of scale in asset purchases, fluctuating demand and capital budgeting constraints. It is shown that the problem structure allows for efficient solution procedures. The paper also generalizes the no splitting property to cases with demand and budgeting constraints.

All the papers discussed earlier assume that the assets are homogeneous. Even though many of the aforementioned papers mention possible methods of incorporating asset heterogeneity in their models, it is not clear whether the proposed algorithms and solution procedures would continue to be valid. Only a small body of published literature explicitly addresses the parallel asset replacement problem with heterogeneous assets.

Wu, Hartman and Wilson (2002) [104] formulate and solve a model for fleet sizing with heterogeneous assets, in context of the truck rental industry. Operational decisions, including demand allocation and empty truck repositioning, and tactical decisions, including asset procurements and sales, are examined in a linear programming model in order to determine the optimal fleet size and mix. A two-phase solution approach, with Benders' decomposition used in Phase-I, and the initial bounds and dual variables from Phase-I are used in Phase-II to improve solution convergence, by using Lagrangian relaxation. Computational studies are presented to show the effectiveness of the approach for solving large problems within reasonable solution gaps.

Hartman and Ban (2002) [44] model a series-parallel replacement problem, where the (heterogeneous) assets are dependent both serially and parallelly, such as in a parallel flow shop environment considered by the authors. An integer programming formulation is used to determine optimal purchase, salvage, utilization and storage decisions for each asset over a finite horizon. The authors illustrate that this model is difficult to solve, provide valid inequalities to improve lower bounds and use a dynamic programming approach to provide initial upper bounds.

Clearly, replacement analysis is a fundamental problem in engineering economics, and active research in this field is on-going, particularly for the solution of large-scale real-life problems. Since the leasing aspect of the problem addressed in this research is quite similar to parallel replacement with heterogeneous assets, the literature discussed in this section is relevant. However, all the papers discussed in this section use deterministic models, which are very useful, but cannot address the uncertainty inherently present in all real-world problems. Therefore, the next section discusses literature on uncertainty in asset replacement problems.

2.2 Literature on uncertainty in asset replacement problems

Existing literature pertaining to uncertainty in asset replacement can be classified primarily into two categories. The first category of problems addresses uncertainty in important asset replacement parameters such as cash flows, machine utilization, planning horizon and interest rates. This literature is discussed in Section 2.2.1. The second category of problems is related to the effects of technological change on key asset replacement decisions. Although technological change primarily affects cash flows and can therefore be regarded as a special case of the category of problems addressing uncertainty in asset replacement parameters, it is a sufficiently important issue in asset replacement problems so as to warrant a separate discussion. This literature is discussed in Section 2.2.2.

2.2.1 Uncertainty in asset replacement parameters

The examination of uncertainty in cash flows and discount rates is central to the discussion of uncertainty in economic analysis in general, and is not restricted only to asset replacement. For example, Quah and Tan (2001) [78] propose a framework for cost-benefit analyses of public projects in the face of uncertain project life and future cash flows. Their work is based on known probabilistic techniques from actuarial literature. Chiu and Park (1994) [25] propose a fuzzy number methodology for evaluating and comparing the present worth of projects with uncertain cash flows and discount rates. The uncertain cash flows and discount rates are modeled as triangular fuzzy numbers, and the present worth is also a fuzzy number, but with a non-linear membership function. The authors then approximate the present worth with a triangular fuzzy number, examine the deviation between the exact present worth and its approximation, and present project selection criteria based on different dominance rules. A numerical example is also presented.

The literature on uncertainty in asset replacement problems is not extensive and has, until recently, concentrated on serial rather than parallel replacement. Some of the relevant literature in the field is discussed below.

Lohmann (1986) [63] introduces a stochastic single-asset replacement model where all cash flows are allowed to be random. The model is solved using Monte Carlo simulation and dynamic programming. Smith and Wetzstein (1992) [86] consider a stochastic asset replacement model for rejuvenated (or rebuilt) assets. The financial returns generated by a productive asset are assumed to be stochastic. The authors also consider the covariance among multiple prices and outputs (or revenues) within the life of a current asset and all future assets. Optimal replacement and rejuvenation policies are derived over an infinite planning horizon. A numerical example of laying hen replacement is presented. Brown (1993) [19] considers a serial replacement problem with uncertain rewards, which may be correlated across replacements. The objective is to maximize the decision maker's expected utility. The correlation across replacements precludes a dynamic programming approach, but the author's bound-based heuristic procedure is shown to outperform existing solution approaches.

Esogbue and Hearnes (1998) [33] discuss a fuzzy number approach for calculating economic asset life as well as for a finite-horizon single asset replacement problem with multiple challengers. Various ranking methods for fuzzy numbers are also mentioned. Chang (2003) [21] presents a very comprehensive fuzzy number approach for replacement analysis, including both deterioration (due to aging) and market obsolescence of equipment. The market share of equipment is considered a function of equipment age as well as acquisition time (intended to capture technological change). All problem parameters (except the planning horizon) such as cash flows, interest rates, market demand and equipment utilization factors are modeled by fuzzy numbers. The author then presents methodologies for determining economic asset life and replacement strategies for a single asset with multiple challengers.

Hartman (2001) [41] focuses on variable asset utilization (a concept introduced by Bethuyne, 1998 [15]) that occurs due to randomness in operating conditions and market demand. The use of an asset is limited by both age and cumulative utilization, and periodic usage levels are probabilistic. A single asset (defender) with multiple challengers is considered. A stochastic dynamic programming approach is used for solution, and the concept of an “economic life frontier” is introduced in order to simplify the definition of economic life. This analysis is extended to parallel asset replacement in Hartman (2004) [42]. In this case, the demand is assumed to be stochastic (with a discrete distribution) and is met by allocating it amongst a group of assets operating in parallel. Clearly, asset utilization is once again a variable. Theoretical results are derived for the two-asset case, an efficient solution procedure is developed, and numerical examples are presented. Insights are also provided into the general *n*-asset case.

2.2.2 Equipment replacement under technological change

The rapid pace of technological progress in the area of electronics and computing has caused computers and other electronic equipment to have a much shorter useful life as compared to railcars or vehicles. This issue is of great interest to both lessors and lessees (users of the leased equipment). Lessors need to make sure that they lease out the latest product offerings to customers (since the early part of the life cycle of a new product is likely to be the most profitable for a lessor) and lessees need to ensure that the equipment that they have meets their business requirements. Therefore, in this section, some relevant literature that addresses the problem is discussed, even though asset replacement under technological change has not been explored in this research.

Hopp and Nair (1991) [49] formulate the problem of equipment replacement with technological change by assuming the costs of currently available and future technologies to be known, but the timing of the technological advances to be uncertain. It is also assumed that the revenue generated by a technology is constant over time. They use a planning horizon approach for incorporating technological forecasts. A “stopping rule” is developed for the case where at most two technological improvements are allowed. Nair and Hopp (1992) [70] extend the problem by allowing the costs and revenues associated with each available technology to vary over time. “Forecast Horizon” techniques are used to convert the infinite horizon problem into a finite horizon problem, and therefore to enable appropriate calculations to be performed to solve it. Nair (1995) [69] further extends this work and derives analytical results for a problem where any number of new technologies may appear sequentially in the future. The author also introduces the concept of “converse functions” and gives an efficient algorithm to solve the problem.

Hopp and Nair (1994) [48] modify a single-asset replacement problem with the possibility of a single (but uncertainly timed) breakthrough in the replacement technology by considering Markovian deterioration of the equipment condition. They conclude that the possibility of a technological change may provide an incentive or disincentive for keeping the current asset rather than replacing it. Similarly, Bethuyne (1998) [15] shows that for asset replacement under ongoing technological progress, one cannot neglect the opportunity cost of foregone technological progress at the time of replacement, and therefore rapid technological progress does not always imply a decrease in replacement intervals. Cheevaprawatdomrong and Smith (2003) [23] use a simple technological change model of a constant factor improvement in equipment costs per period, and show (with certain cost assumptions) that the effect is to optimally delay the introduction of new technology.

A more comprehensive paper by Rajagopalan *et al.* (1998) [80] simultaneously considers capacity expansion and replacement under technological change. The authors first formulate a model for a deterministic case, derive some structural results and extend the results to the general case with stochastic technological evolution, which is modeled as a semi-Markov process. The authors give an efficient solution procedure for their model, perform computational studies and explore the impact of key problem parameters on the solution.

Amongst other methods for analyzing equipment replacement under technological change, the most prominent is the assumption of a known function of technological change. Oakford, Lohmann and Salazar (1984) [76] present a single-asset replacement model where technological change affects cash flows via known mathematical functions. Regnier *et al.* (2004) [83] extend Grinyer's model (1973) [38] of using a known function of technological change, and consider a single asset replacement problem with ongoing technological progress that affects assets available after multiple future replacements. The authors allow for variable non-identical service lives of future replacements, and it is shown that a stationary policy is necessarily sub-optimal when capital and O&M costs change at different rates. They also find that considering the effect of future assets can substantially affect the first replacement decision and resulting total discounted costs.

The effects of uncertainty on optimal lease length and product flow decisions are examined in this dissertation. Since this research addresses more than a simple equipment replacement problem, the key uncertainties to be addressed are not the same as those in literature cited in this section. However, the issues addressed by the literature discussed in this section remain relevant to the research problem. The next two sections discuss reverse logistics models and environmental legislation, issues that are also strongly related to this research.

2.3 Quantitative models for reverse logistics

This research also involves some aspects of reverse logistics because there exists a “reverse” flow of products from customers back to the leasing company. However, due to the unsuccessful attempt at locating any analytic reverse logistics models for leasing company decisions in current literature, this section cites the most closely related reverse logistics literature, which includes mathematical models for the design of reverse logistics systems. A few details are provided for results concerning electronic products, and reverse logistics literature related to other products is cited for further reference by the interested reader.

Fleischmann *et al.* (1997) [36] present a review of quantitative models for reverse logistics. Reverse logistics was a very young field at that time, and they conclude that many reuse or recycling activities required new planning methods and more comprehensive approaches than those that had been used up to that time. In accordance with this philosophy, Fleischmann (2001) [35] proposes a generic recovery network model, and tests it on case studies for copier and paper remanufacturing. The mixed integer linear programming (MILP) model decides the number of uncapacitated facilities, their locations (from among a discrete set of possible locations), and the allocation of corresponding goods flows. The objective is to minimize total investment and operational costs for a single product. The model is solved using CPLEX, one of the most widely used commercial mathematical programming optimization solvers. Variability in product returns is addressed by running the model on a set of scenarios with different parameters.

By solving the case studies, the authors attempt to determine the sensitivity of the solution to problem parameters. Some possible extensions to the model are also proposed.

Ammons *et al.* (1999) [4] develop a generic network design model for the carpet industry (Realff *et al.*, 1999 [81] and Realff *et al.*, 2004 [82]) and use it on studies for an international producer and distributor of high value network routing units. The model is solved using the commercial solver AIMMS. Uncertain product take-back volumes are studied by solving the model for different quantities of take-back amounts. The authors also examine the effects of product redesign on the reduction of noxious wastes generated by the recycling process.

Krikke *et al.* (1999) [60] discuss a business case for the Dutch copier manufacturer Océ. The objective is to redesign the reverse logistics network in order to minimize cost. The authors use a MILP model and solve it using LINDO, another commercial software available for mathematical programming. Due to company requirements, the authors have been forced to design the reverse logistics networks assuming a fixed forward logistics network, a method that does not minimize true costs. Another paper by the same authors (1999) [61] describes a business case study concerned with the determination of an optimal recovery strategy for the recycling of discarded computer monitors. The aim is to analyze the economical viability of monitor recycling on the one hand and to validate the practical viability of the models developed in earlier research on the other hand.

A working paper by Krikke *et al.* [59] discusses logistics network design for a production and return network for refrigerators, and the model is applied to the real-life data of a Japanese consumer electronics company. The MILP model incorporates both supply chain costs and its environmental impact by including location-allocation decisions and product design options as decision variables.

Shih (2001) [85] formulates a MILP model for design of an optimal collection and recycling system plan for end-of-life computers and home appliances. The optimal physical flows of end-of-life products flowing through collection points, storage sites, recycling plants and final disposition sites are obtained. The objective function consists of the fixed cost of new (capacitated) facilities, transportation costs, final treatment costs and the revenue obtained from selling reclaimed materials. The model parameters have been estimated due to the absence of historical data for Taiwan.

So far, all papers discussed in this section addressed uncertainty in product returns by examining a finite set of scenarios. Ammons *et al.* (2002) [3] extend this idea by developing a solution methodology using an upper and lower-bounding scheme on the robust objective function. Assavapokee (2004) [5] extends it further to develop a methodology to solve problems where the parameters can take values from a compact real interval. The application of these approaches is demonstrated by a case of reverse production system planning for the reuse and recycling of electronic equipment (TVs, CRTs and CPUs) collected from residential sectors of the state of Georgia, with particular emphasis on avoiding the disposal of hazardous materials in landfills.

Mathematical models have also been proposed for recycling of paper (Bloemhof-Ruwaard *et al.*, 1996 [16]), steel (Spengler *et al.*, 1997 [87]), sand (Barros *et al.*, 1998 [8]), and perhaps other materials as well. In recent times, more literature on stochastic inventory models for reverse product flows has started to appear. Other literature that involves reverse product flows belongs to the fields of warranty and service parts logistics (Cohen *et al.*, 1997 [27], Cohen *et al.*, 1999 [28], and Murthy and Djamaludin, 2002 [68]). The primary consideration here is to strike a good balance between inventory holding costs and good customer service, and therefore, most of this literature focuses on stochastic inventory models as well. Formulation of stochastic inventory models is not a part of this research, and therefore, such literature will not be discussed here.

Reverse logistics and related inventory and environmental issues are important for this research, even though logistics network design and inventory management are not its objectives. The discussion in this section suggests that this research presents the first known model to integrate reverse logistics decisions with equipment leasing decisions (lease lengths, logistics system utilization and disposition actions after end of lease) from the perspective of an electronic equipment leasing company.

2.4 Environmental legislation on electronic waste

The global emergence of increasingly stricter legislation on “Electronic Waste,” or Waste Electronic and Electrical Equipment (WEEE), necessitates proper handling and disposal of the used equipment at the end of its useful life. Two key concepts related to environmental concerns are Sustainable Development and Extended Producer Responsibility (EPR). For perspective, a brief overview of current and impending WEEE legislation across the globe is given in this section.

The European Union (EU) Directives on the management of WEEE and the restriction on the use of certain hazardous substances in electronic equipment (RoHS) issued by the European Parliament and the Council of the European Union were adopted in November 2002. WEEE proposes take-back obligations for electronics manufacturers (free of charge for the final user, a visible up-front fee can be added to the new product's price until August 13, 2005 to account for “historical” waste), a minimum rate of separate collection of WEEE of four kilograms on average per inhabitant and year by 2006, and product-type specific recycling targets. Users of electrical and electronic equipment from private households should have the possibility of returning WEEE free of charge, but member states may make users other than private households partly or fully responsible for the financing of recycling operations. Producers are to be responsible for providing guarantees that future costs will be covered for all WEEE sold after August 13, 2005 [34][93]. RoHS proposes a ban on heavy metals (lead, mercury, cadmium and hexavalent chromium) in electronic equipment that will commence in July 2006. Member states are required to transpose the directive into national legislation by September 2004. Prior to the adoption of the WEEE Directives, take-back and recycling legislation for certain electronic goods had already been in force in some member states such as Belgium, The Netherlands, Norway, Switzerland and Sweden, and these countries will revise their legislation in accordance with the EU WEEE Directive.

However, there is still considerable debate about the effectiveness of the proposed EU directives. For example, Stevels (2002) [88] highlights the three environmental aspects of “green” (emissions, natural resource utilization and potential toxicity) and argues that the European policies and directives are one-dimensional. He also states that different stakeholders (scientists, governments and consumers) possess different perspectives on “green,” and therefore contribute to the debate. He proposes a method to balance environmental dimensions and stakeholder perspectives, stresses on defining terms clearly in order for operationalization of directives to be effective and highlights the role of "Eco-Design." Huisman (2003) [50] formalizes these ideas by defining a concept called QWERTY/EE, an integrated approach that takes into account economic, environmental, product redesign and legislative aspects of take-back and recycling programs for electronic products.

The Environmental Protection Administration (EPA) of Taiwan announced a Scrap Home Appliances and Computers Recycling Regulation in March 1998 that mandates manufacturers and importers to take-back their products [85]. An end-of-life measure, which covered selective WEEE items (computers not included), was enacted in Japan in April 2001. This legislation requires individual consumers to pay the direct costs of transporting and recycling their goods at the point of recycling - as much as ¥4000 (approximately $40) for a large appliance. However, a Computer Recycling Law has been enacted, effective October 2003, whereby it is compulsory for electronics manufacturers to collect and recycle PCs. As a result, the recycling costs are included in the sales price for most appliances. Consumers can drop off used electronic equipment at post offices, or contact the manufacturer for arranging pick-up [53][54][84].

Among the countries where legislation is not as strict but awareness about the scale of the electronic waste problem is rapidly growing, are Australia, Canada and the United States. There is considerable debate about suitable legislation and policy roadmaps for dealing with the problem in a fair and effective manner. The Australian Department of the Environment and Heritage has recommended the establishment of a National Electrical and Electronic Products Recovery Program. The program would cover personal computers and peripherals, TVs, VCRs, white goods and other electrical appliances. The proposed initiatives include a voluntary and transparent levy on the sale of new computers, peripherals and TVs to fund electronics recycling infrastructure and implementation of landfill bans or higher landfill charges for computers and TVs [6].

In Canada, electronics manufacturers are expected to create, manage and finance an E-waste management program targeting both consumer and commercial waste. An industry-led non-profit organization called Electronics Product Stewardship Canada (EPS Canada) [31] is developing a national electronics end-of-life program in Canada. However, provincial priorities are expected to be important in the development of solutions, and EPS Canada would like the establishment of a national program that would meet or exceed the requirements of provincial governments. In May 2004, the province of Alberta announced an electronics recycling program, whereby computers, TVs and peripherals would be collected, reused and recycled, effective October 2004. The Alberta Recycling Management Authority (ARMA) will manage the program, which would be financed by an end-of-life fee ranging from \$5 to \$45, depending on the item [2]. Laws governing electronics product disposal are also likely to come into force in the provinces of Ontario, Manitoba and British Columbia in 2004, and ultimately in all provinces.

There are diverse activities in the U.S. The U.S. Environmental Protection Agency (EPA) believes in shared responsibility that places greater, but not sole, responsibility on producers [97][98], but has not yet put forth any ideas for comprehensive national legislation. The result is a patchwork of alternative state-level legislation. Legislation is pending or in force in many states across the country, and is being actively debated in many others. The National Caucus of Environmental Legislators [71] tracks the status of electronic waste legislation across various states, some of which is summarized below.

A landfill ban on the disposal of Cathode Ray Tubes (CRTs) is in effect in Massachusetts [64]. A similar ban is scheduled to come into force in Minnesota (July 2005), Maine (January 2006) and Washington (January 2006). Several states have set up (or passed legislation to set up) committees and councils to look into viable options for environmentally friendly disposal of electronic waste. Examples include Georgia, Oregon, Rhode Island and Washington. A recent California bill establishes an Advance Recycling Fee (ARF) of \$6-\$10 on all electronic products containing CRTs, which would be used to fund an electronics recycling system in the state. Maine has mandated a similar \$6 fee on televisions from 2005 to 2011. Maine has also approved EPR for computer manufacturers (starting 2006) and television manufacturers (starting 2012). Washington has proposed a similar EPR initiative, but it has not been enacted so far. In addition, several states have passed legislation mandating the phase-out of heavy metals from electronic products (similar to the EU's RoHS Directive), with California and Maine being the most active [71]. These developments strongly suggest that the legislative developments on stricter environmental requirements for electronic products in Europe and Asia are certain to have an impact on U.S. firms, especially those that operate in these regions.

An indirectly related, but nevertheless very important, issue is the Basel Convention [12], an international treaty to which 134 nations are a party, and which restricts the movement of hazardous wastes and their disposal across national borders. A huge amount of electronic waste from the U.S. is being exported to third-world countries like India, China and Pakistan [10]. A recent report also suggests that Canada is exporting E-waste to third-world countries, contrary to its obligations under the Basel Convention [9].

This discussion brings to light the fact that there currently exists great uncertainty and considerable debate about environmental legislation throughout the world. A significant portion of the debate is about who pays for the system to be "environmentally friendly," which often leads to divergent points of view held by businesses, governments and consumers. A fair agreement on the economic aspect of environmental policies allows them to be effectively implemented, and it is anticipated that this research will also be able to provide insights into the expected effectiveness of formulated environmental policies.

2.5 Summary of literature review

Surprisingly, there seem to be very few mathematical models that address business operations like asset management and logistics simultaneously. There is a great deal of literature in the individual fields of study related to the various aspects of this problem, and some of it is briefly overviewed in this chapter.

Asset replacement has been and continues to be a popular research area. This literature examines the problem from the perspective of the user of equipment rather than the lessor, but the decision is analogous for leasing companies, and hence Section 2.1 discusses relevant literature on parallel asset replacement. Most of the research in this area has tended to address the problem primarily from an engineering economy or finance point of view. Therefore, all characteristics of the assets are captured in terms of money. Peculiar characteristics of some assets that significantly distinguish them from other types of assets seem to have been taken into account only in limited ways.

Since uncertainty is present in all real problems, and this research investigates the effect of certain problem uncertainties on lease length and product flow decisions, literature on asset replacement under uncertainty is presented in Section 2.2. The key uncertainties for this research are different, and issues of technological change are not explored here. However, these issues remain very relevant because the rapid pace of technological progress in the area of electronics and computing results in computers and some other electronic equipment having a much shorter useful life as compared to railcars or vehicles.

Reverse logistics has emerged as an important area of study recently. The earlier literature primarily addresses various kinds of real-world problems, and such work continues to be published. However, many of the recent papers have also been more theoretical in nature, such as the inventory models mentioned at the end of Section 2.3. Taking into account the fact that forward logistics and inventory systems have been extensively studied by now, it does seem that reverse logistics is the next new frontier.

Environmental issues have been studied under various fields like civil and environmental engineering, chemical engineering and recently, as a part of research on reverse logistics. Companies that lease electronic products are expected to be impacted by environmental legislation on electronic waste, and hence the status of environmental legislation on electronic waste is the subject of Section 2.4. The discussion also highlights the three primary reasons for the difficulties faced in the formulation of fair and effective environmental policies throughout the world [88]. First, there is yet to emerge a universally accepted or understood definition and metric for the term “environmentally friendly.” The second reason is economic considerations (policies would not be effective if they did not make economic sense), and the third is that the environment is an issue interpreted very differently by various stakeholders (businesses, government and consumers) involved in the process.

It is possible to represent some of these issues, particularly economic issues, reasonably well through mathematical models. This makes it possible to obtain insight not only into business operations like asset management and logistics, but also into the effectiveness of environmental policies. One rare example of the consideration of the effect of environmental legislation on asset replacement is a paper by Hartman and Dearden (1999) [45], in which they examine a two-period economic model for replacing assets causing emissions, where the amount of emissions allowed in each period is equal to the number of right-to-pollute permits acquired. Surprisingly though, there seem to be very few other mathematical models that attempt to get these insights simultaneously. The research focus in this dissertation is an intersection of the fields of reverse logistics, equipment replacement and environmental policy formulation. It therefore bridges across existing research directions.

The next chapter presents a mathematical model that allows decision-makers for electronics leasing companies to simultaneously make decisions about lease lengths, product flows and legal end-of-life product disposal. It also allows the examination of the impacts of transportation costs and legislative uncertainties on these key decisions.

CHAPTER 3

MATHEMATICAL MODEL AND A DETERMINISTIC CASE STUDY

The mathematical model developed in this chapter allows decision-makers for electronic equipment leasing companies to simultaneously make optimal decisions about lease lengths, product flows and end-of-life product disposal. The model is deterministic, but the examination of uncertainty in problem parameters (detailed in Chapter 4) is possible by solving multiple scenarios (with different parameter values) using this model.

A description of the problem is outlined in Section 3.1 and the mathematical model, which takes the form of a mixed integer linear program (MILP), is then presented in Section 3.2. Section 3.3 briefly discusses the characteristics of the model, including comments on its structure as well as its strengths and limitations. Section 3.4 presents a case study that validates the model, demonstrates its utility in answering the key research questions, and provides interesting insights into the problem. Finally, Section 3.5 comprises a chapter summary and concluding remarks.

3.1 Problem description

Figure 3.1 shows a schematic representation of product flows in the system. During the given time horizon, every customer has a demand for a certain number of each type of product in each period, which the leasing company must satisfy. An appropriate set of leases that satisfy demand for each order is to be determined. Products are provided from an existing inventory of assets. An inventory of assets and their constituent components is maintained at one or more “logistics facilities” (warehouses). Asset inventory is bolstered through purchasing from outside sources, refurbishing (“rebuilding”) from component inventory or component purchases, and products returned at their end-of-lease. Inventory is depleted through the disposal of assets, their disassembly to components, and fulfillment of demand. Each time any equipment for an order is shipped to a customer (from one or multiple sources), assembly, aggregation and/or installation may be required. After a certain time lag (end-of-lease), equipment is de-installed, collected from the customer and transported back to one or more of the logistics facilities. Subsequently, products (assets) may be inventoried for reuse, cannibalized for parts, or disposed of by way of landfilling or metal/glass/plastic recycling. Due to legislative constraints, both disposal options may not be available at every logistics facility. Repairs are not considered within the scope of the problem; it is assumed that any repairs needed on the leased equipment will be carried out at the customer site and that the associated costs are absorbed in the O&M costs of the lease.

3.2 The mathematical model

This section presents the mathematical model developed for the research problem. The model takes the form of a MILP. The indices used as subscripts for decision variables and parameters are listed first, followed by definitions of the decision variables

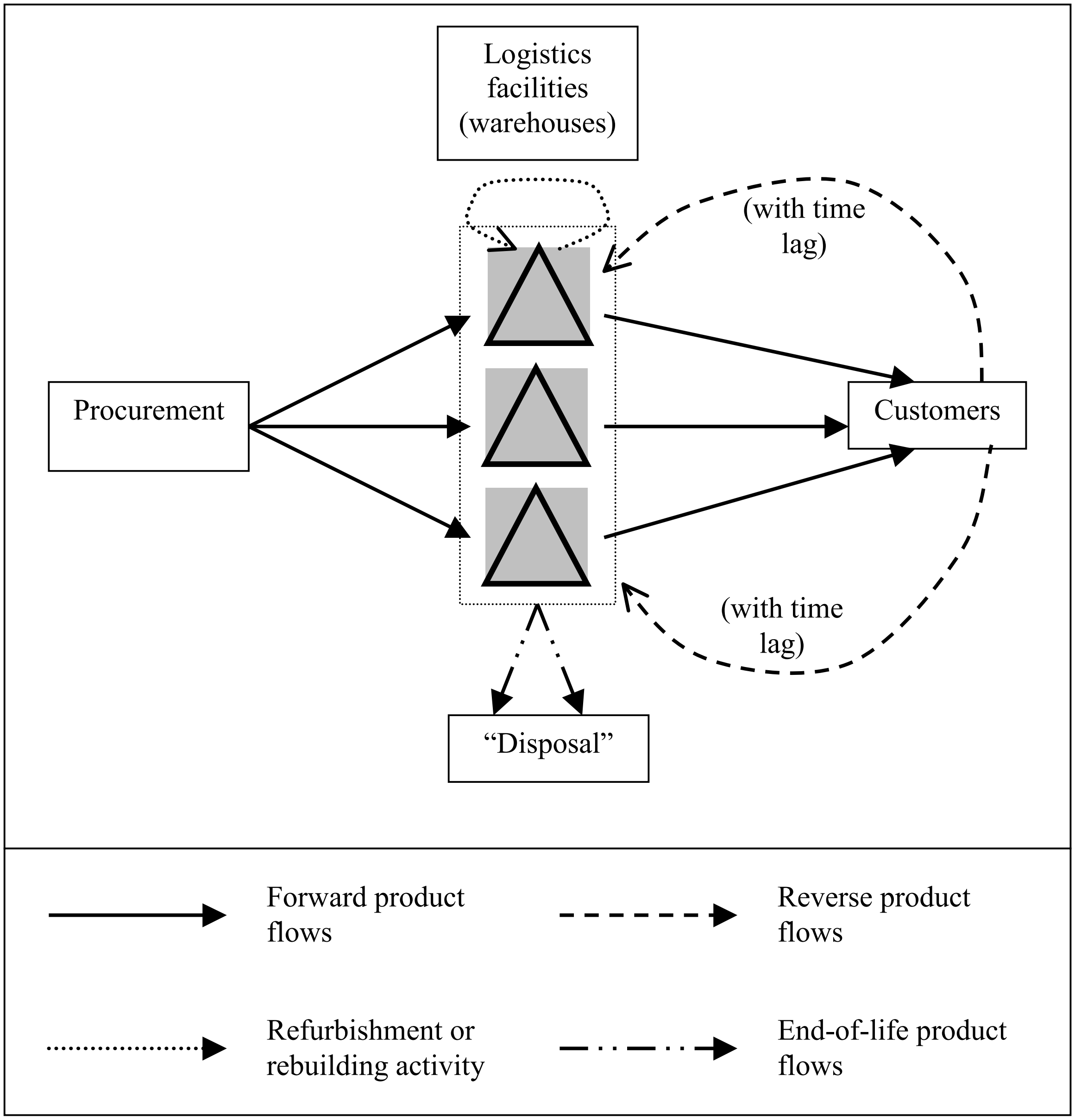

Figure 3.1: Schematic representation of product flows

and the parameters themselves. The objective function follows, and finally, the model constraints are presented.

Indices for decision variables and parameters

p: Asset types
h: Asset forms (new or rebuilt)
c: Customer orders
w: Logistics facilities (warehouses)
j: Time periods; $j = 1, 2, \ldots, T$, where T is the time horizon for the problem
i: Asset age in time periods; $i = 0, 1, 2, \ldots, N_{p,h}$, where $N_{p,h}$ is the maximum service life for asset type p in form h
r: An index for time periods, used to denote lease starting periods
s: Another index for time periods, used to denote lease ending periods
f: Asset disposal options (landfilling or metal/glass/plastic recycling)[*]
q: Component types

A listing of the indices facilitates the definition of the model decision variables and parameters, which are presented next.

Decision variables

The model consists of binary variables (Y's) and continuous variables (X's and I's), indexed as appropriate. Since this is a multi-period model, it must be clarified that the words "in period j" mean the time interval from after the end of the time period j-1 up to and including the end of time period j. A list of variables and their corresponding definitions is as follows.

---

[*] Also note that a second-hand market can be readily incorporated into the model by providing a third disposal option of "resale," without any change in the model structure.

$YA^{A}_{c,j}$	$\begin{cases} =1 & \text{if any assets are put into active use for order } c \text{ in period } j \\ =0 & \text{otherwise} \end{cases}$
$YD^{A}_{c,j}$	$\begin{cases} =1 & \text{if any assets are taken out of active use for order } c \text{ in period } j \\ =0 & \text{otherwise} \end{cases}$
$XB^{A}_{p,h,w,j}$	Number of assets of type *p* in form *h* purchased at warehouse *w* in period *j*
$XL^{A}_{p,h,c,i,r,s}$	Number of *i*-period old assets of type *p* in form *h*, that are leased for customer order *c* at the beginning of period *r* (start of the lease), and that age to *i*+(*s*-*r*+1) periods old at the end of period *s* (end of the lease)
$XA^{A}_{p,h,w,c,i,j}$	Number of *i*-period old assets of type *p* in form *h* taken out of asset inventory in warehouse *w* and put into active use for customer order *c* in period *j*
$XD^{A}_{p,h,c,w,i,j}$	Number of *i*-period old assets of type *p* in form *h*, taken out of active use from order *c* and added to asset inventory in warehouse *w* in period *j*
$XU^{A}_{p,h,c,i-1,j-1,i,j}$	Number of assets of type *p* in form *h*, in use for order *c* from after the end of period *j*-1 (or, the start of period *j*) up to and including the end of period *j*, which age from *i*-1 periods to *i* periods old
$XF^{A}_{p,h,w,f,i,j}$	Number of *i*-period old assets of type *p* in form *h*, disposed from asset inventory at warehouse *w*, via option *f*, in or at the end of period *j*
$XC^{A}_{p,h,w,i,j}$	Number of *i*-period old assets of type *p* in form *h*, that are disassembled to components at warehouse *w* in period *j*
$XR^{A}_{p,w,j}$	Number of assets of type *p* rebuilt in warehouse *w* in period *j* (these assets are available as rebuilt assets of age zero immediately thereafter)
$I^{A}_{p,h,w,i-1,j-1,i,j}$	Starting inventory of assets of type *p* in form *h* in warehouse *w*, from after the end of period *j*-1 (or, the start of period *j*) up to and including the end of period *j*, which age from *i*-1 periods to *i* periods old
$I^{C}_{q,w,j}$	Starting inventory of component type *q* in warehouse *w* in period *j*
$XB^{C}_{q,w,j}$	Number of components of type *q* purchased at warehouse *w* in period *j*

$XF^{C}_{q,w,j}$	Number of components of type *q* disposed at warehouse *w* in period *j*

Problem complexity and the relatively large number of variable indices can occlude notational intuition. Figure 3.2 illustrates how some of the decision variables are related. The diagram shows one lease cycle for assets of one particular type *p* (in form *h*) at one particular customer site *c*.

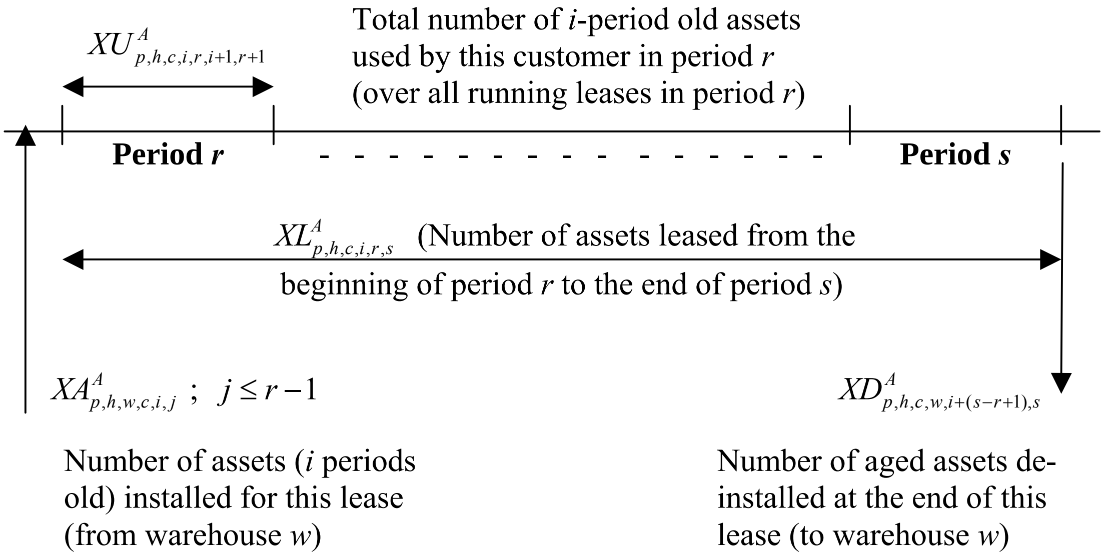

Figure 3.2: Representation of selected model variables for one particular leasing cycle

Parameters

Most of the model parameters are costs (*C*’s) that are closely associated with variable definitions, and are hence named and indexed very similarly to the decision variables. A list of parameters and their corresponding definitions is as follows.

$D_{p,c,j}$	Demand for asset type *p* for order *c* in time period *j*
T	The time horizon for the problem

$N_{p,h}$	The maximum service life of asset type p in form h
λ	A discount factor = $(1 + MARR)^{-1}$, for the time value of money; $MARR$ ≡ Minimum Acceptable Rate of Return
$CB^{A}_{p,h,w,j}$	Unit purchase cost of assets of type p in form h purchased at warehouse w in period j
$L_{\min,c}$	The minimum lease length (in periods) for customer order c
$L_{\max,c}$	The maximum lease length (in periods) for customer order c
$RL^{A}_{p,h,c,i,r,s}$	Unit revenue per period from leased assets of type p in form h, that are leased for order c as i-period old assets at the beginning of period r (start of the lease), and that age to $i+(s-r+1)$ periods old at the end of period s (end of the lease)
$CT^{AO}_{p,w,c,j}$	Unit cost of transportation and handling for asset type p from warehouse w to the site of order c, in period j
$CA^{A}_{c,j}$	"Installation cost" for every instance of asset activation for order c in period j
$CT^{AI}_{p,c,w,j}$	Unit cost of transportation and handling for asset type p from the site of order c to warehouse w, in period j
$CD^{A}_{c,j}$	"De-installation cost" for every instance of asset deactivation for order c in period j
$CU^{A}_{p,h,c,i,j}$	Unit operating and maintenance (O&M) cost of leased i-period old assets of type p in form h, in use for order c in period j
$CF^{A}_{p,w,f,i,j}$	Unit cost of disposal via option f (landfill or metal/glass/plastic recycling) of i-period old assets of type p at warehouse w, in period j
$CC^{A}_{p,w,i,j}$	Unit cost of disassembling i-period old assets of type p in warehouse w in period j
$MD^{A}_{p,h,q,i}$	Number of components of type q obtained from disassembly of each i-period old asset of type p in form h
$MA^{A}_{p,q}$	Number of components of type q needed for rebuilding each asset of type p
$CR^{A}_{p,w,j}$	Unit cost of rebuilding asset type p in warehouse w in period j

$CH^{A}_{p,w,j}$	Unit holding cost of asset type *p* at warehouse *w* in period *j*
$CH^{C}_{q,w,j}$	Unit holding cost of component type *q* at warehouse *w* in period *j*
$CB^{C}_{q,w,j}$	Unit purchase cost of component type *q* at warehouse *w* in period *j*
$CF^{C}_{q,w,j}$	Unit cost of disposal of component type *q* at warehouse *w* in period *j*

Objective function

The objective is to maximize the discounted net profit of the system. In the current version of the model, the only explicit source of revenue is the periodic revenue from leasing assets. However, some of the costs, such as asset or component disposal costs, can be negative and are thus able to contribute to revenue. The objective can be stated verbally and mathematically as follows.

Maximize Total discounted net profit =

Lease revenue
- Purchase cost (assets)
- Transportation cost (warehouses to customers)
- Transportation cost (customers to warehouses)
- Asset activation cost - Asset deactivation cost
- O&M cost
- Disassembly cost
- Refurbishment/Rebuilding cost
- Disposal cost (assets)
- Holding cost (assets) - Holding cost (components)
- Purchase cost (components)
- Disposal cost (components)

It must be noted that each of the objective function components above refers to the **total discounted value** of that cost (or revenue), because the objective function is the total discounted net profit. The mathematical expression for the objective function is:

Maximize $\boldsymbol{Z}$ =

$$\sum_{p}\sum_{h}\sum_{c}\sum_{\substack{r=max(1,\\ s-L_{\min,c}+1)}}^{s-L_{\min,c}+1}\ \sum_{s=L_{\min,c}}^{T}\ \sum_{i=0}^{N_{p,h}-(s-r+1)}\ \sum_{j=r}^{s}\lambda^{j-1}RL^{A}_{p,h,c,i,r,s}XL^{A}_{p,h,c,i,r,s}$$

$$-\sum_{j=1}^{T}\lambda^{j-1}\left(\begin{array}{l}\displaystyle\sum_{p}\sum_{h}\sum_{w}CB^{A}_{p,h,w,j}XB^{A}_{p,h,w,j}+\sum_{p}\sum_{h}\sum_{w}\sum_{c}\sum_{i=0}^{N_{p,h}-1}CT^{AO}_{p,w,c,j}XA^{A}_{p,h,w,c,i,j}\\ \displaystyle+\sum_{p}\sum_{h}\sum_{c}\sum_{w}\sum_{i=1}^{N_{p,h}}CT^{AI}_{p,c,w,j}XD^{A}_{p,h,c,w,i,j}+\sum_{c}CA^{A}_{c,j}YA^{A}_{c,j}+\sum_{c}CD^{A}_{c,j}YD^{A}_{c,j}\\ \displaystyle+\sum_{p}\sum_{h}\sum_{c}\sum_{i=0}^{N_{p,h}}CU^{A}_{p,h,c,i,j}XU^{A}_{p,h,c,i-1,j-1,i,j}+\sum_{p}\sum_{h}\sum_{w}\sum_{i=1}^{N_{p,h}}CC^{A}_{p,w,i,j}XC^{A}_{p,h,w,i,j}\\ \displaystyle+\sum_{p}\sum_{w}CR^{A}_{p,w,j}XR^{A}_{p,w,j}+\sum_{p}\sum_{h}\sum_{w}\sum_{f}\sum_{i=1}^{N_{p,h}}CF^{A}_{p,w,f,i,j}XF^{A}_{p,h,w,f,i,j}\\ \displaystyle+\sum_{p}\sum_{h}\sum_{w}\sum_{i=0}^{N_{p,h}}CH^{A}_{p,w,j}I^{A}_{p,h,w,i-1,j-1,i,j}+\sum_{q}\sum_{w}CH^{C}_{q,w,j}I^{C}_{q,w,j}\\ \displaystyle+\sum_{q}\sum_{w}CB^{C}_{q,w,j}XB^{C}_{q,w,j}+\sum_{q}\sum_{w}CF^{C}_{q,w,j}XF^{C}_{q,w,j}\end{array}\right)\qquad(3.1)$$

Constraints

In order to facilitate understanding of the mathematical representation of model constraints, it would be instructive to begin by briefly describe the constraints in words. In this version of the model, the constraints are:

- **Initialization and termination conditions**: In this version of the model, it is assumed that there are no assets in use or in inventory before the beginning of the time horizon, and none at the end of the time horizon. These conditions are not presented in mathematical form here, but are incorporated into the computer implementation of the model. Also, these conditions could be readily modified to incorporate existing physical assets as needed.

- **Meet demand**: In each time period, the demand of each customer order for each asset type must be met.

$$\sum_{h} \sum_{i=1}^{N_{p,h}} XU^{A}_{p,h,c,i-1,j-1,i,j} = D_{p,c,j} \qquad \forall\, p,c,j \tag{3.2}$$

- **Flow conservation**: From each time period to the next, there must be a conservation of flow of assets and components in inventory at each warehouse, and also a conservation of flow of assets in use for each order. These constraints also need to ensure that assets are not used or kept in inventory beyond the end of their useful life.

Flow conservation for asset inventory

Ind(h) is an indicator used to ensure that rebuilt assets are not included in the flow conservation for new assets. Therefore, *Ind("New")* = 0 and *Ind("Rebuilt")* = 1.

For assets of age 0,

$$\begin{aligned} I^{A}_{p,h,w,i-1,j-1,i,j} + XB^{A}_{p,h,w,j} - \sum_{c} XA^{A}_{p,h,w,c,i,j} & \\ + XR^{A}_{p,w,j} Ind(h) &= I^{A}_{p,h,w,i,j,i+1,j+1} \qquad \forall\, p,h,w,j,i=0 \end{aligned} \tag{3.3}$$

For assets with some life greater than 0,

$$\begin{aligned} I^{A}_{p,h,w,i-1,j-1,i,j} - \sum_{c} XA^{A}_{p,h,w,c,i,j} + \sum_{c} XD^{A}_{p,h,c,w,i,j} & \\ - XC^{A}_{p,h,w,i,j} - \sum_{f} XF^{A}_{p,h,w,f,i,j} &= I^{A}_{p,h,w,i,j,i+1,j+1} \qquad \forall\, p,h,w,j,1 \le i \le N_{p,h} \end{aligned} \tag{3.4}$$

Flow conservation for component inventory

$$\begin{aligned} I^{C}_{q,w,j} + XB^{C}_{q,w,j} + \sum_{p} \sum_{h} \sum_{i=1}^{N_{p,h}} MD^{A}_{p,h,q,i} XC^{A}_{p,h,w,i,j} & \\ - XF^{C}_{q,w,j} - \sum_{p} MA^{A}_{p,q} XR^{A}_{p,w,j} &= I^{C}_{q,w,j+1} \qquad \forall\, q,w,j \end{aligned} \tag{3.5}$$

Flow conservation for assets with customer orders

$$\begin{aligned}\sum_{w} XA^{A}_{p,h,w,c,i,j} &+ XU^{A}_{p,h,c,i-1,j-1,i,j} \\ &- \sum_{w} XD^{A}_{p,h,c,w,i,j} = XU^{A}_{p,h,c,i,j,i+1,j+1} \qquad \forall\, p,h,c,j,0 \le i \le N_{p,h} \qquad (3.6)\end{aligned}$$

- **Follow logical requirements for relationships between lease periods and asset activation, deactivation and use**

$$\sum_{w} XA^{A}_{p,h,w,c,i,r-1} = \sum_{s=r}^{T} XL^{A}_{p,h,c,i,r,s} \qquad \forall\, p,h,c,0 \le i \le N_{p,h} - 1, r \qquad (3.7)$$

$$\sum_{w} XD^{A}_{p,h,c,w,i,s} = \sum_{\substack{r=1 \\ 0 \le i-(s-r+1) \le N_{p,h}-1}}^{s} XL^{A}_{p,h,c,i-(s-r+1),r,s} \qquad \forall\, p,h,c,0 \le i \le N_{p,h} - 1, s \qquad (3.8)$$

$$XU^{A}_{p,h,c,i-1,j-1,i,j} = \sum_{\substack{r=1 \\ i-(j-r+1) \ge 0}}^{j} \sum_{s=j}^{T} XL^{A}_{p,h,c,i-(j-r+1),r,s} \qquad \forall\, p,h,c,1 \le i \le N_{p,h}, j \qquad (3.9)$$

- **Logical constraints for setting the values of the binary variables *YA*'s**

$$\sum_{p}\sum_{h}\sum_{w}\sum_{i=0}^{N_{p,h}-1} XA^{A}_{p,h,w,c,i,j} \ge YA^{A}_{c,j} \qquad \forall\, c,j \qquad (3.10)$$

$$\sum_{h}\sum_{w}\sum_{i=0}^{N_{p,h}-1} XA^{A}_{p,h,w,c,i,j} \le YA^{A}_{c,j}\left(\sum_{j} D_{p,c,j}\right) \qquad \forall\, p,c,j \qquad (3.11)$$

$$\sum_{j} YA^{A}_{c,j} \ge 1 \qquad \forall\, c \qquad (3.12)$$

- **Logical constraints for setting the values of the binary variables *YD*'s**

$$\sum_{p}\sum_{h}\sum_{w}\sum_{i=1}^{N_{p,h}} XD^{A}_{p,h,c,w,i,j} \ge YD^{A}_{c,j} \qquad \forall\, c,j \qquad (3.13)$$

$$\sum_{h}\sum_{w}\sum_{i=1}^{N_{p,h}} XD^{A}_{p,h,c,w,i,j} \qquad \leq YD^{A}_{c,j}\left(\sum_{j} D_{p,c,j}\right) \qquad \forall\, p,c,j \qquad (3.14)$$

$$\sum_{j} YD^{A}_{c,j} \qquad \geq 1 \qquad \forall\, c \qquad (3.15)$$

- **Variable requirements**: All the continuous decision variables (*X*'s and *I*'s) are non-negative and the *Y*'s are binary variables.

$$YA^{A}_{c,j} \in \{0,1\},\ YD^{A}_{c,j} \in \{0,1\} \qquad \forall\, c,j \qquad (3.16)$$

$$XB^{A}_{p,h,w,j} \geq 0 \qquad \forall\, p,h,w,j \qquad (3.17)$$

$$XL^{A}_{p,h,c,i,r,s} \geq 0 \qquad \forall\, p,h,c,i,r,s \geq r \qquad (3.18)$$

$$XU^{A}_{p,h,c,i-1,j-1,i,j} \geq 0 \qquad \forall\, p,h,c,i,j \qquad (3.19)$$

$$XA^{A}_{p,h,w,c,i,j} \geq 0,\ XD^{A}_{p,h,c,w,i,j} \geq 0 \qquad \forall\, p,h,w,c,i,j \qquad (3.20)$$

$$XF^{A}_{p,h,w,f,i,j} \geq 0 \qquad \forall\, p,h,w,f,i,j \qquad (3.21)$$

$$XC^{A}_{p,h,w,i,j} \geq 0 \qquad \forall\, p,h,w,i,j \qquad (3.22)$$

$$XR^{A}_{p,w,j} \geq 0 \qquad \forall\, p,w,j \qquad (3.23)$$

$$I^{A}_{p,h,w,i-1,j-1,i,j} \geq 0 \qquad \forall\, p,h,w,i,j \qquad (3.24)$$

$$I^{C}_{q,w,j} \geq 0,\ XB^{C}_{q,w,j} \geq 0,\ XF^{C}_{q,w,j} \geq 0 \qquad \forall\, q,w,j \qquad (3.25)$$

Note that it is not necessary to define the variables $XU^{A}_{p,h,c,i-1,j-1,i,j}$ for the correctness of the model, because constraint set (3.9) provides a direct substitution for them. This also implies that constraint set (3.6) is not required. However, definition of these variables greatly assists in the understanding of the mathematical model. The next section briefly discusses the main characteristics of the model, including some comments on model structure.

3.3 Model structure and characteristics

A few points about the structure of the model are worth noting. First, the constraints on the binary variables are not highly restrictive. The constraint sets (3.12) and (3.15) only specify that for each customer, asset installation and de-installation should occur *at least* once over the entire time horizon. These constraints are trivially satisfied if the total demand at each customer site is non-zero and the time horizon is long enough so that more than one leasing cycle can be completed for each customer. Therefore, one would not expect extensive branching during the MILP solution, and no significant increase in computational time is expected even with the inclusion of binary variables in the model.

Second, under conditions that do not require the use of the binary variables in the model (one such set of conditions is discussed in Section 3.4.1), the model is completely separable in asset type p, but for constraint set (3.5). This constraint set creates an economic interdependence between assets. However, the interdependence exists only for the subset of assets for which the option of disassembling and rebuilding is allowed. For other asset types, the model is still separable in asset type. Other common factors causing interdependence between assets in typical parallel asset replacement problems are demand and budget constraints. Demand does not cause economic interdependence in this problem because demand for each asset type at each customer site is considered separately – asset types do not contribute to the satisfaction of a “cumulative” demand. A budget constraint is not incorporated in this model, but if incorporated, the model would no longer be separable in asset type p.

Another observation is that except in constraints (3.11) and (3.14) on the binary variables, and in constraint set (3.5), all variables have coefficients of –1, 0 or 1 in the constraint matrix. Therefore, in the absence of binary variables, the structure of the constraint matrix would approach unimodularity. When the constraint matrix has this structure, integral values of the right-hand side parameters and of the variable coefficients in the constraint matrix guarantee integral optimal values for all variables, with no explicit model constraints requiring variables to be integral.

The strength of this model is that it can be used to make the key decisions faced by a company leasing electronic equipment, *e.g.*, length of leases, product flows, inventory, and end-of-life disposal options. Although the deterministic MILP model does not explicitly incorporate uncertainty, insight into questions like the effects of differences in relevant parameters on the optimal decisions can be obtained by changing these parameters (*e.g.*, transportation costs, sets of available disposal options at different locations, disposal costs, etc.) and solving multiple scenarios. A detailed exercise on the examination of uncertainty in problem parameters is undertaken in Chapter 4. These case study results provide insights to business asset managers. In addition, a study of the differences in product flows between scenarios with varying transportation costs and legislative effects can provide case study insight into formulation of environmental policies on electronic waste, which is the subject of Chapter 5.

Implementation issues need to be considered for this model. This research does not consider a dynamic multi-stage solution approach that guarantees optimality over a time horizon greater than the one used for solving the model. This can be viewed as a limitation, even though the model is very useful in its current form. However, a "rolling-horizon” approach could be implemented to take advantage of changes in system parameters over time.

Some other important decisions like pricing have not been taken into account in this model. Pricing is a strategic decision that is affected by many other factors like market competition, sales and marketing strategies, economic and political conditions, etc. Taking all these additional factors into account would not only make the model mathematically intractable, but would also detract from the main research focus of integrating reverse logistics and environmental issues with equipment replacement decisions. The next section presents an industrial case study that validates the model, demonstrates a few of its strengths and provides insight into the key research questions.

3.4 Industrial case study

In order to validate the MILP model discussed in Section 3.2, and then draw insights from application of the model, computational testing has been done with industry representative data. The general problem description and key data have been provided by the Vice President for Asset Management of a large technology leasing company. The data have been changed in order to respect company confidentiality and scaled down in order to facilitate computational requirements.

The company under study currently operates only one warehouse, but in order to enhance the generality and applicability of the model, three warehouses are considered in this case study. The time increments in this model are half-years (six months), because it is assumed that leases are offered in six-month increments. In addition, discussions with the Asset Manager suggested that it is quite uncommon for leases to be renegotiated by either party (the lessor or the lessee), especially in the early part of the lease. Therefore, it is assumed that the asset management company that forms the basis for the case study makes the most important asset management decisions twice a year. For a slightly reduced version of the industrial problem, typical magnitudes of the model indices are shown in Table 3.1.

Table 3.1: Magnitudes of model indices for the case study

p:	Asset types	25
c:	Customer orders	100
w:	Logistics facilities (warehouses)	3
j:	Time periods; $j = 1, 2, \ldots, T$, where T is the time horizon for the problem	T = 14
i:	Asset ages in time periods	6 or 8 periods
f:	Asset disposal options	2
q:	Component types	14

It must be noted that most of the variables and constraints with a large number of indices are indexed by asset types (*p*), customer orders (*c*), asset age (*i*), and time periods (*j*). Therefore, the problem size (the number of variables times the number of constraints) increases in proportion to the **square** of: 1) the number of asset types; 2) the number of customer orders; 3) the maximum asset age; and 4) the total number of time periods. However, a limit on the minimum and maximum lease lengths prevents the problem size from growing as fast as suggested by the discussion above. The number of leasing decision variables $XL^{A}_{p,h,c,i,r,s}$ is particularly prone to a fast increase if the lease length limits are expanded. This happens because the variables $XL^{A}_{p,h,c,i,r,s}$ have two time indexes, *r* and *s*. It may be possible to reformulate the model so that problem size does not increase very fast with the number of indexes, but the resulting tradeoff would perhaps be the inclusion of more integer or binary variables instead of continuous variables, which may result in a large increase in computational time. Examination of more efficient modeling approaches is a topic for future research.

In Section 3.4.1, the key data for the base case of the model are discussed in some detail, inclusive of those in Table 3.1. Model validation issues are discussed in Section 3.4.2. The solution results from the base case and two scenarios are presented and compared in Section 3.4.3 in order to demonstrate how the model can be used to examine the impacts of various problem parameters on the optimal decisions. Section 3.4.4 is an examination of legislative impact on the end-of-life management of CRT monitors. Two other scenarios, different from those used in Section 3.4.3, are considered in this section.

3.4.1 Data for the base case of the model

The case study considers 25 asset types that cover a broad range of electronic products used by business enterprises. They consist of four configurations of personal computers (PCs), four types of monitors (two types of CRT monitors and two types of LCD flat panel monitors), four configurations of laptops, three types of printers, two types of scanners, four configurations of PC servers and four configurations of midrange servers. The purchase costs of individual assets range from \$200 to \$2 million.

The assets are available in two forms: “New” and “Rebuilt.” Rebuilt assets are defined as assets that are not new products from an electronics assembly line and have instead been remanufactured or assembled from new or used components. These could also include assets that are not dismantled completely but only have some of their components replaced by newer ones. However, for the purposes of this research, the first definition is used. Discussions with the Asset Manager suggest that it is unprofitable to rebuild relatively inexpensive assets like PCs and laptops and that it is very rare for companies to buy these types of used assets. Therefore, only two of the 25 assets (two high-end midrange servers) are considered in rebuilt form. Additionally, it is assumed that every individual asset that is purchased (either brand new or rebuilt) begins service with age zero. However, it is possible for new and rebuilt assets of the same type to have different useful lifespans.

For the case study, the 100 customer orders and their respective demands for various kinds of assets have been generated randomly using parameters for the demand and business mix provided by the Asset Manager. In order to highlight the significance of the results obtained from a limited number of model runs, it is also assumed that demand is constant throughout the time horizon under consideration. The order size can be classified into small, medium and large categories. The total asset demands for these three categories of orders average 242 assets, 874 assets and 2,277 assets respectively. There is a significant geographic dispersion of the orders, but with a slight bias towards the U.S. East coast.

The three logistics facilities are located in Georgia, Massachusetts and California. Due to different sales tax rates in different states, prices of purchased assets vary slightly by the warehouse location at which they are purchased. Transportation costs are assumed to depend linearly on the distances from logistics facilities to customer sites, and approximate distances are used for calculation of transportation costs.

The time horizon for the problem has been chosen to be 14 periods (seven years). The possibility of end-effects with a finite time horizon must be recognized, but a longer time horizon would not provide any additional value because of the difficulty of long-term demand forecasting and the rapid technological change in the electronics industry.

The most common asset lease periods offered by the company are 24, 30 and 36 months, and therefore the minimum lease duration is assumed to be four periods (24 months) for all orders. The maximum lease duration is assumed to be eight periods (48 months). The maximum service lives of individual assets vary from six to eight periods (three to four years), and therefore an asset with a life of eight periods can be turned over at most twice during the time horizon.

The *residual value* of an asset at age *i* periods is defined as the current value of the asset as a fraction of the original value (purchase price). Based on information provided by the Asset Manager, a *residual value curve* of the form *exp*(-0.2624 * *i*) is used to approximate residual values for all asset types. Prices of rebuilt assets are assumed to be 80% of the prices for purchased assets [106]. The prices for each different length of lease are determined based on the residual value of assets. For a lease of *t* periods, the lease cost every period equals:

$$\text{Original purchase price} * \left(\frac{\text{residual value (lease start) - residual value (lease end)}}{t} \right) \quad (3.26)$$

The actual lease price is then obtained by inflating this cost by a constant factor to account for discounting and profit margins. It is assumed that profit margins for small orders are higher than the profit margins for large orders. This is because a large leasing company would like to do business repeatedly with large customers, by offering them competitive prices and better service.

Landfilling and metal/glass/plastic recycling are the two disposal options for assets. In the base case, both options are assumed available at each logistics facility, and the disposal costs are the same at every location. The disposal costs are based on landfilling fees for hazardous waste and prices offered by a large electronics recycler in Florida. The recycler offers money for many types of assets, and therefore recycling costs for these assets are negative. Estimates are used for the few values that could not be obtained directly from the leasing company or other sources. The model solutions for the base case problem and alternative scenarios are presented and discussed in Section 3.4.3.

Installation, deinstallation and O&M costs are assumed to be zero, mainly because these costs are rarely incurred by the actual leasing company. Under this assumption, the model is greatly simplified, because the binary variables are no longer required, and constraints (3.10) through (3.16) can be eliminated, along with the relevant terms in the objective function. With these changes, the model reduces from a MILP to a linear program (LP), and larger problems can be solved.

3.4.2 Model validation

Before results from computational runs of the model can be used to draw case study conclusions, the model must be validated and verified. There are a few different aspects to model validation. This section discusses how each of these aspects has been addressed during the course of this research.

The first task in model validation is to ensure internal model consistency. This implies that the computer implementation of the model must match its mathematical representation, and the optimal values of the decision variables must satisfy all the constraints. During this research, the match between the computer implementation of the model and its mathematical representation has been ensured by exporting the computer-generated model as a text file and checking the correctness of a number of objective function terms comprising each of the cost (or revenue) components, and of a number of constraints from each constraint set. In addition, internal consistency can be checked again after running the model, by checking that the optimal values of a small subset of the decision variables satisfy all the model constraints. This has not been done after every model run, but frequently enough during the research duration to justify confidence in the model's correctness.

The second aspect is to ensure that the model is a reasonable representation of the real world. Case study guidance from industry experts and obtaining industry representative data for this problem (as discussed in the beginning of Section 3.4) has been very helpful in this regard. However, it must also be ensured that the model output resembles the real situation faced by a leasing company. For example, it is instructive to look at the overall revenues and costs for the optimal solution of the base case, which are as follows.

Revenues	
Lease revenue	$1,567,103,041
Asset disposal	$ 5,370,031
Component disposal	$ 191,162
Costs	
Asset purchase	$1,297,341,180
Transportation (warehouses to customers)	$ 5,975,069
Transportation (customers to warehouses)	$ 2,978,801
Asset disassembly	$ 215,725
Asset rebuilding	$ 343,022
Net profit	**$ 265,810,437**

It is clearly seen that lease revenue is the most significant source of revenue, and asset purchase cost is the most significant cost for this leasing company, which is what one would expect in reality. In addition, it is observed that transportation costs constitute a little less than 1% of the total cost, which is not drastically different from the realistic figure of 1.5% (as mentioned in Chapter 1). In addition, characteristics of parallel asset replacement, such as replacement in clusters [55][47][43], are observed at optimality.

The final model validation aspect is to check on an ongoing basis the appropriateness of model parameter choices and to perform additional checks if the results obtained from the model do not match expected outputs. As an example of checking the appropriateness of model parameters, consider the question of whether the 14-period time horizon in the model may induce significant end effects (particularly on lease lengths). Bean, Lohmann and Smith (1985) [13] point out that in order to avoid end effects, the length of the time horizon needs to be approximately twice the maximum asset age. This indicates that a 14-period time horizon may be suitable for this case. However, in addition, the model is run for 15 periods instead of 14 to check this experimentally. The first period asset replacement decisions (*i.e.*, the length of the first leasing cycle) are found to vary only for four of the 25 asset types, and for only about ten percent of the customer orders for three out of these four asset types. In addition, the differences in the optimal objective function value (and its major cost/revenue constituents) between 14- and 15-period time horizons are less than 5%. This indicates that the chosen 14-period time horizon is not expected to induce significant end effects. Additional checks on model correctness can be performed as appropriate if the model provides counterintuitive results. The remainder of this chapter focuses on solving alternative scenarios with the model and on obtaining insights from these results.

3.4.3 Comparison of model results for the base case and two alternative scenarios that prohibit 1) landfilling; and 2) rebuilds

In this section, results from different model scenarios are compared to the results for the base case, and insights are developed from the results. Two alternative scenarios are considered. In the first alternative scenario, landfilling of assets is not a disposal option permitted at any warehouse location. In the second scenario, landfilling is allowed, but none of the asset types can be rebuilt.

The model for the case study scenarios is solved using the commercial optimization solvers CPLEX [51] and Xpress IVE [29] on an IBM computer with a 1.8 GHz Intel® Pentium-4® processor and 640 MB of RAM. All of the model runs, including the base case and the various scenarios, contain approximately 650,000 continuous variables and approximately 200,000 constraints. No computational limitations have been experienced, and the solution times range from one minute to two minutes.

Figure 3.3a) and Figure 3.3b) are graphical representations of product flow quantity percentages in the base case. For the optimal solution of the base case, the percentages of activated assets transported from warehouses to customers, by warehouse location, are identical to the numbers in Figure 3.3a) after asset rebuilds are taken into account. It can also be seen that the total transportation cost from warehouses to customers is significantly higher than the total transportation cost from customers to warehouses. Since the model does not provide for inter-warehouse transportation, the inference is that there is a tradeoff between the total asset purchase costs (due to the effect of local tariffs like sales tax, which leads to slightly different prices at different locations), and the total forward transportation costs. The sales tax in Massachusetts is the lowest (5%) of all the states, and so the highest proportion of assets is purchased in Massachusetts.

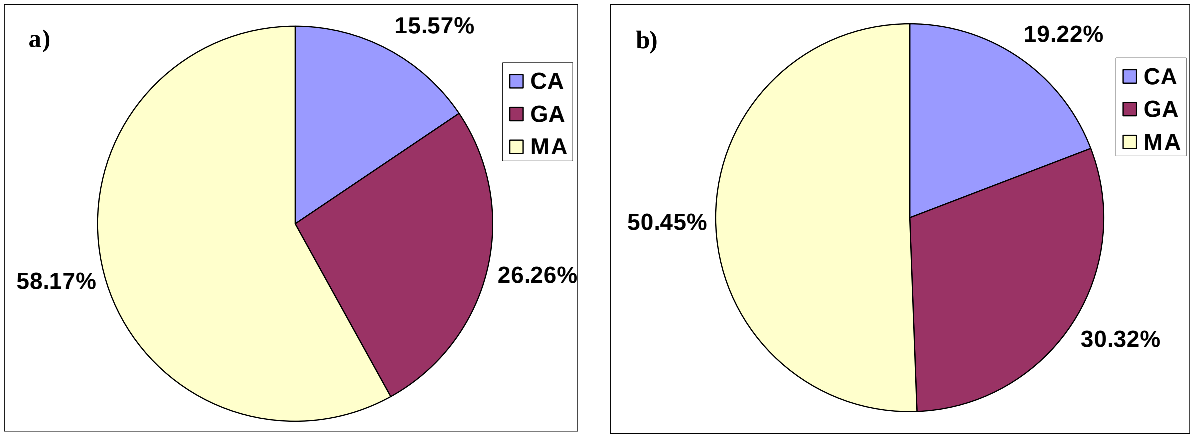

Figure 3.3: Percentage quantities (base case), by warehouse location [California (CA), Georgia (GA), or Massachusetts (MA)], of: a) assets purchased; and b) deactivated assets transported from customer sites

Figure 3.3b) shows the flows of deactivated assets, *i.e.*, product flows from customers to warehouses. Adjusting for disassembled and rebuilt assets, these percentages are identical to the percentages of assets disposed by warehouse location, *i.e.*, 19.22% of assets are disposed in California, 30.32% in Georgia and the rest in Massachusetts. Since the input values for disposal costs in the base case are the same for all warehouse locations, it can be inferred that transportation costs drive the end-of-life product flow decisions for the base case. However, if disposal costs were changed so as to make them different at different warehouse locations (*e.g.*, as a result of alternative environmental legislation in different geographic areas), then there would be a tradeoff between the total asset disposal costs and the total reverse transportation costs.

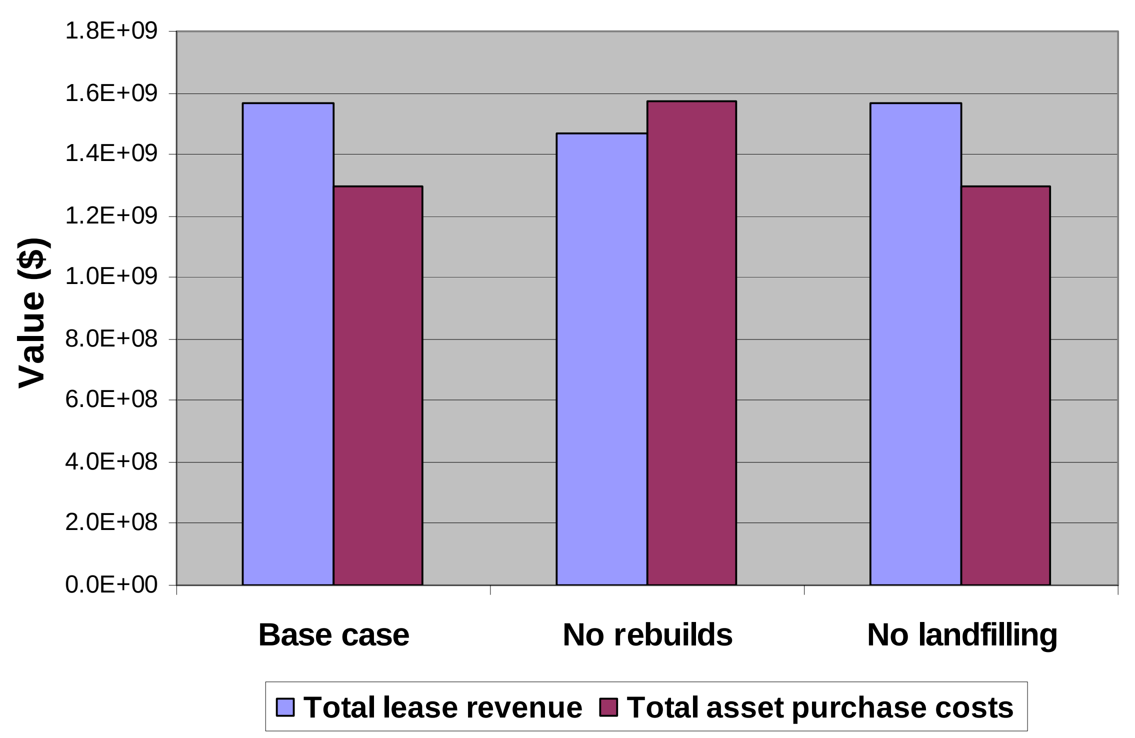

Figure 3.4: Total lease revenues and asset purchase costs in the optimal solutions for the base case and two other scenarios

Figure 3.4 compares lease revenues and asset purchase costs for the optimal solution of the base case and the two scenarios described previously. It is clear that rebuilding is a profitable activity. Without rebuilding, the lease revenues are slightly lower and the asset purchase costs are much larger as well, and the resulting net profit is negative. The savings of rebuilding and disassembly costs are insignificant compared to the magnitude of increase in asset purchase costs, especially for expensive assets. Therefore, ignoring the option of rebuilding has resulted in a $372 million decrease in profit for this case study. When landfilling is disallowed, there is no change in the lease revenues or the asset purchase costs (this is also seen in Figure 3.4). However, asset disposal revenues become slightly lower than those for the base case, because it is then necessary to recycle some assets that it would be more profitable to have disposed in a hazardous waste landfill. Asset disposal revenues are higher for the case without rebuilds, because the assets that are rebuilt in other scenarios are disposed of to obtain revenue in this scenario.

This section highlights a few key tradeoffs between various kinds of costs in the system and demonstrates how the model can be used to make leasing and logistics decisions simultaneously. The next section presents a more specific analysis that examines legislative impact on end-of-life management of specific assets, and Cathode Ray Tube (CRT) monitors in particular.

3.4.4 Examination of legislative impact on management of CRT monitors

Equipment leasing companies also need to understand the impact of state-sponsored environmental initiatives on the end-of-life flows of products. An example with CRT monitors is presented in this section to demonstrate the ability of the model to examine such questions. The results from the base case are used again as comparisons for the results from two other scenarios in this section, with a special focus on the individual results for CRT monitors.

The first legislative scenario considers legislation in California, whereby an advance recycling fee (ARF) of $10 is charged on every CRT sold in the state, and there is no cost or revenue for disposal of CRT monitors at end-of-life. Legislation with a potentially similar cost impact has been passed by the California legislature and is slated to come into effect later in 2004, but it is still mired in controversy and uncertainty (California Senate Bill 20, 2003).

The second legislation alternative scenario considers the existing landfill ban on CRTs in Massachusetts [64]. In order to enforce this selective landfilling ban on CRTs in the first legislative scenario, the landfilling costs for CRT monitors in Massachusetts have been forced to prohibitively high values in the input data. Additionally, it is assumed that an end-of-life recycling cost of $15 is charged in Massachusetts due to the landfill ban. For this scenario, the base case disposal values are used at the other two warehouse locations, and these values are lower than the value in Massachusetts.

The model is solved for the first alternative scenario that incorporates potential California legislation and for the second scenario that incorporates Massachusetts legislation, using the solution approach (with similar execution requirements) described earlier. The optimal solution for each scenario differs from the base case, with different net revenues associated with the different solutions. In the optimal solution for the first scenario, all of the California CRTs remain in California just like in the base case. This contrasts what happens in the second scenario, where many of the Massachusetts-based CRTs are shipped to Georgia at end of life. Figure 3.5a) shows the disposal quantities of CRT monitors at the three warehouse locations and the identical optimal solutions for both the base case and first legislative scenario. These results can be contrasted to the very different optimal solution results shown in Figure 3.5b) for the second legislative scenario incorporating Massachusetts legislation. Figure 3.6 compares the transportation costs and asset disposal revenues for CRT monitors in the base case and in the two alternative legislative scenarios.

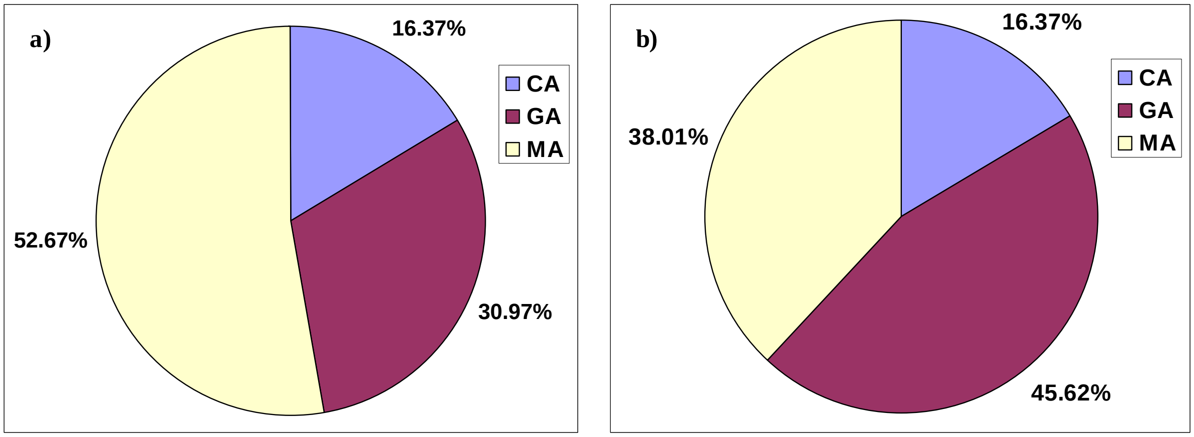

Figure 3.5: CRT disposal quantities, by warehouse location: a) for base case and for legislative scenario one with California ARF; and b) legislative scenario two with Massachusetts CRT landfill ban

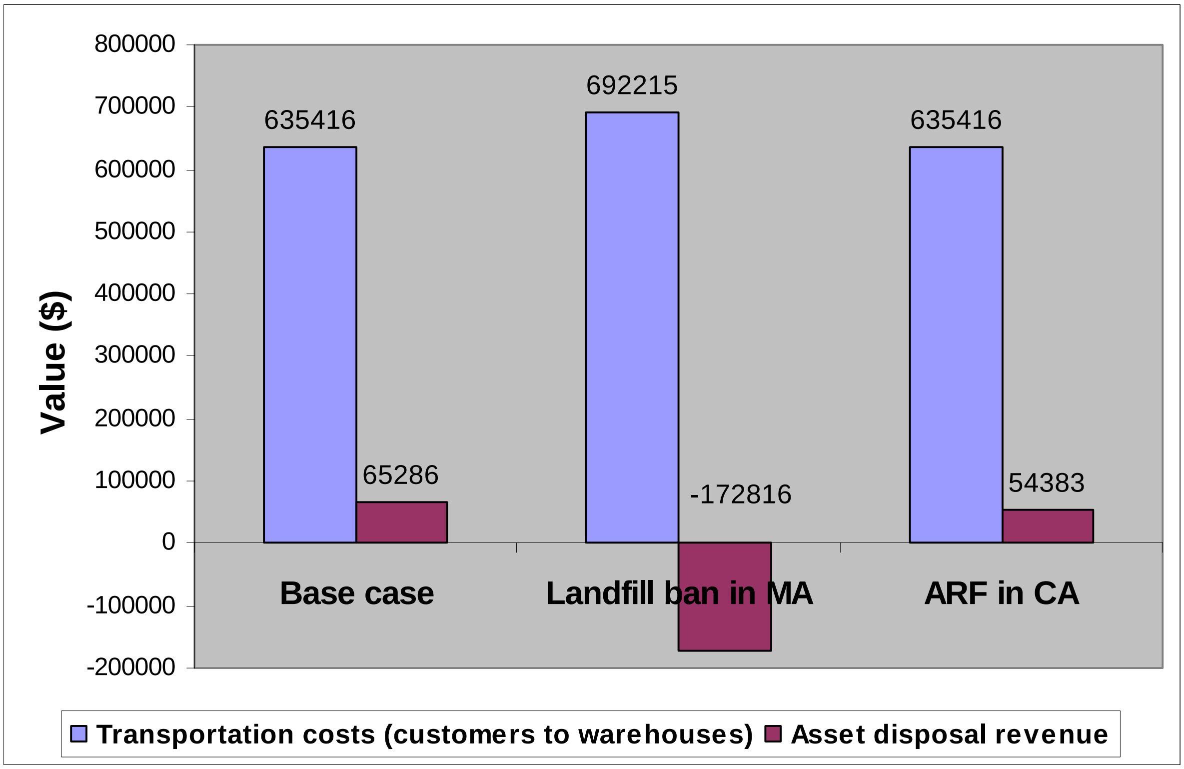

Figure 3.6: Comparisons between transportation costs and asset disposal revenues for CRT monitors in the base case and the two legislative scenarios

The figures show that for the case study, a CRT landfill ban in Massachusetts leads to a significantly higher end-of-life flow of CRT monitors into Georgia, even though the transportation costs from customers to warehouses are higher. There is also significant net negative revenue from the disposal of CRT monitors as a result of the landfill ban.

For the case study problem, an advance recycling fee of $10 in California is not found to affect the optimal product flows in the system, even though the optimal solution total purchase cost for CRTs increases and the revenue from asset disposal is slightly reduced. This is because the transportation costs in this system are high enough to make the tradeoff between increased asset purchase costs and transportation costs unprofitable for the overall system.

One final scenario is examined for the case study problem. A combination of the two legislative scenarios (simultaneous ARF in California and landfill ban in Massachusetts) yields precisely the same optimal product flows as that for the Massachusetts landfill ban alone. This is expected, since the introduction of the California ARF in the case study did not affect any optimal product flows by itself.

In summary, this industrial case study demonstrates the ability of the model to answer the key research questions posed in Chapter 1. The case highlights the trade-offs between various costs in the system, the desirability of rebuilding and refurbishing activities, and the impacts of state-sponsored environmental initiatives on end-of-life flows of specific asset types. The chapter is summarized in the next section.

3.5 Conclusions and summary

This chapter presents a MILP formulation that would allow an electronic equipment leasing company to make simultaneous decisions about lease lengths, product flows and end-of-life management of assets. The model becomes a LP under certain conditions, as discussed in the deterministic case study. The case study validates the model and demonstrates the utility of the model in providing useful insights into the problem.

It is shown in the case study that for asset purchase decisions and forward product flows, there exists a tradeoff between asset purchase costs and transportation costs. On the other hand, environmental legislation and transportation costs affect the reverse product flows. An increase in asset disposal costs due to a landfill ban in one location can lead to a significant increase in the disposal of assets at other locations. In addition, it is observed that rebuilding is a profitable activity, especially for high-end assets. Therefore, a leasing or asset manager for a large leasing company could apply the model developed in this chapter, and the insights obtained thereof, to gain a competitive advantage by managing the business more efficiently.

The next chapter discusses a more realistic situation, by undertaking a detailed examination of the effects of uncertainty in problem parameters on the optimal values of the objective function and the decision variables. An approach to make near-robust decisions under uncertainty is also discussed.

CHAPTER 4

EXAMINATION OF UNCERTAINTY IN PROBLEM PARAMETERS

Chapter 3 presents an optimization model that allows the leasing company to make simultaneous decisions about lease lengths, product flows and end-of-life management of assets. The subsequent deterministic case study validates the model and demonstrates its potential utility. It also points towards the existence of tradeoffs between various kinds of costs in the system. However, a more realistic approach would consider uncertainty in parameter values. Although all parameter values may be uncertain, some sources of uncertainty are clearly more important than others. Section 4.1 discusses the sources of uncertainty in the problem and their relative importance for this research. Section 4.2 discusses a robust optimization approach to address key uncertainties identified in Section 4.1. Section 4.3 illustrates the impact of important uncertainties on the optimal decisions and provides further interesting insights into the problem. Section 4.4 summarizes the chapter and presents concluding remarks.

4.1 Identification of key sources of uncertainty

The focus of this research is the intersection of the fields of equipment replacement and reverse logistics. It has been demonstrated in Chapter 2 that no known analytical approaches exist for this problem in current literature, even though there is a great deal of published literature on each of the related fields. Of key interest in this chapter is the examination of uncertainty in problem parameters and its effects on decisions that span across the individual fields of study related to the problem.

Important problem parameters that may be uncertain include the demand for assets, asset purchase costs, lease revenues, transportation costs, inventory costs and asset disposal costs. These parameters may in turn be affected by factors such as market conditions, technological change and environmental legislation. In this section, each of these factors and uncertainties is discussed in turn. Subsequently, the key uncertainties to be addressed in this research are identified and discussed in more detail.

Uncertainty in demand for electronic equipment leasing is one of the major sources of uncertainty because it affects asset purchase and inventory decisions. However, uncertainty in demand and the inventory management techniques for it have been extensively studied in operations research literature and this research is unlikely to make a strong contribution to the study of asset and inventory management under uncertain demand.

The uncertainty associated with technological change is another important aspect of this problem due to the short life cycle of electronic equipment. Technological change can drastically affect both asset purchase costs and asset lease revenues. Once again though, there exists a body of literature for asset replacement with technological change, from which a few representative papers have already been cited in Chapter 2.

The results from the deterministic case study in Chapter 3 (Section 3.4) indicate that tradeoffs between transportation costs, asset purchase costs and asset disposal costs can potentially cause significant changes in product flows. It is observed that the effects of legislation are not only limited to changes in the optimal value of the objective function, but can also result in changes in the optimal solution due to the changes in asset purchase and asset disposal costs effected by legislative measures. Therefore, the investigation of uncertainty in logistics costs and legislation, and the interactions thereof, provides novel insight, and these uncertainties are the key uncertainties in problem parameters to be addressed in this research. However, given that fact that asset purchase costs constitute a very large proportion of the total costs, it is important to recognize that uncertainties in asset purchase costs (caused by reasons other than environmental legislation) and in a few other problem parameters are important. These uncertainties, while not examined in detail, will be discussed briefly where appropriate during the remainder of this chapter.

Figure 4.1 depicts the relationships between the key sources of uncertainty in the system in the form of a schematic diagram. An arrow leading from one box to another indicates that a change in problem parameters at the tail of the arrow effects a change in problem parameters or decision variables at the head of the arrow. For example, a change in environmental legislation can affect both asset purchase costs and asset disposal costs (although not necessarily both at the same time). Advance Recycling Fees (ARFs) affect both asset purchase and asset disposal costs, while landfill bans only affect asset disposal costs. Similarly, a change in second-hand market conditions can change both asset purchase costs and asset disposal costs. The dashed lines associated with second-hand markets mean that these effects, while important, are not being considered explicitly in this research.

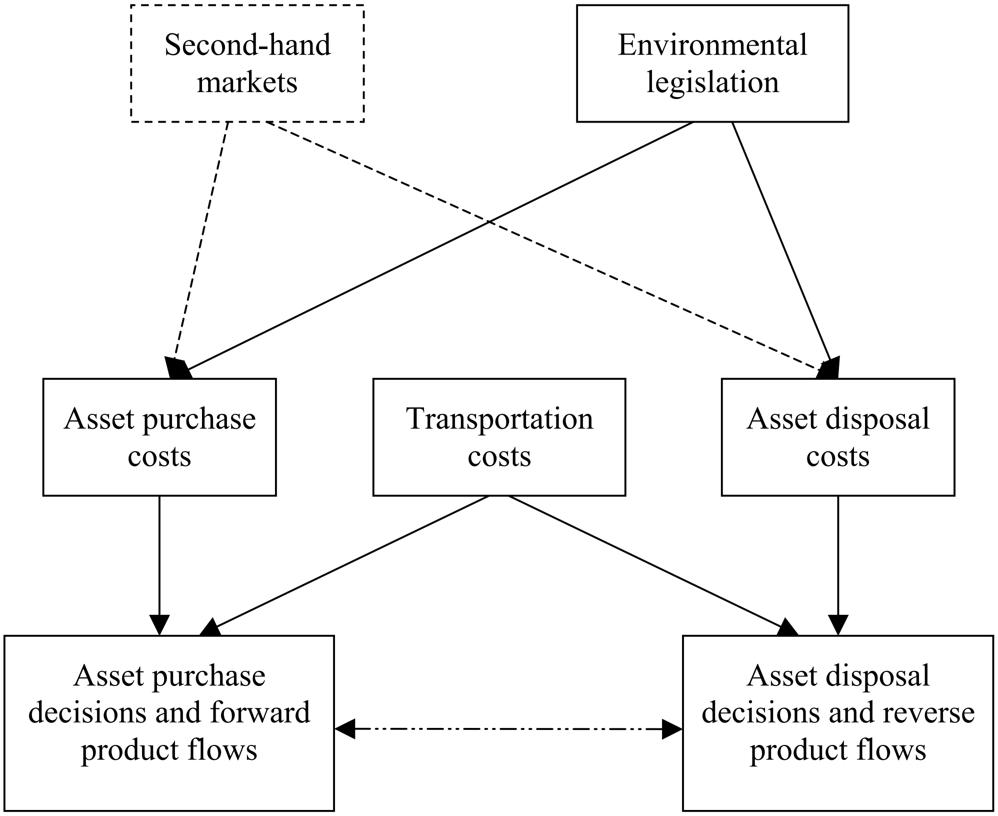

Figure 4.1: Relationships between the key sources of uncertainty

Transportation costs interact with both asset purchase and asset disposal costs and hence affect forward as well as reverse flows. The two-way interaction between transportation costs and asset purchase costs affects asset purchase decisions and hence forward product flows. The two-way interaction between transportation costs and asset disposal costs affects asset disposal decisions and hence reverse product flows.

The differently dashed double-ended arrow, which connects forward and reverse product flows, represents the three-way interaction between transportation costs, asset purchase costs and asset disposal costs, effecting a simultaneous change in forward and reverse product flows. This interaction arises as a result of the possibility of multiple leasing cycles for assets. For example, an asset could be taken out of service at one customer site and subsequently put back into service at another customer site, in which case the choice of logistics facility to use at the end of the first leasing cycle is an important link between the forward and reverse flows.

The results of a detailed investigation to determine the effects of these interactions between uncertainty in transportation costs and environmental legislation are presented in Section 4.3. However, before presenting the results, the next section discusses a robust optimization approach for analyzing these key uncertainties and demonstrates how the leasing company can make robust leasing decisions in the face of uncertainty in transportation costs and environmental legislation.

4.2 Decision robustness under uncertainty

This section discusses a robust optimization approach for the research problem addressed in this dissertation. Robust optimization approaches to address uncertainty have been used frequently in recent literature on strategic supply chain design, with some key literature cited in Section 4.2.1. Since decisions about the opening and closing of logistics facilities often involve large fixed costs and are hence long-term decisions, the objective is to achieve a logistics network configuration that performs "well" across several potential realizations of uncertainty. However, the definition of "good performance" is context-dependent and therefore, there exist several alternative definitions of robustness. Section 4.2.1 discusses the meaning of robustness in the context of the problem faced by the electronic equipment leasing company. Section 4.2.2

discusses methods by which the leasing company can make good decisions in the face of uncertainty.

4.2.1 Definitions of robustness

One of the components of a robust optimization problem formulation is a set of specific realizations of uncertainty, called *scenarios*. According to one definition (Bai, Carpenter and Mulvey, 1997 [7]), the goal of robust optimization is to find a near-optimal solution that is not overly sensitive to a specific realization of uncertainty. Alternatively, Mulvey, Vanderbei and Zenios (1995) [67] describe robust optimization as finding a solution whose objective value is close to that of the optimal solution for each scenario. This latter definition is used for *regret models* of robust optimization, while the former is used for models that include variability measures (such as variance or standard deviation) in the objective function.

Typically, robust optimization formulations also include a set of *robust variables*, *i.e.*, the values of those variables must remain the same across all scenarios being considered. For example, in robust formulations of supply chain design problems, facility location variables are chosen as the robust variables, *i.e.*, the same set of facilities must be open in all scenarios.

In regret models, the regret of a scenario is measured as the difference between the optimal objective function value (cost or profit) for that scenario and the best objective value that can be obtained by choosing the fixed values of robust variables for that scenario. The difference can be expressed in absolute or relative terms. According to robustness criteria defined by Kouvelis and Yu (1997) [58] (both absolute and relative), a *robust solution* is one that achieves the best worst-case deviation from optimality. Another approach, proposed by Gutierrez, Kouvelis and Kurawarwala (1996) [40] require a robust solution to be within *p* percent of the optimal solution for each realizable scenario. However, this approach may lead to infeasibility for small values of *p*, especially if there is a huge difference between the best-case and worst-case scenarios.

On the other hand, variability models attempt to simultaneously minimize expected costs (or maximize expected profits) and reduce the variability over all considered scenarios. Some examples of these models can be found in literature due to Mulvey, Vanderbei and Zenios (1995) [67], Yu and Li (2000) [107] and Goetschalckx *et al.* (2001) [37]. However, the inclusion of variability measures (most typically, variance or standard deviation) in the objective function makes it non-linear. Also, these methods assume symmetric risk, *i.e.*, it is equally bad for costs to be above or below the mean. Asymmetric measures such as those used by Ahmed and Sahinidis (1998) [1] are often hard to compute.

An additional issue arises when the right-hand side coefficients in a model are uncertain. In this case, all constraints may not be satisfied in every scenario, and it is convenient to introduce additional variables that represent the slack or surplus in the constraints. These variables, called *recourse variables*, are included in the objective function as an infeasibility penalty (Mulvey, Vanderbei and Zenios, 1995 [67]; Yu and Li, 2000 [107]).

In light of the preceding discussion, it is now possible to discuss the appropriateness of robustness criteria in the context of the problem faced by an electronic equipment leasing company. In the face of uncertainty, it would be preferable for the leasing company to use a regret model. This is because a variability minimization criterion would tend to push all scenario solutions towards an average value, which implies that the risk posed by unfavorable scenarios is reduced, but so is the profit potential in favorable scenarios. The leasing company would not want to miss out on an opportunity to make high profits, should one present itself in a particular scenario. In other words, they would prefer that the optimal profit in any scenario should not be too much lower than that which could have been realized had all parameter values been known with certainty. This reasoning points to a regret model of robustness. An absolute robustness criterion is chosen in this research, which implies that the regret is measured in dollars.

The next decision to be made is the choice of robust variables. It must be noted that robustness is more important for some decisions as compared to others. For example, leases are contractual in nature and therefore, more difficult to change than product flows. Hence the leasing company would prefer to have leasing decision variables as the robust variables, *i.e.*, a fixed set of leases would be chosen across all potential scenarios. Given this fixed set of leases, the remaining decisions must be made for each scenario such that the deviation from the optimal solution for that scenario is as small as possible.

Another point to be noted here is that if the leasing company uses third-party logistics providers (3PL) to manage logistics activities, it is likely that there would exist contracts about the amounts of product flow on various routes and the variability of those flows. Therefore, the set of robust variables would now have to be expanded to include product flows as well. However, the following discussion assumes that the leasing company manages logistics activities itself and therefore, the focus is on making robust leasing decisions only.

For extending the mathematical model formulated in Chapter 3 so as to make it a robust optimization formulation, one needs to define a set of scenarios Ω, and hold the set of variables $XL^{A}_{p,h,c,i,r,s}$ to a fixed value for all $\omega \in \Omega$. All other variables are additionally indexed by the subscript ω because they can take different values for each scenario. R_ω denotes the optimal profit obtained for scenario ω with the robust variables held to a fixed value across all scenarios, and O_ω^{*} denotes the original optimal profit for that scenario. The variable δ denotes the *maximum regret*, and a robust solution would minimize the value of δ. Mathematically, a robust optimization formulation of the problem can be expressed as follows.

Problem "Robust"

Minimize δ

subject to:

$$\delta \geq O^{*}_{\omega} - R_{\omega} \qquad \forall \omega \in \Omega \;;$$

Constraint sets (3.2), (3.9) and (3.18) - (3.19); and

Constraint sets (3.3) - (3.8), (3.10) - (3.17) and (3.20) - (3.25), each additionally indexed by ω.

Although demand uncertainty is not being considered in this research, addressing this kind of uncertainty with a robust optimization approach would require the use of recourse variables for constraints (3.2).

For better exposition, the single scenario deterministic model formulated in Chapter 3 is henceforth referred to as "Problem Original" and the robust formulation presented above is referred to as "Problem Robust." The steps involved in solving a formal robust optimization problem would be as follows.

- Define a set of scenarios, Ω.
- Solve Problem Original for each of the scenarios individually and obtain values for O_ω^*.
- Solve Problem Robust. A *robust solution* is defined as the set of values of decision variables in Problem Robust that minimizes the value of δ. Clearly, $\delta \geq 0$.

It must be noted that the robust optimization formulation of a problem can lead to a significant increase in the number of variables and constraints, because many of the variables and constraints are uniquely defined for each scenario. Since the single scenario deterministic model in Chapter 3 contains a large number of variables and constraints, computational issues could be encountered in the solution of Problem Robust. Therefore, before the actual adoption of a formal robust optimization approach, it is worthwhile to examine the practical utility of this detailed theoretical and computational exercise for the purposes of this research. Section 4.2.2 extends the deterministic case study, and results from twelve scenarios are examined in order to identify the opportunities offered by robust optimization.

4.2.2 Robust leasing decisions: An extended case study

This section extends the deterministic case study presented in Chapter 3. First, a set of twelve uncertainty scenarios is defined. The scenarios themselves are tabulated in Table 4.1. The columns in the table represent four alternatives for environmental legislation. "No legislation" implies that both asset purchase and asset disposal costs remain the same as those in the base case. As it has already been stated in Chapter 3

(Section 3.4.1), asset purchase costs at different warehouse locations are assumed to be differentiated by local tariffs like sales tax, and asset disposal costs are assumed to be the same at all warehouse locations in the base case. The Advance Recycling Fee (ARF) in California is assumed to raise the purchase cost of every asset type by $10, and asset disposal is assumed to be cost neutral for those asset types for which the original disposal cost was between -$10 (*i.e.*, revenue generation of $10 on disposal) and $10. The net effect of this is to increase the average asset disposal costs in California, by approximately $3. The landfill ban in Massachusetts not only disallows the landfilling of all types of assets, but also raises the recycling costs of assets by an average of approximately $15.

Table 4.1: Uncertainty scenarios

	No legislation	**ARF in CA**	**Landfill ban in MA**	**Both ARF and landfill ban**
Base case transportation rates	Scenario 1	Scenario 4	Scenario 7	Scenario 10
Transportation rates 0.1 times base case	Scenario 2	Scenario 5	Scenario 8	Scenario 11
Transportation rates 10 times base case	Scenario 3	Scenario 6	Scenario 9	Scenario 12

The rows in Table 4.1 represent alternatives for transportation rates, which are assumed to depend linearly on the distance for which an asset is transported. The alternatives for transportation rates are taken as one-tenth and 10 times the base case transportation rates. It is expected that this particular choice of values should provide a sufficiently high contrast to distinguish the effect of transportation costs on the optimal solutions across scenarios.

4.2.2.1 Intuitive reasoning for the identification of near-robust solutions

This section presents a few results from the extended case study. These results provide some information about the structure of the problem. This information is then used to form intuitive reasoning that can be used to obtain near-robust solutions. The intuitive reasoning is verified by results from another small extension of the case study.

A first step to forming intuitive reasoning is to examine high-level results from the case study. Clearly, the best high-level results for examination are the optimal objective function values (total net discounted system profit) under various scenarios (obtained by solving each of the scenarios individually) and the differences in the components of the objective function (total revenues and costs) across scenarios. The optimal objective function values for various scenarios are shown in Table 4.2.

The results indicate that uncertainty in transportation costs affects the objective function more strongly than the uncertainty in asset purchase and asset disposal costs caused by environmental legislation. In other words, for a given level of transportation cost rates, the objective function is not affected as much by changes in asset purchase and asset disposal costs as it is affected when environmental legislation is given and transportation cost rates are varied. For example, for a given level of transportation costs, the **maximum** change in the optimal objective function value with changes in environmental legislation is approximately $1.9 million. Whereas, across scenarios with the same environmental legislation but different levels of transportation cost, the **minimum** change in the optimal objective function value is more than $7 million.

Table 4.2: Optimal objective function values ($ million) for the case study problem with various scenarios of transportation rates and environmental legislation

	No legislation	**ARF in CA**	**Landfill ban in MA**	**Both ARF and landfill ban**
Base case transportation rates	265.81	265.32	264.60	264.12
Transportation rates 0.1 times base case	276.59	276.50	276.30	276.20
Transportation rates 10 times base case	194.73	194.14	193.41	192.82

It can be argued here that this strong effect of transportation costs on the objective function is due to a large range of variation considered in transportation rates (a factor of 100 between the highest and lowest levels). However, the effect of transportation rates is stronger even when the range of variation considered in transportation rates is much smaller, *i.e.,* when the highest and lowest transportation rate levels differ only by a factor of only 3.0 (or in other words, when transportation rates vary only by 50% on either side of the base case rates).

In addition, a large portion of the change in the objective function value between scenarios with different levels of transportation cost rates is a result of the change in total transportation costs. For example, the transportation costs increase by approximately $68 million from Scenario 1 to Scenario 3, and by a very similar amount from Scenario 10 to Scenario 12. This increase in total transportation costs is almost the same as the decrease in total profits (approximately \$71 million) between the corresponding scenarios. Similarly, the total transportation costs decrease by approximately \$7.5 million from Scenario 1 to Scenario 2, compared to a profit increase of approximately \$10.5 million. The only other cost component that changes within the same order of magnitude is the total asset purchase cost – the change in other cost components is comparatively very small. This result confirms that transportation costs strongly influence total profit, but at the same time, it also cautions that changes in asset purchase costs may become significant if the considered range of uncertainty in transportation costs is small. Once again, uncertainties in asset purchase costs (due to factors other than environmental legislation) are not examined in this research, but this aspect is discussed briefly at the end of Section 4.2.2.2.

With the observations made above, it should be possible to identify a solution that is close to robust. Even though the robustness of this solution cannot be guaranteed (*i.e.*, it is not guaranteed that this solution would yield the minimum possible value of the maximum regret), this solution would make the maximum regret low (quite close to zero in relative terms, which is a lower bound on robustness). This is formally stated below in the form of Hypothesis 1.

Hypothesis 1: Given the particular data for this case study, the optimal values of the leasing decision variables from at least one of the twelve scenarios in Table

4.1 could be chosen as a set of values for the robust variables $XL^{A}_{p,h,c,i,r,s}$, without making the maximum regret very large.

In order to verify the correctness of the hypothesis, it would suffice to show that by fixing the optimal values of lease variables from one of these 12 scenarios as the values of the robust variables $XL^{A}_{p,h,c,i,r,s}$ and re-optimizing all the other scenarios, the new optimal profit thus obtained for any scenario would not be significantly different from the original optimal profit under that scenario (in Table 4.2).

The immediately obvious next question is: How should one choose a scenario whose optimal leasing decision variables provide a near-robust solution? Once again, intuitive logic provides an answer. Suppose a scenario with very high transportation rates were chosen. All decisions in such a scenario would attempt to keep total transportation costs low. This is expected to lead to longer leases on average, because shorter leases imply more transportation of assets. Therefore, a decrease in total lease revenues would be expected in other scenarios if the optimal values of lease variables from this high transportation rate scenario were chosen as the values of the robust variables. However, this decrease in total lease revenues should be counterbalanced by a simultaneous decrease in total transportation costs (and other costs are not expected to change significantly). The converse applies for choosing a scenario with very low transportation rates. In this case, the increase in total lease revenues in other scenarios would be counterbalanced by a simultaneous increase in total transportation costs. However, given that with a large change in transportation rates, the magnitude of the change in total transportation costs is significantly higher as compared to the change in other kinds of costs (and revenues), a scenario with high transportation rates is a better intuitive choice.

Results are compared for the values of robust variables $XL^{A}_{p,h,c,i,r,s}$ chosen from a scenario with each level of transportation rates, *i.e.*, Scenarios 11, 10, and 12 respectively for low, “medium” (base case) and high transportation rates. The results are presented in Table 4.3. $R_{\omega}(\omega_0)$ denotes the optimal net discounted profit for scenario ω when the optimal values of lease variables from scenario ω_0 are chosen as the values for the robust variables. The highlighted cells in the table correspond to results for scenario ω_0.

It can clearly be seen that the results confirm Hypothesis 1 and other intuitive reasoning. The maximum regret is \$0.82 million (0.30% in relative terms) if one chooses the optimal values of leasing decision variables from a scenario with the highest transportation rates as the values for the robust variables $XL^{A}_{p,h,c,i,r,s}$. This is not a very high value in relative terms. The maximum regret is significantly higher (\$1.56 million, or 0.81% in relative terms) if a scenario with the lowest transportation rates provides the values for the robust variables. It must be noted that although such a choice performs better than the high transportation rate scenario in eight out of twelve scenarios, it performs worse in the other four scenarios (all of these being the ones in which transportation rates are very high).

Table 4.3: Optimal net discounted profits and the deviation from optimal values (in $ million) for all scenarios, with various choices of values for robust variables

Scenario (ω)	O_{ω}^{*}	$\omega_0 = 11$ **Low transportation rates**		$\omega_0 = 10$ **Base case transportation rates**		$\omega_0 = 12$ **High transportation rates**	
		$R_{\omega}(11)$	$O_{\omega}^{*} - R_{\omega}(11)$	$R_{\omega}(10)$	$O_{\omega}^{*} - R_{\omega}(10)$	$R_{\omega}(12)$	$O_{\omega}^{*} - R_{\omega}(12)$
1	265.81	265.81	0.00	265.81	0.00	265.20	0.61
2	276.59	276.59	0.00	276.59	0.00	275.77	0.82
3	194.73	193.17	1.56	193.26	1.47	194.73	0.00
4	265.32	265.32	0.00	265.32	0.00	264.72	0.60
5	276.50	276.50	0.00	276.49	0.00	275.67	0.83
6	194.14	192.59	1.55	192.67	1.47	194.14	0.00
7	264.60	264.60	0.00	264.60	0.00	264.00	0.60
8	276.30	276.30	0.00	276.29	0.00	275.48	0.82
9	193.41	191.85	1.56	191.93	1.48	193.41	0.00
10	264.12	264.11	0.00	264.12	0.00	263.51	0.61
11	276.20	276.20	0.00	276.20	0.0000	275.38	0.82
12	192.82	191.26	1.56	191.34	1.48	192.82	0.00

4.2.2.2 Simple empirical methods for reducing the maximum regret

The results from the extended case study confirm the intuitive reasoning presented in Section 4.2.2.1. However, it would be more desirable if intuitive reasoning provides a more specific method of obtaining low values of maximum regret and can be verified without solving a large number of scenarios each time new data is encountered. This section presents simple empirical methods for choosing the values of robust leasing variables so as to obtain a low value of the maximum regret.

Given the discussion that supports Hypothesis 1 in Section 4.2.2.1, Hypothesis 1 should hold for all realistically imaginable transportation cost ranges for this particular research problem if it holds for a case where there is a difference of two orders of magnitude in the extreme values of the transportation rates. If the extreme values have a smaller range, then the maximum regret obtained by using the optimal values of the leasing decision variables from any scenario as the robust leasing decisions should be even smaller than the one obtained in the extended case study.

However, the choice of a scenario whose optimal leasing decision variables provide a better near-robust solution than others is not as clear. For example, consider a case where transportation rate variations of only 50% on either side of the base case need to be studied, *i.e.*, the minimum possible transportation rate is 0.5 times the base case rate and the maximum possible one is 1.5 times the base case rate. It is now more likely that the lowest transportation rate scenario may provide a better balance between the change in total lease revenues and the change in total transportation costs, as compared to the highest transportation rate scenario.

Further computational analysis with other values of transportation rates is presented below in order to provide more insight into this issue. To make the discussion more coherent, the effects of legislation are not considered in this analysis. However, given the strongly dominant effect of transportation costs on the objective function, this exclusion of legislative effects should not change any of the insights obtained (In fact, it is formally shown in Section 4.3.3 that for this case study, environmental legislation has no significant effect on leasing decisions).

It is helpful to define a few additional terms and notation for a concise expression of the ideas that follow. The scenarios being considered for this computational analysis only differ in their respective levels of transportation cost rates. The transportation rate *level* is denoted by l, which implies transportation rates l times the base case rates. The minimum level is denoted by l_{min} and the maximum level by l_{max} (in this extended case study, these levels are 0.1 and 10 respectively). A scenario with a transportation rate level l is denoted by $\omega(l)$. For the remainder of this section, the reference to transportation rates is implicit in the word "level(s)." This is done in order to enhance expressional simplicity.

Similar to the notation in Section 4.2.2.1, $R_{\omega(k)}(\omega(l))$ denotes the optimal objective function value of a scenario with level k, when the optimal values of leasing decision variables from a scenario with level l are used as the robust leasing decisions. Therefore, when a scenario with level k is realized, and the optimal values of leasing decision variables from a scenario with level l are used as the robust leasing decisions, one can define the resulting regret (denoted by *Reg(k,l)* hereafter) as

$$Reg(k,l) = O^{*}_{\omega(k)} - R_{\omega(k)}(\omega(l)) \qquad (4.1)$$

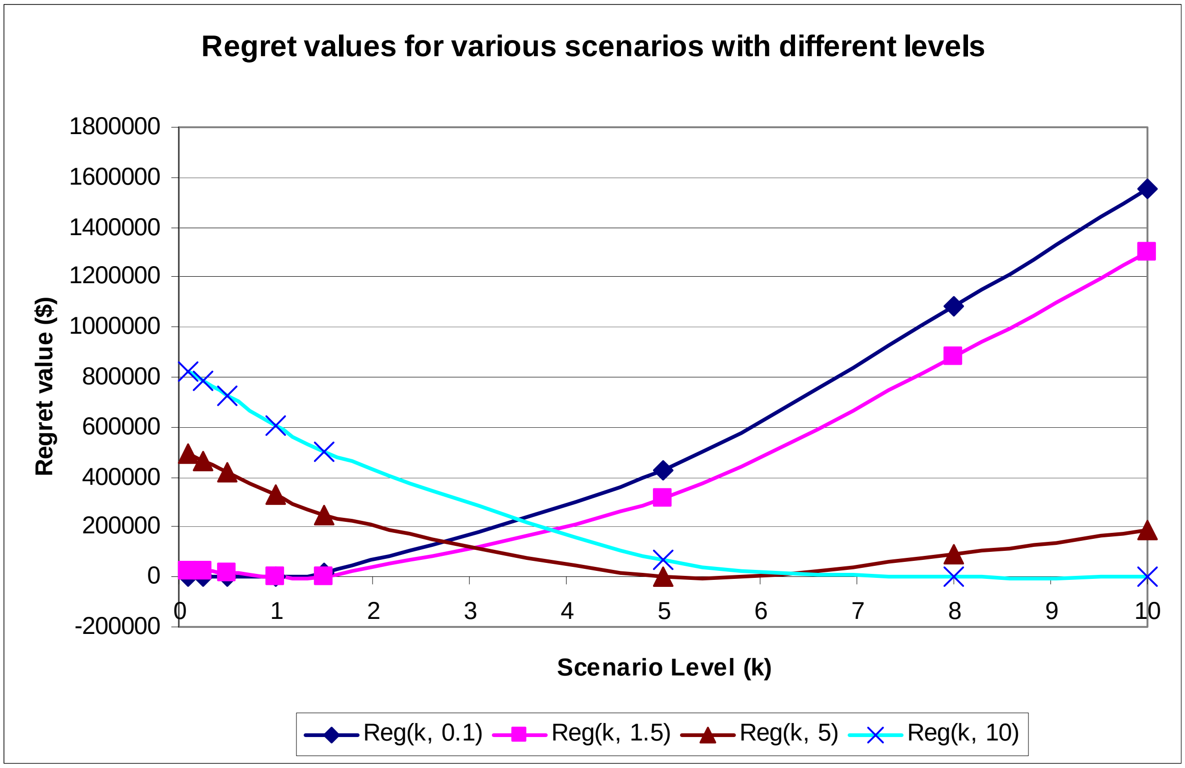

Figure 4.2: Observed regret values (in $), when the optimal values of leasing decision variables from various scenarios are used as robust leasing decisions

Figure 4.2 shows the regret values obtained in eight scenarios, with levels ranging from 0.1 to 10, when the optimal values of leasing decision variables from four of these scenarios (with levels 0.1, 1.5, 5 and 10 respectively) are used as the robust leasing decisions. Therefore, the graph consists of four data series, each with eight points.

Before any observations are made about the graph, it is very helpful to cite a theoretical result due to Assavapokee (2004) [5], who proves that if an uncertain parameter is present only in the objective function of a MILP problem, and a min-max regret robust optimization approach is used, the maximum regret always occurs at one of the two extreme values of that parameter.

This result implies that in order to find the maximum regret when the optimal values of leasing decision variables from a scenario with level l provide the robust leasing decisions, it should suffice to look only at the regrets for scenarios with levels $k = l_{min}$ and $k = l_{max}$, and the greater of these two values provides us the answer. Figure 4.2 agrees with this implication of the theoretical result, because it is observed that only either endpoint of each data series provides the maximum regret for that scenario level l.

The observed parabolic shapes of the data series suggest a method of choosing a scenario that provides low maximum regret when the optimal values of its leasing decision variables are used as the robust leasing decisions. Scenarios with levels $l = l_{min}$ and $l = l_{max}$ are clearly not the best choices. One would ideally like to find a scenario with level l for which the regret value at the extreme levels ($k = l_{min}$ and $k = l_{max}$) is the same. Let this level be called the "pseudo-optimal level" l^*. This strange nomenclature is due to the fact that even if one were to find a scenario with this level and use the optimal values of its leasing decision variables as the robust leasing decisions, it is not necessary that the maximum regret thus obtained would actually be mathematically optimal (*i.e.*, the minimum possible value).

It can be observed in Figure 4.2 that the scenario with level 5 seems to be close to pseudo-optimal. However, it is still not clear how one would actually go about finding a pseudo-optimal scenario without guesswork and the expenditure of substantial computational effort. An educated guess would point to using the average value of $(l_{min} + l_{max})/2$ as l^*, which happens to be 5.05 in this particular case. But it can also be observed that the real pseudo-optimal level should be less than 5, because $Reg(0.1, 5) > Reg(10, 5)$. So, how is it possible to do better? The parabolic shapes of the data series in Figure 4.2

suggest that it might be possible to find patterns in the computational data that generates the figure. Data analysis procedures (and the results thereof) are described in the remainder of this section.

Clearly, in light of the theoretical result discussed earlier, it is instructive to look only at the regrets for scenarios with levels $k = l_{min}$ and $k = l_{max}$. Four data series imply that four "observations" are available for the regret value (in $) at each of these extreme levels. However, it is necessary to take into account the fact that the regret value depends not only on the "independent" scenario level l (in other words, the scenario level providing the robust leasing solutions and generating the observations at levels $k = l_{min}$ and $k = l_{max}$), but also the actual values of the extreme levels (Equation (4.1)). Therefore, it is helpful to define the concept of a *level multiple* (denoted by *LM* from here on). During the analysis of a scenario with level l, any other scenario with level k has a level multiple of k/l for the scenario with level l. In other words, $LM(k,l) = k/l$. Using level multiples, a subset of the computational data plotted in Figure 4.2 can be presented in the form of Table 4.4.

Table 4.4: Observed regret ($) for the extreme level scenarios, with optimal values of leasing decision variables from various scenarios used as the robust leasing decisions

Scenario level (l)	$LM(l_{min}, l) = LM(0.1, l)$	$Reg(l_{min}, l)$	$LM(l_{max}, l) = LM(10, l)$	$Reg(l_{max}, l)$
0.1	1	0	100	1,556,942
1.5	0.067	25,686	6.667	1,301,942
5	0.02	493,944	2	191,569
10	0.01	822,358	1	0

Level multiples take into account both levels k and l, and provide a single independent variable to work with in the data analysis. Graphs of level multiples versus regret values can then be plotted. The data plots of $LM(l_{min}, l)$ versus $Reg(l_{min}, l)$ and $LM(l_{max}, l)$ versus $Reg(l_{max}, l)$ indicate no obvious relationship. However, when the natural logarithms of these quantities are plotted (the zero values are dealt with by adding a small number like 10^{-12} to them), a regular relationship is observed. The transformed data seem to follow either a quadratic or exponential trend. Analysis using the curve-fitting software Lab Fit® [62] indicates that an offset exponential trend of the form $a + be^{cx}$ is a good fit for both $Reg(l_{min}, l)$ and $Reg(l_{max}, l)$, with high R^2-values. Therefore, the following relationships are obtained.

$$\begin{aligned} \ln(Reg(0.1,l)) &= 14.514 - 46.751e^{0.8783*\ln(LM(0.1,l))} \\ &= 14.514 - 46.751*LM(0.1,l)^{0.8783} \end{aligned} \tag{4.2}$$

$$\begin{aligned} \ln(Reg(10,l)) &= 14.1736 - 46.408e^{-4.528*\ln(LM(10,l))} \\ &= 14.1736 - 46.408*LM(10,l)^{-4.528} \end{aligned} \tag{4.3}$$

Using these relationships, it is now possible to predict (for this extended case study) the regret values at the extreme level scenarios, and hence the maximum regret, for a scenario (with any level) that provides the robust leasing decisions. It is also possible to determine the pseudo-optimal level l^*, by setting $ln(Reg(l_{min}, l^*)) = ln(Reg(l_{max}, l^*))$. The resulting equation can easily be solved numerically (say, using Microsoft Excel Solver), and it is found that **$l^* = 4.539$**. This value makes more intuitive sense than the "average" value of 5.05, due to the observation from Figure 4.2 that the pseudo-optimal level should be less than 5 for the extended case study presented in this chapter.

However, a high R^2-value for relationships (4.2) and (4.3) does not necessarily imply good prediction, because the small number of data points may lead to over-fitting of the data. Therefore, it is necessary to verify how "good" the predicted values are. Table 4.5 shows a comparison between the predicted regret values and the actual regret values for scenarios with various levels for the extended case study.

Table 4.5: Comparison between predicted and actual values of regret ($) for various scenario levels in the extended case study

Scenario level (*l*)	**Predicted values**			**Actual values**		
	Reg(0.1,*l*)	*Reg*(10, *l*)	Maximum regret ($)	*Reg*(0.1,*l*)	*Reg*(10, *l*)	Maximum regret ($)
0.25	0	1,430,594	**1,430,594**	97	786,100	**786,100**
0.5	23	1,430,513	**1,430,513**	755	726,317	**726,317**
1	4,132	1,428,631	**1,428,631**	3,755	609,113	**609,113**
8	742,561	0	**742,561**	1,081,348	4,917	**1,081,348**
4.539	390,560	390,560	**390,560**	465,528	223,472	**465,528**

It can be observed that for some of the scenario levels, especially the predicted pseudo-optimal scenario level, the prediction error for the maximum regret is high, which indicates over-fitting of the experimental data. The value of the actual maximum regret with scenario level l^* is substantially lower ($0.465 million) as compared to the value of $0.82 million obtained with $l = 10$. However, it is clearly not pseudo-optimal, because the actual values of *Reg*(0.1, 4.539) and *Reg*(10, 4.539) are quite different from each other. The value of $465,528 is also not substantially lower than the one that would have been obtained ($493,944) by simply using $l^* = (l_{min} + l_{max})/2$. Therefore, it may not always be worthwhile to expend even the small computational effort required to fit functional forms for the calculation of l^*.

The parabolic shapes of the data series in Figure 4.2 also arouse curiosity. It is interesting to examine whether it is possible to fit a functional form to these $Reg(k,l)$ data series *per se*. Once again, it is convenient to use level multiples $LM(k,l)$ as the independent variables for data analysis. Data analysis with both the statistical software Minitab® [66] and the curve-fitting software Lab Fit® [62] shows that for a particular scenario level l, a quadratic relationship between $Reg(k,l)$ and $LM(k,l)$ is a good fit for the observed data. That is, the observed relationships are of the following form.

$$Reg(k,l) = a_l LM(k,l)^2 + b_l LM(k,l) + c_l \tag{4.4}$$

Once again, the R^2-values are high – better than 99.5% for three of the four cases, and about 98% for the remaining one. Table 4.6 shows the values of a_l, b_l and c_l for the four scenarios.

Table 4.6: Value of fitted regression coefficients for Equation (4.4), from case study observations of regret values with various scenario levels

Scenario level (l)	a_l	b_l	c_l
0.1	138	2204	-19014
1.5	31058	-9609	9166
5	345125	-829363	493329
10	1389392	-2195488	830024

It must be cautioned that even though the R^2-values are very high, the functional relationships cannot be treated as exact fits. This is evident if one considers the properties that a truly quadratic relationship would satisfy. The value of *Reg*(*k,l*) can be zero only at a level multiple *LM*(*k,l*) = 1 and nowhere else. Therefore, the quadratic equation (4.4) must have a repeated root at $l = k$. This implies that the coefficients must satisfy the relationships $b_l^2 - 4a_l c_l = 0$ and $b_l = -2a_l$. However, this is clearly not the case.

From Table 4.6, it is possible to elicit further functional relationships between the scenario level *l* and the coefficients a_l, b_l and c_l, which could be used to predict the *Reg*(*k,l*) curve for any scenario level *l*. This way, it is possible to predict (for a particular scenario level *l*) not only the *Reg*(*k,l*) values for $k = l_{min}$ and l_{max}, but also for any other scenario level *k*. Due to the propagation of prediction errors from one step to the next in this two-step method, it would have lower accuracy than the previously described method that only predicts *Reg*(l_{min}, *l*) and *Reg*(l_{max}, *l*).

Although the empirical methods discussed in this section have only been verified for the case study, it is possible to argue their applicability to more general cases. Two important characteristics drive these empirical methods. The first is the occurrence of maximum regret only at the extreme scenario levels, and the second is the parabolic shapes of the regret curves in Figure 4.2. Assavapokee's result, being a theoretical proof, ensures that the first criteria would be satisfied if the uncertainties being examined in the problem are the coefficients of decision variables only in the objective functions of the optimization problems for individual scenarios. The parabolic shapes of the curves follow from the intuitive reasoning that leads to Hypothesis 1. The hypothesis is based on the effect of one particular type of uncertainty overshadowing the effect of others in the possible scenarios being considered. The uncertainty with a strong effect happens to be the uncertainty in transportation rates in this case. Now, if a particular scenario with transportation rate level *k* were realized, and a scenario with level *l* were used to obtain the values of the robust leasing variables, then it is reasonable to expect that the farther away level *l* is from level *k*, the higher the regret *Reg*(*k,l*) should be.

However, an appropriate note of caution also needs to be added at this point. This research addresses uncertainty in transportation costs and uncertainty in asset purchase and asset disposal costs due to environmental legislation, but other uncertainties may also be important. As discussed in Sections 4.1 and 4.2.2.1, uncertainty in asset purchase costs (due to causes other than environmental legislation) could rival or overshadow the uncertainty in transportation costs. While these uncertainties in asset purchase costs are not explicitly considered in this research, it is appropriate to discuss them briefly before concluding this section.

Consider a situation where the decision maker for the leasing company would like to make robust leasing decision in the presence of uncertainty in asset purchase costs (instead of uncertainty in transportation costs). Clearly, since asset purchase costs constitute almost all of the total costs for the leasing company, the realized profit is expected to be sensitive to changes in asset purchase costs. The most obvious means for the leasing company to respond to changes in asset purchase costs is to change lease prices (and hence lease revenues), but since lease pricing is not a decision variable in this model, the decision maker encounters the same situation as the one that is encountered when addressing uncertainty in transportation costs. That is, once a level of asset purchase costs is realized, the differences in profit across all scenarios with that level of asset purchase costs would not be very large. In other words, it can be assumed that asset purchase costs would have a much stronger effect on profit than other types of uncertainties.

Therefore, it seems reasonable to assume that the methodology for making near-robust decisions in the presence of uncertainty in transportation costs can be extended to address uncertainty in asset purchase costs. This is explained as follows. Suppose that asset purchase costs were high. Then one would expect the leasing company to lease assets for longer periods in order to cover the time horizon with the minimum number of leasing cycles. This leads to a decrease in lease revenues (shorter leases are more profitable as the computational results in Section 4.3.3 indicate) and in transportation costs. In addition, a large increase in rebuilding activities would be observed, but it can safely be assumed that sufficient rebuilding capacity would not be available to rebuild all types of assets to satisfy all the customer demand. Now, if leasing decisions from this high asset purchase cost scenario were used as robust leasing decisions, lease revenues would decrease for scenarios with lower asset purchase costs, but this decrease would be counterbalanced by a corresponding decrease in transportation costs. One would therefore not expect a very high value of maximum regret. However, if the optimal leasing decisions from a low asset purchase scenario were used as the robust leasing decisions, one would expect a much higher value of maximum regret, because a scenario with low asset purchase costs would encourage shorter leasing cycles and hence more purchases of new assets. Therefore, one would expect to see the same shapes of regret curves as in Figure 4.2, but the curves would have significantly steeper slopes for scenario levels higher than the one being used to provide the values of the robust leasing decision variables. This would have the effect of shifting l^* to the right (*i.e.*, towards scenarios with high asset purchase costs).

In light of the above discussion, an interesting topic for future research would be the simultaneous examination of uncertainties in problem parameters that have comparable influences on the objective function value. Moreover, if these uncertainties were strongly correlated (*i.e.*, if they exhibited strong interaction effects), the problem of making robust decisions would become more challenging and interesting.

In summary, this section presents simple empirical procedures that can be used by an electronic equipment leasing company to obtain near-robust solutions for leasing decision variables under the key uncertainties considered in this research. In order to choose a scenario level l that provides low maximum regret when the optimal values of its leasing decision variables are used as the robust leasing decisions, the simplest method is to choose the average of the extreme scenario levels. A more elaborate approach is to calculate the regret values at the extreme levels with different "independent" levels l and to fit empirical functional forms to these values. These functional forms can then be used to predict the maximum regret at any other scenario level and also to calculate an approximate value for the pseudo-optimal level l^*. If one wants to predict the regret values at scenario levels other than the extreme levels, then even more computational runs are required to obtain a sufficient number of values to elicit the functional (parabolic) forms observed in Figure 4.2 and to avoid large prediction errors.

4.2.2.3 Conclusions on the robustness of leasing decisions

Since robust optimization approaches have gained popularity in academic literature, Section 4.2 discusses as a whole the potential use of a robust optimization approach for the research problem addressed in this dissertation. The concept of robustness is defined in the context of this problem and it is argued that the most desirable robust decisions for an electronic equipment leasing company would be the lease lengths.

However, a cursory examination of the problem structure from the extended case study data shows the stronger effects of uncertainty in transportation costs as compared to uncertainty in other kinds of costs, which leads to Hypothesis 1. The hypothesis argues that it is possible to use the optimal values of leasing decision variables from at least one scenario as the robust leasing decisions without making the maximum regret too large.

Admittedly, the hypothesis has been verified only for the particular data of this case study, but it is argued at the beginning of Section 4.2.2.2 that it should hold for all realistically imaginable transportation cost ranges for this particular research problem. If this hypothesis were to hold, then simple empirical methods (also discussed in Section 4.2.2.2) involving minimal computational effort can be used effectively to obtain low values of the maximum regret. A reasonable argument for the applicability of these methods to more general cases (along with appropriate notes of caution) is made near the end of Section 4.2.2.2.

The above discussion implies that given the kinds of uncertainty on which this research focuses, a standard robust optimization approach would add little additional insights into the problem. Hence, the robust optimization model described in Section 4.2.1 is not solved in this dissertation. The remainder of this chapter is dedicated to a more detailed examination of the results from the twelve scenarios in Table 4.1 in order to thoroughly investigate important cost tradeoffs and uncertainty effects in this system.

The next section first presents intuition-based hypotheses about the expected effects of uncertainty in transportation costs and environmental legislation on product flows and lease lengths. These hypotheses are then tested computationally and interesting insights into the problem are obtained.

4.3 Effects of sources of uncertainty on product flows and lease lengths

The previous section discussed a methodology for the leasing company to make robust leasing decisions with respect to their total profit. However, it is also very important to examine the effects that the key uncertainties in problem parameters have on optimal decisions about product flows and lease lengths. This investigation would help in understanding the tradeoffs between various types of costs in the system and the effects that interactions between sources of uncertainty can have on the optimal decisions. Section 4.3.1 presents intuitive hypotheses about the expected effects of uncertainty on the optimal decisions. The remainder of the section analyzes computational results for the extended case study described in Section 4.2.2, compares the results to the intuitive hypotheses formulated in Section 4.3.1, and discusses the insights thus obtained.

4.3.1 Expected effects of uncertainty

Based on the understanding of uncertainty interactions discussed in Section 4.1, it is possible to present intuitive hypotheses about expected changes in optimal decisions for product flows and leasing periods as a result of changes in transportation costs and environmental legislation. This is done in a tabular form for product flow decisions.

Table 4.7 presents hypotheses on expected changes in optimal asset purchase decisions in twelve scenarios similar to those in Table 4.1. The possibilities for environmental legislation remain the same as in those scenarios and they appear as column headings in the table. However, for the purpose of formulating hypotheses on expected changes in optimal solutions, the possibilities for transportation rates have been slightly modified. Transportation rates are assumed to be zero instead of one-tenth the base case rates, and infinity instead of ten times the base case rates. The nature of the expected changes in product flows becomes immediately clear if these extreme cases are used, hence leading to improved clarity and increased conciseness of presentation.

Table 4.7: Expected changes in optimal asset purchase decisions due to uncertainty in transportation rates and environmental legislation

	No legislation	**ARF in CA**	**Landfill ban in MA**	**Both ARF and landfill ban**
Base case transportation rates	Tradeoff between transportation costs and asset purchase costs	Tradeoff between transportation costs and asset purchase costs, but purchase less in California	Same as scenario with no legislation	Same as scenario with ARF in California
Very low transportation rates (zero)	Purchase all assets at the cheapest warehouse location	Purchase all assets at the cheapest warehouse location	Purchase all assets at the cheapest warehouse location	Purchase all assets at the cheapest warehouse location
Very high transportation rates (∞)	Purchase all assets at warehouse location nearest to customer	Purchase all assets at warehouse location nearest to customer	Purchase all assets at warehouse location nearest to customer	Purchase all assets at warehouse location nearest to customer

In some scenarios, it is not possible to say precisely what the expected optimal solutions would be, because the exact values depend on the relative values of the actual costs being traded off. However, comparing such scenarios with other scenarios indicates the expected changes that would be caused by uncertainty in transportation costs and environmental legislation.

For asset purchase decisions, there is a tradeoff to be made between transportation costs and asset purchase costs. However, if transportation rates are very low, it is clear that all assets should be purchased at the cheapest warehouse location and if they are very high, all assets must be purchased nearest the customer site at which they would be used. The solutions for all scenarios with either very low or very high transportation rates are expected to be identical to each other. Since a landfill ban does not affect asset purchase costs, it is not expected to have any effect on asset purchase decisions. With an ARF in place at a particular warehouse location, asset purchase costs at that location increase. Therefore, in scenarios with base case transportation rates, asset purchases at that warehouse location are expected to decrease due to the tradeoff between asset purchase costs and transportation costs.

Table 4.8 presents hypotheses on expected optimal asset disposal decisions, using the same scenarios as those used for asset purchase decisions. It is more difficult to formulate hypotheses for asset disposals, because both landfill bans and ARFs affect asset disposal costs. An ARF can increase or decrease asset disposal cost for a particular asset type, depending on the original disposal cost for that asset type, because it makes disposal for some kinds of assets cost neutral. A landfill ban always increases asset disposal costs. For asset disposal decisions, there is a tradeoff to be made between transportation costs and asset disposal costs, and the tradeoff that is ultimately made depends on the relative changes in asset disposal costs across warehouse locations. In addition, there are two possible modes of asset disposal (technically, landfilling is a viable option with a landfill ban in place at a particular warehouse location, because the ban makes the costs of landfilling infinitely large at that location), but once the location for disposing an asset has been determined, the asset will always be disposed via the cheapest disposal option.

Table 4.8: Expected changes in optimal asset disposal decisions due to uncertainty in transportation rates and environmental legislation

	No legislation	ARF in CA	Landfill ban in MA	Both ARF and landfill ban
Base case transportation rates	Tradeoff between transportation costs and asset disposal costs	Tradeoff between transportation costs and asset purchase costs, but asset disposals depend on relative changes in asset disposal costs across locations	Tradeoff between transportation costs and asset disposal costs, but dispose more at other locations (California and Georgia)	Same reasoning as for scenario with ARF in CA, but lesser disposal expected in Massachusetts due to effect of landfill ban
Very low transportation rates (zero)	Dispose via cheapest disposal mode at warehouse location with lowest asset disposal costs	Dispose via cheapest disposal mode at warehouse location with lowest asset disposal costs	Dispose via cheapest disposal mode at warehouse location with lowest asset disposal costs	Dispose via cheapest disposal mode at warehouse location with lowest asset disposal costs
Very high transportation rates (∞)	Dispose via cheapest disposal mode at warehouse location nearest to customer	Dispose via cheapest disposal mode at warehouse location nearest to customer	Dispose via cheapest disposal mode at warehouse location nearest to customer	Dispose via cheapest disposal mode at warehouse location nearest to customer

In addition, it must be noted that even though the intuition is identical for scenarios with low transportation rates, the actual optimal solutions for these scenarios may not be identical. Once again, this is due to the fact that an ARF in a particular location can either increase or decrease disposal costs for a particular asset at that location.

It is more difficult to hypothesize about expected changes in leasing periods as a result of uncertainty in transportation costs, and uncertainty in asset purchase and asset disposal costs due to environmental legislation. This is because leasing decisions involve both forward and reverse flows, whose magnitude and timing may simultaneously be affected by the three-way interaction between transportation costs, asset purchase costs and asset disposal costs. The only hypothesis that can be formulated intuitively is that higher transportation costs should lead to longer leases, so that multiple leasing cycles can be avoided and the transportation costs do not have to be paid for each leasing cycle.

The remainder of Section 4.3 presents computational results that reveal the effects of uncertainty in individual parameter sets as well as the effects of the interactions between multiple parameters on the leasing and product flow decisions.

4.3.2 Product flows: Observed effects of uncertainty and interaction effects

This section tests the intuitive hypotheses presented in the Section 4.3.1 using the same extended case study as that used in Section 4.2.2. The model presented in Chapter 3 (Section 3.2) is run individually for each of the twelve scenarios summarized in Table 4.1 and detailed analyses of the computational results are carried out. The first set of analyses, presented in this section, examines asset purchase decisions and forward product flows, and in particular the effect of various sources of uncertainty and the interactions between those uncertainties on the decisions. A similar set of analyses follows for asset disposal decisions and reverse product flows.

Table 4.9 shows the percentage of total asset purchases at each warehouse location in the optimal solutions for each scenario. It would be instructive to define the term "*transportation rate multiplier*" before proceeding. This term is defined to express various transportation rate scenarios more concisely. A transportation rate multiplier of 1.0 corresponds to the transportation rates in base case scenarios. Therefore, a scenario with a transportation rate multiplier of 0.1 has transportation rates one-tenth that of the base case rates and one with a multiplier of 10.0 has transportation rates ten times that of the base case rates.

The results exactly match the hypotheses presented in Table 4.7. As expected, the results show that the imposition of an Advance Recycling Fee (ARF) in California has the effect of reducing the total number of assets purchased in California. A landfill ban in Massachusetts has, expectedly, no effect on asset purchases. However, a change in transportation rates can dramatically alter product flows, because of the tradeoff that exists between asset purchase costs and transportation costs.

Since the computation results from the twelve scenarios constitute a $2^2 3^1$ factorial experimental design [103], a formal statistical analysis in Table 4.10 provides additional confirmation for the hypotheses stated in Table 4.7. The statistical software Minitab® [66] has been used to perform statistical analyses. In the analysis, "TptRate" denotes the experimental factor of transportation rate, which has three levels. "PurchCA," "PurchGA," and "PurchMA" are respectively the fractions of total assets purchased in California, Georgia and Massachusetts.

Table 4.9: Percentage of total asset purchases, by warehouse location, in optimal solutions under various transportation rates and legislative scenarios

Legislative scenario	Transportation rate multiplier	% purchased in CA	% purchased in GA	% purchased in MA
No legislation	1.0	15.57 %	26.26 %	58.17 %
ARF in CA	1.0	14.94 %	26.26 %	58.80 %
Landfill ban in MA	1.0	15.57 %	26.26 %	58.17 %
Both ARF and landfill ban	1.0	14.94 %	26.26 %	58.80 %
No legislation	0.1	3.11 %	5.49 %	91.40 %
ARF in CA	0.1	0.00 %	6.71 %	93.29 %
Landfill ban in MA	0.1	3.11 %	5.49 %	91.40 %
Both ARF and landfill ban	0.1	0.00 %	6.71 %	93.29 %
No legislation	10.0	19.28 %	29.81 %	50.92 %
ARF in CA	10.0	19.28 %	29.81 %	50.92 %
Landfill ban in MA	10.0	19.28 %	29.81 %	50.92 %
Both ARF and landfill ban	10.0	19.28 %	29.81 %	50.92 %

Table 4.10: Statistical output for analysis of asset purchase decisions

```
Factor     Type Levels Values
TptRate   fixed      3 0 1 2
ARF       fixed      2 0 1
LF ban    fixed      2 0 1

Analysis of Variance for PurchCA, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS       F      P
TptRate     2   0.069056   0.069056   0.034528  446.43  0.000
ARF         1   0.000468   0.000468   0.000468    6.05  0.044
LF ban      1   0.000000   0.000000   0.000000    0.00  1.000
Error       7   0.000541   0.000541   0.000077
Total      11   0.070065

Analysis of Variance for PurchGA, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS       F      P
TptRate     2   0.130820   0.130820   0.065410 4637.17  0.000
ARF         1   0.000049   0.000049   0.000049    3.50  0.104
LF ban      1   0.000000   0.000000   0.000000    0.00  1.000
Error       7   0.000099   0.000099   0.000014
Total      11   0.130968

Analysis of Variance for PurchMA, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS       F      P
TptRate     2   0.389375   0.389375   0.194687 7314.60  0.000
ARF         1   0.000213   0.000213   0.000213    8.02  0.025
LF ban      1   0.000000   0.000000   0.000000    0.00  1.000
Error       7   0.000186   0.000186   0.000027
Total      11   0.389774
```

From a combination of the computational results (Table 4.9) and the statistical analyses (Table 4.10), the following conclusions can be made about the effects of key uncertainties in problem parameters on optimal asset purchase decisions.

- Both transportation rates and the ARF legislation are significant factors affecting asset purchase decisions, although the effect of transportation rates tends to dominate the effect of the ARF. Figure 4.3 provides further confirmation. The graph is drawn only for one response, namely “PurchGA.” Other responses show similar patterns, with the only difference being that the sign of the transportation rate effect is reversed for Massachusetts.

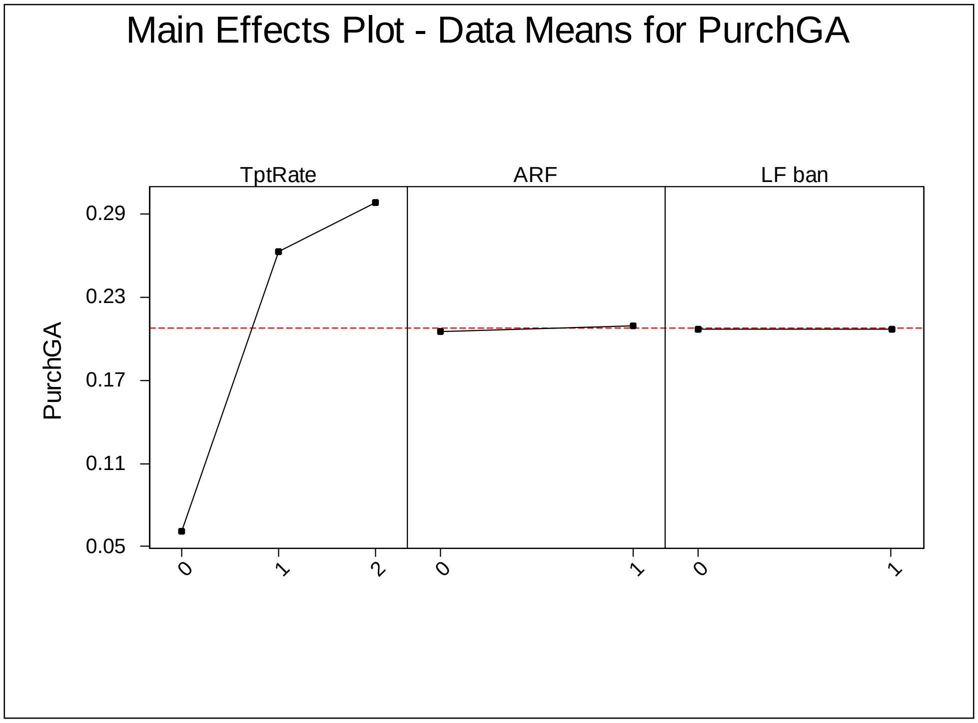

Figure 4.3: Main effects plot for response “PurchGA”

- There are no significant interaction effects between any of the three factors, although there is a small interaction effect between transportation rates and the ARF legislation at the lowest level of transportation rates (Figure 4.4).

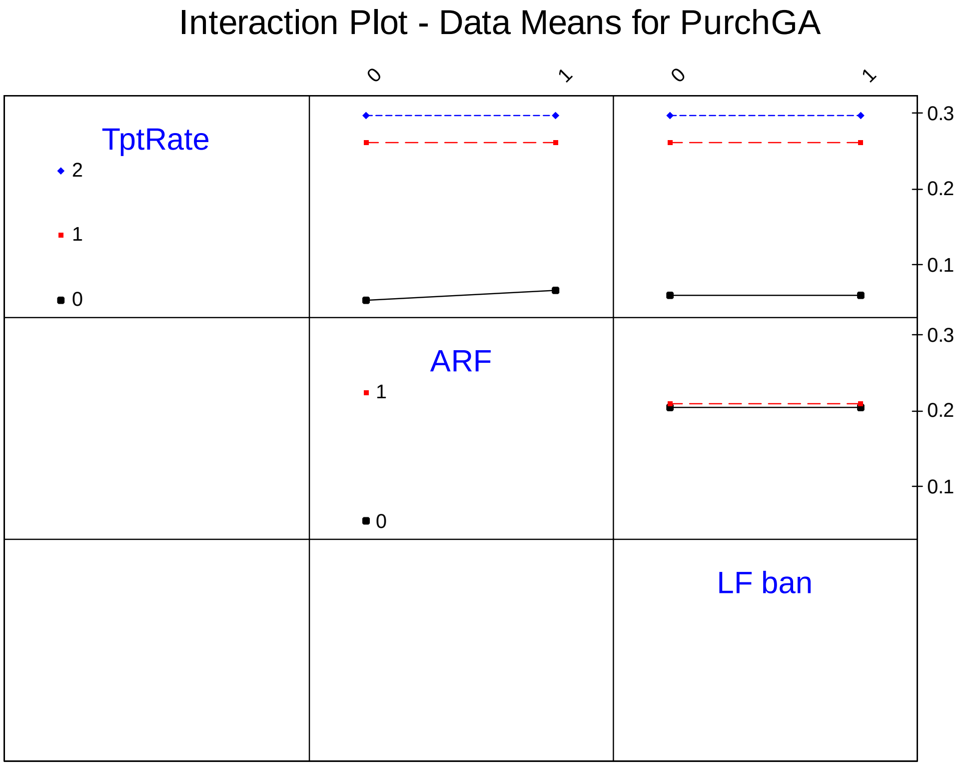

Figure 4.4: Interaction plot for response "PurchGA"

Similar analyses can be carried out for asset disposal decisions. Table 4.11 presents the number of assets disposed at each of the three warehouse locations, as a percentage of total asset disposals, in the optimal solution of each of the twelve scenarios.

Once again, the intuitive hypotheses presented in Table 4.8 seem to have been confirmed. Statistical analyses of the results are presented in Table 4.12. In the statistical analyses, "DispCA," "DispGA," and "DispMA" are respectively the fractions of total assets disposed in California, Georgia and Massachusetts.

Table 4.11: Percentage of total asset disposals, by warehouse location, in optimal solutions under various transportation rates and legislative scenarios

Legislative scenario	**Transportation rate multiplier**	**% disposed in CA**	**% disposed in GA**	**% disposed in MA**
No legislation	1.0	19.43 %	30.21 %	50.36 %
ARF in CA	1.0	19.47 %	30.17 %	50.36 %
Landfill ban in MA	1.0	19.43 %	41.83 %	38.75 %
Both ARF and landfill ban	1.0	19.47 %	41.78 %	38.75 %
No legislation	0.1	19.43 %	30.21 %	50.36 %
ARF in CA	0.1	19.94 %	29.55 %	50.50 %
Landfill ban in MA	0.1	19.43 %	80.08 %	0.50 %
Both ARF and landfill ban	0.1	20.83 %	79.17 %	0.00 %
No legislation	10.0	19.43 %	30.21 %	50.36 %
ARF in CA	10.0	19.43 %	30.21 %	50.36 %
Landfill ban in MA	10.0	19.43 %	30.21 %	50.36 %
Both ARF and landfill ban	10.0	19.43 %	30.21 %	50.36 %

Table 4.12: Statistical output for analysis of asset disposal decisions

```
Factor     Type Levels Values
TptRate   fixed      3 1 2 3
ARF       fixed      2 0 1
LF ban    fixed      2 0 1

Analysis of Variance for DispCA, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS       F      P
TptRate     2  0.0000585  0.0000585  0.0000292    2.25  0.176
ARF         1  0.0000337  0.0000337  0.0000337    2.59  0.151
LF ban      1  0.0000065  0.0000065  0.0000065    0.50  0.502
Error       7  0.0000910  0.0000910  0.0000130
Total      11  0.0001897

Analysis of Variance for DispGA, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS       F      P
TptRate     2    0.13166    0.13166    0.06583    3.40  0.093
ARF         1    0.00002    0.00002    0.00002    0.00  0.973
LF ban      1    0.12548    0.12548    0.12548    6.48  0.038
Error       7    0.13547    0.13547    0.01935
Total      11    0.39263

Analysis of Variance for DispMA, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS       F      P
TptRate     2    0.13717    0.13717    0.06859    3.48  0.089
ARF         1    0.00000    0.00000    0.00000    0.00  0.994
LF ban      1    0.12729    0.12729    0.12729    6.45  0.039
Error       7    0.13805    0.13805    0.01972
Total      11    0.40251
```

From the computational results (Table 4.11) and statistical analysis (Table 4.12), the following conclusions can be made about the effects of key uncertainties on optimal asset disposal decisions.

- Both transportation rates and the landfill ban legislation are significant factors affecting asset disposal decisions in Georgia and Massachusetts, but the ARF legislation is not. Figure 4.5 confirms this result. The response for “DispMA” is very similar to that for “DispGA,” except that it has opposite signs for the “TptRate” and “LF ban” factor coefficients.

- The landfill ban does not create any significant impact on the fraction of asset disposals in California, where the ARF legislation remains more significant. Also, the fraction of asset disposals in California is less sensitive to changes in transportation rates as compared to that in Georgia or Massachusetts. This is clear from Figure 4.6.

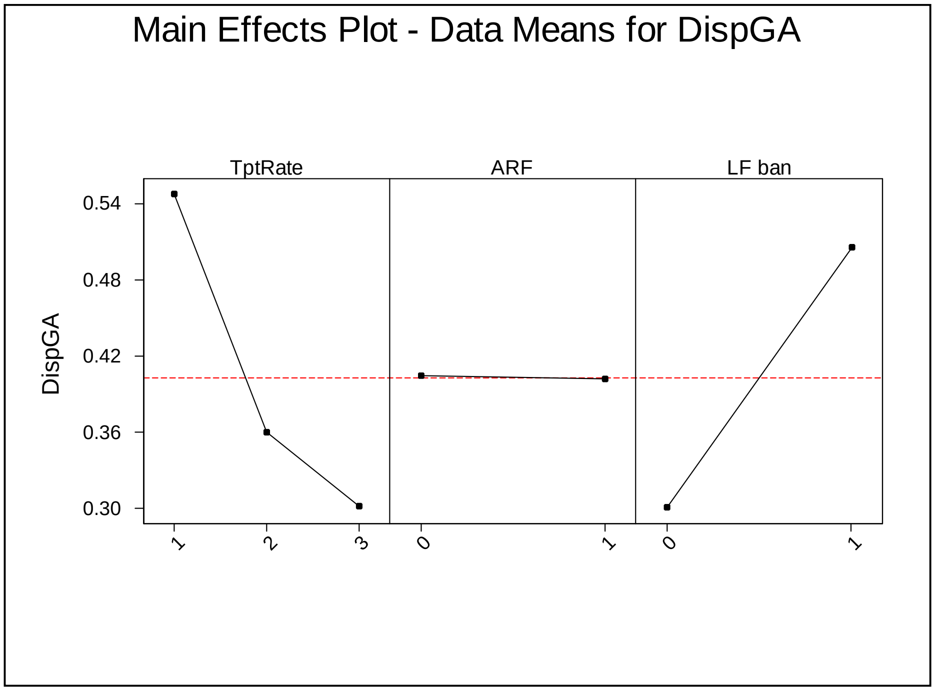

Figure 4.5: Main effects plot for response “DispGA”

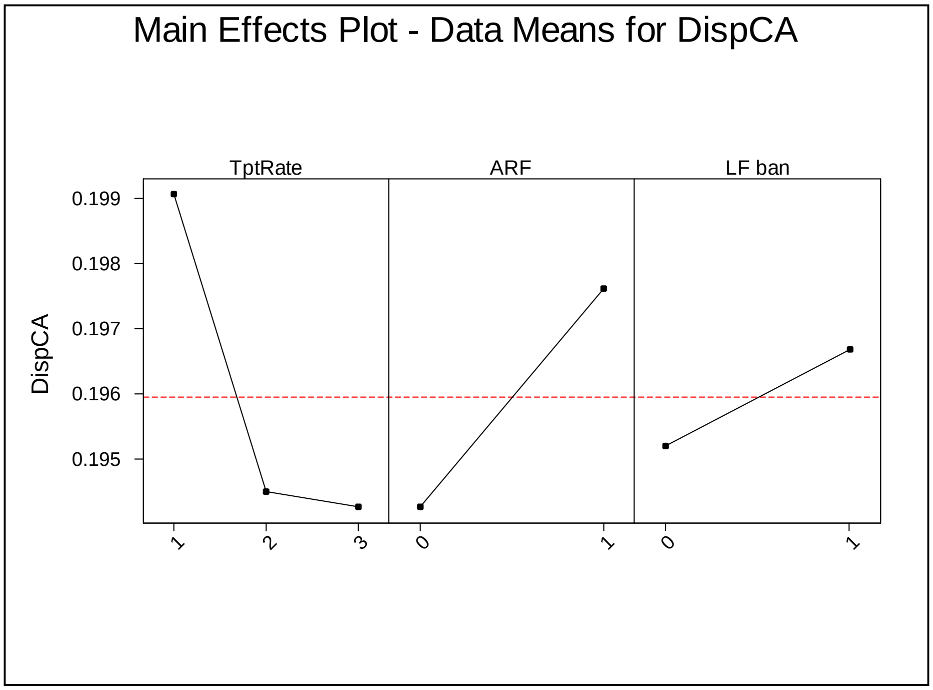

Figure 4.6: Main effects plot for response “DispCA”

- There exist very strong interaction effects between transportation rates and the landfill ban legislation for asset disposals in Georgia and Massachusetts, as shown in Figure 4.7. For California, the interaction effect between transportation rates and the ARF legislation remains strong for low transportation rates (Figure 4.8). This difference most likely arises because the distance between the warehouse locations in Georgia and Massachusetts is much smaller than the distance between either of those locations and California.

- There also appears to be a weak interaction effect between the ARF and the landfill ban legislations in the case of asset disposals in California. Once again, this is evident from Figure 4.8.

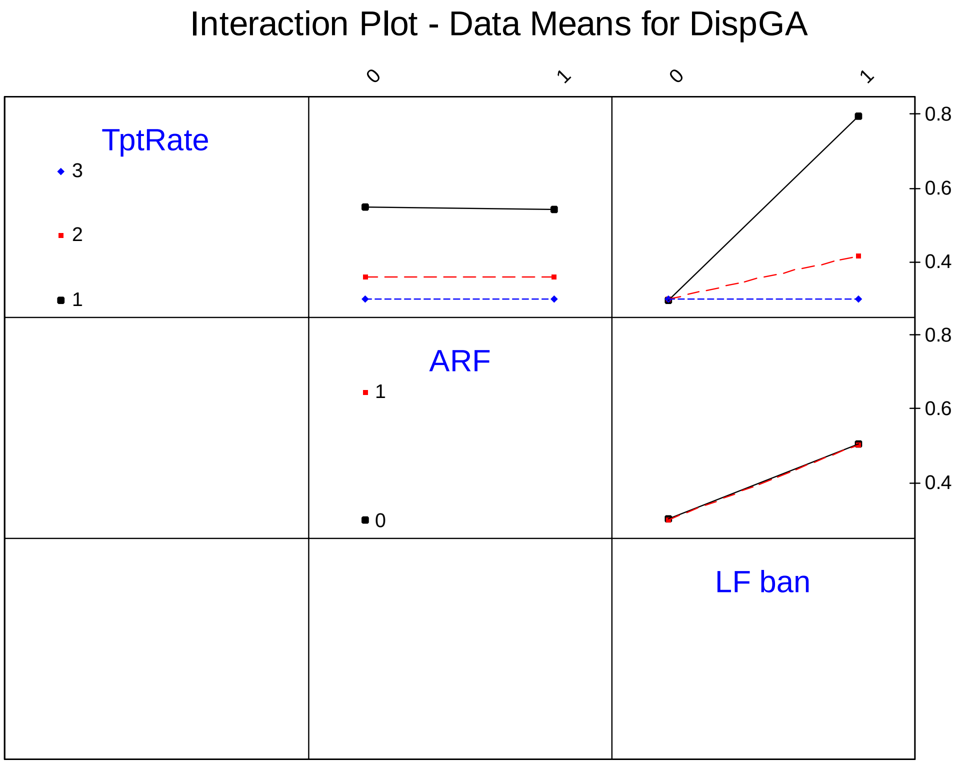

Figure 4.7: Interaction effects plot for response “DispGA”

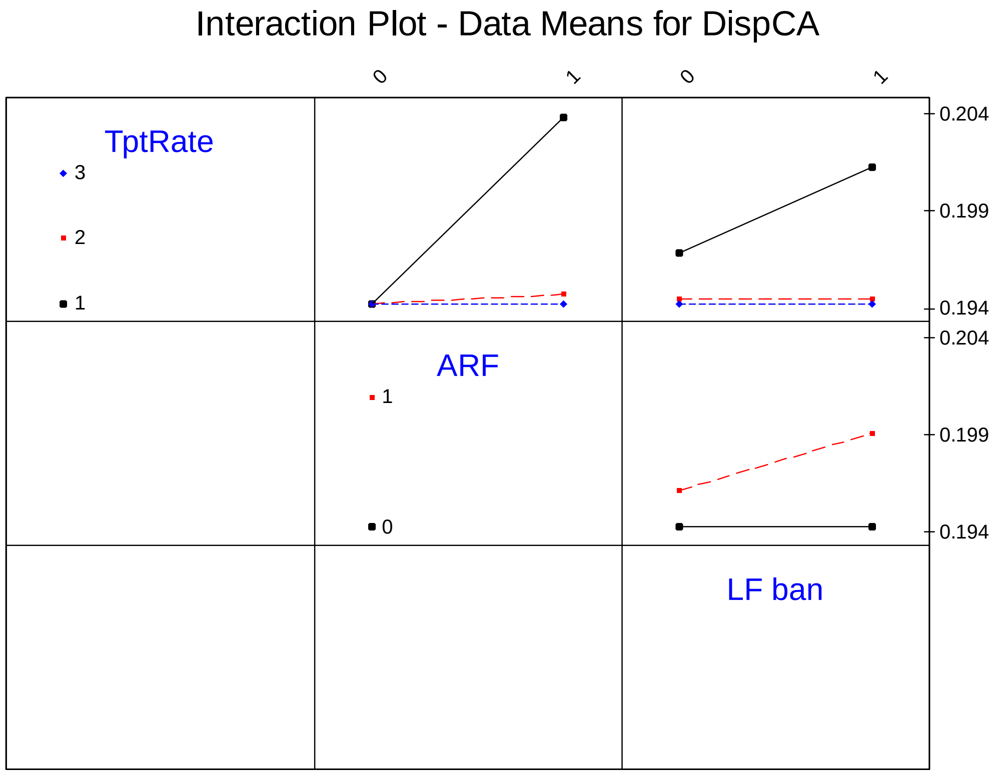

Figure 4.8: Interaction effects plot for response “DispCA”

A few concluding remarks about the effects of uncertainties on product flows are as follows. First, the strong effect of transportation costs on product flows would be revealed even if the range of considered variations in transportation cost were smaller than the one considered here (a factor of 100 between the lowest and highest levels), because the identification of significant factors in statistical analyses is scale invariant.

Second, it is also important to hypothesize on the expected effects of other uncertainties, such as uncertainty in asset purchase costs (due to factors other than environmental legislation), on product flows. Clearly, asset purchase costs are not expected to have any effect on the geographic distribution of reverse product flows and asset disposal decisions. However, the effects on forward product flows and asset purchase decision could be quite significant. Note that the geographic distribution of forward product flows and asset purchases is driven by **differences** in asset purchase costs across locations. Therefore, as long as asset purchase costs are the same across all warehouse locations, the geographic distribution of flows will not be affected. However, if one adds on local tariffs (such as sales tax) to these costs, then the differences between asset purchase costs across locations increase as asset purchase costs increase from a base-level value. This would significantly affect the geographic distribution of forward product flows and asset purchase decisions. In addition, strong interaction effects are likely to be observed between asset purchase costs and transportation costs (as opposed to the weak interaction effect observed between an ARF and transportation costs). The simultaneous examination of these two uncertainties would be an interesting topic for future research.

4.3.3 Lease lengths: Observed effects of uncertainty and interaction effects

It is also hypothesized in Section 4.3.1 that higher transportation rates should lead to longer leases and that it is difficult to comment intuitively on the effects of uncertainty in legislation on lease lengths. Using the same case study data as in the previous sections, optimal asset leasing decisions are analyzed in this section. However, a slightly different methodology is required to subject lease lengths to the same kind of analyses as those performed for optimal asset purchases and asset disposals.

Analyses of optimal lease lengths in the twelve scenarios reveal that for 15 out of 25 asset types, there is no change in optimal lease lengths in any of the twelve scenarios.

Therefore, statistical analysis needs to be performed for the remaining 10 asset types. A response variable must be selected before statistical analysis is possible, and one choice of response variable that immediately comes to mind is the average optimal lease length for each kind of asset, which needs to be calculated. However, this average value may not capture the changing nature of leasing decisions.

An explanation of this shortcoming is based on some of the problem data described in Chapter 3 (Section 3.4.1). The total time horizon is 14 periods, minimum and maximum asset lives are six and eight periods respectively, and the minimum and maximum lease periods are four and eight periods respectively. Therefore, either two or three leasing cycles are possible during the time horizon for every type of asset, and there exist multiple options for splitting up the 14-period time horizon into leasing cycles. For an asset with a maximum useful life of six periods, the options are 4-4-6, 4-5-5, 4-6-4, 5-4-5, 5-5-4 and 6-4-4. For an asset with a maximum useful life of eight periods, there are three additional options, *i.e.*, 6-8, 7-7 and 8-6. Now, if all assets of a particular type were leased with a 5-5-4 option in one scenario and with a 6-4-4 option in another scenario, the average lease length would be 14/3 = 4.67 periods for both options. However, these are clearly not the same leasing decisions. Therefore, the average lease period is not a good indicator of the changes in leasing decisions as a result of uncertainty in problem parameters.

A closer analysis reveals that out of the 10 assets whose lease lengths are to be analyzed, four have a maximum life of six periods, and they are only leased with a 5-5-4 or 6-4-4 option in all scenarios. The other six assets have a maximum life of eight periods and are leased only with a 4-4-6 or 8-6 option in all scenarios. An 8-6 option clearly implies “longer” leases than a 4-4-6 option, although the same cannot be said with certainty of a comparison between 6-4-4 and 5-5-4. However, it is plausible to claim 6-4-4 as a “longer” lease than 5-5-4, especially if transportation rates are very high. This is because a 6-4-4 lease option (longer first lease) offers the opportunity to defray the transportation costs to a later period, and as a result of discounting, this leads to a reduction in the total transportation costs over the planning horizon. It is possible that this option may offer lower total net revenue as well, but following the reasoning in Section 4.2, this decrease in revenues may be compensated by a simultaneous decrease in transportation costs.

Based on these results, it is possible to obtain a more accurate indicator of changes in leasing periods for the 10 assets in question. The response variable is chosen as the fraction of shorter leases in the optimal solution (called “ShLease” in the statistical analysis), which is defined for each asset type as the ratio of the number of assets leased via shorter leases to the total number of assets leased over the planning horizon. For example, the total demand for asset type PC-H1 over the planning horizon is 17525 units. Since demand must be met exactly (constraints (3.2)), this is also equal to the total number of assets of type PC-H1 leased over the planning horizon. In the optimal solution for Scenario 1, 250 out of 17525 units are leased with a 5-5-4 option, and thus “ShLease” is calculated as $(250 \div 17525) = 0.014$.

The 10 asset types provide multiple replicates for given levels of transportation rate, ARF legislation and the landfill ban legislation. The asset type is used as a blocking factor in the experimental design, and this prevents the effects of differences among asset types from being confounded with the actual factor effects that need to be studied.

Table 4.13: Statistical output for analysis of lease lengths

```
Factor     Type Levels Values
Asset     fixed     10 PC-H1   PC-L1   PC-L2   PC-LW1  PCS-LE1 P-HVBW1 P-LVBW1
                       P-MVBW1 S-HC1   S-LC1
TptRate   fixed      3 0 1 2
ARF       fixed      2 0 1
LF ban    fixed      2 0 1

Analysis of Variance for ShLease, using Adjusted SS for Tests

Source               DF     Seq SS     Adj SS     Adj MS       F      P
Asset                 9    16.2622    16.2622     1.8069   43.84  0.000
TptRate               2     4.8511     4.8511     2.4255   58.85  0.000
ARF                   1     0.0000     0.0000     0.0000    0.00  1.000
LF ban                1     0.0000     0.0000     0.0000    0.00  0.974
TptRate*ARF           2     0.0000     0.0000     0.0000    0.00  1.000
TptRate*LF ban        2     0.0001     0.0001     0.0000    0.00  0.999
ARF*LF ban            1     0.0000     0.0000     0.0000    0.00  1.000
TptRate*ARF*LF ban    2     0.0000     0.0000     0.0000    0.00  1.000
Error                99     4.0803     4.0803     0.0412
Total               119    25.1937
```

Based on the computational results for the case study and their statistical analysis (Table 4.13), the following conclusions can be made about the effects of key uncertainties on optimal leasing decisions.

- Transportation rates significantly affect lease lengths. Environmental legislation is not a significant factor affecting optimal lease length decisions. Figure 4.9 supports this conclusion. In addition, lease lengths also depend strongly on the particular asset type being leased, because asset type is used as a blocking factor in the statistical analysis, and it is found to be very significant.

- There are no interaction effects between transportation rates and either kind of legislation (ARF or landfill ban). Figure 4.10 supports this conclusion.

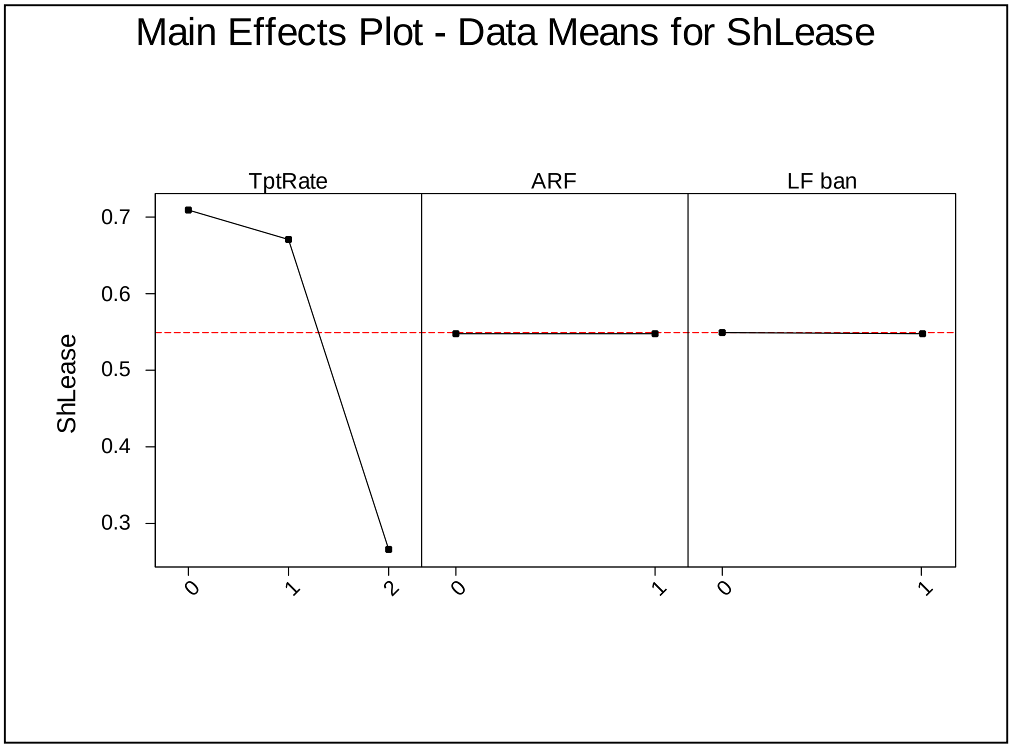

Figure 4.9: Main effects plot for response "ShLease"

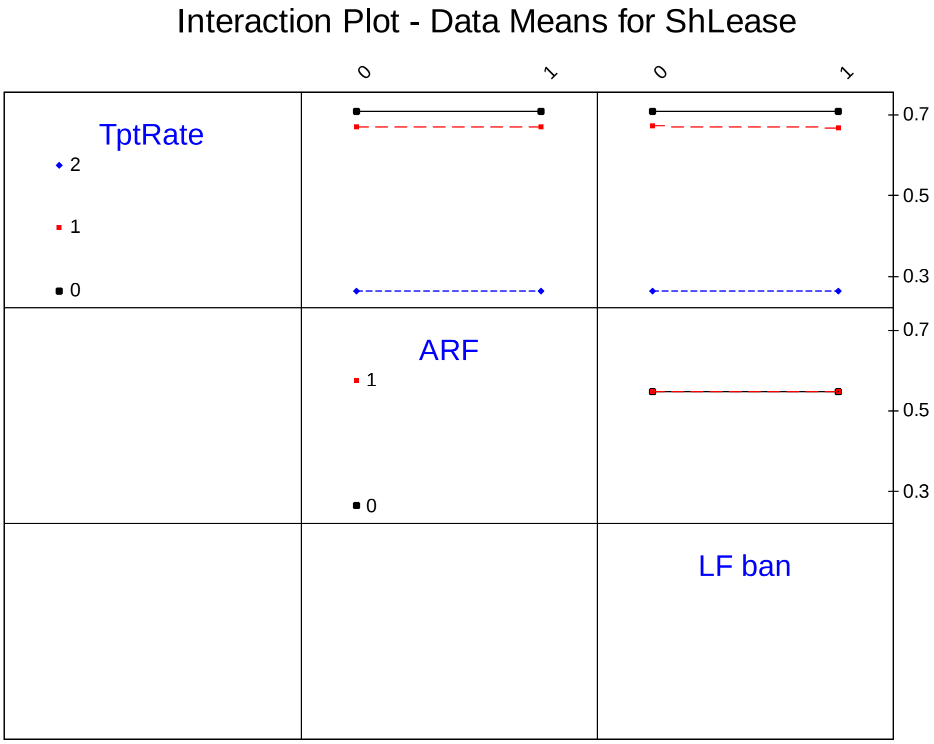

Figure 4.10: Interaction effects plot for response "ShLease"

It is also interesting to try and intuitively answer questions about differences in leasing decisions for various types of assets. For example, why does uncertainty in transportation costs affect lease lengths for only 10 out of 25 asset types? What are the characteristics of leases among the 15 asset types for which optimal lease lengths are not affected in any scenario? What possible reasons could be attributed to those lease characteristics?

Seven out of the 15 asset types for which optimal leases do not change across scenarios have an average purchase price of $7,500 or more, which is substantially higher than the average purchase price for all other assets. Two out of seven can be rebuilt. The assets with rebuild options are purchased at the beginning of the first leasing cycle but only rebuilt thereafter. This is not surprising in light of the case study result in Chapter 3 that rebuilding is a profitable activity. For all these seven assets, shorter initial leases (4-4-6) are chosen. This indicates that shorter leasing cycles are more profitable than longer ones, and in the case of these seven asset types, profitable enough to overcome even very high levels of transportation cost. For the 10 assets whose leasing cycles do change with transportation costs, a graduation from “short” leases to “longer” ones is seen as transportation costs increase, which also indicates the profitability of shorter leases. The transition to “longer” leases is, as discussed earlier, due to the tradeoff between lease revenues and transportation costs.

However, the remaining eight asset types for which optimal leases do not change across scenarios have optimal leases in which the initial lease cycle is longer (6-4-4). This is quite a puzzling fact, especially in light of the discussion in the previous paragraph, which points to the profitability of shorter leases. These eight assets have average purchase prices ranging from approximately $200 to $3,500, with all of them having maximum useful lives of 6 periods. Some of the 10 asset types for which lease lengths change with transportation costs also share these characteristics. Why then are 4-4-6 lease options not seen for these eight asset types even in scenarios with very low transportation costs?

Of course, this counterintuitive result raises concerns about the correctness, even though the model has been validated in Chapter 3. However, additional runs of the model with a forced 4-4-6 lease option for these asset types leads to a decrease in the optimal net discounted profit. This outcome reaffirms faith in the correctness of the model, but points towards the existence of additional factors affecting lease lengths. Some possible factors include the particular location of demand for these assets and the differences in profit margins between small, medium and large orders. Further investigation of this issue and the determination of these unknown factors affecting lease lengths is an interesting question for future research.

In summary, this section discusses in detail the various kinds of cost tradeoffs and parameter uncertainty interactions in the system, as observed from the case study. Many interesting insights have been obtained, and the discussion poses interesting questions that would extend the work done in this dissertation. The next section summarizes and concludes this chapter.

4.4 Conclusions

This chapter discusses the uncertainties in problem parameters that are important from the point of view of this research, which addresses a problem at the intersection of the fields of equipment replacement and reverse logistics. Several sources of uncertainty are considered, and the key uncertainties are identified.

Next, a robust optimization problem formulation is discussed and results from an extended case study with twelve scenarios are examined. Based on the observation that the uncertainty in transportation costs has a stronger effect on profit than the uncertainty in asset purchase and asset disposal costs due to environmental legislation, it is shown how intuitive logic and simple empirical methods can be used for making near-robust leasing decisions. Thus, given the particular problem data, a standard robust optimization approach is unlikely to provide additional useful insight into the problem.

Subsequently, the optimal solutions from the twelve scenarios of the extended case study are examined in detail and the tradeoffs and interactions between various kinds of costs in the system are revealed. It is found that for optimal product flow decisions, there exist significant interactions between uncertainty in transportation costs and the uncertainty in asset purchase and asset disposal costs caused by environmental legislation. On the other hand, uncertainty in transportation costs strongly affects optimal lease length decisions (higher transportation costs imply longer lease lengths); legislation has a miniscule effect on lease lengths, if any.

Although the results presented in this chapter are based on one particular case study, it can be argued that it is possible to extend these results and insights to a broader set of problems similar to the one addressed in this research. First, the case study data have been generated after guidance from industry practitioners, and are hence representative of typical situations that electronic equipment leasing companies might face. The wide range of transportation costs and realistic legislative effects considered in the uncertainty scenarios for the case study are also important and helpful in making the results generally applicable to many typical problems. Finally, the use of intuitive reasoning, along with computational results and statistical analyses, to explain the expected effects of uncertainty and the interactions between various sources of uncertainty also helps in enhancing the generality of insights obtained during this investigation. Of course, the peril of making sweeping general conclusions from case studies has been recognized and notes of caution have been added where necessary.

Given the results obtained in this chapter and the previous one (Chapter 3), it can be concluded that incorporating logistics issues and environmental considerations into asset management decisions is an important and interesting problem that has not yet been addressed in existing literature. Ignoring the strong interaction effects between these decisions and treating asset management and logistics as mutually exclusive problems can lead to decreases in profitability for an equipment leasing company. The situation can be further exacerbated when product lifecycles are short (and as a result lease lengths too), refurbishment is an end-of-lease or end-of-life option for assets, and environmental legislation affects some costs in the system.

The large impact of refurbishment of expensive assets on net profit has already been demonstrated in Chapter 3. The impact of ignoring transportation costs and environmental legislation on net profit is now demonstrated via an illustrative example from the case study results. Consider a situation where the objective function in the model consists only of lease revenues, asset purchase costs and asset disposal costs, which are typical cost components considered in asset replacement problems. With base case transportation rates and no legislation, the actual profit thus realized is about $5.5 million lower than that which could have been realized if optimal asset replacement (leasing) and logistics decisions had been made simultaneously. With the existence of environmental legislation in both California and Massachusetts, this decrease in profit becomes close to $11 million. Clearly, this profit reduction due to the failure to consider leasing, logistics and end-of-life decisions simultaneously increases further as transportation rates increase.

Therefore, the results of this research provide valuable insights to leasing company managers. However, the results can also inform environmental policy formulation. Insights for environmental policy makers are discussed at length in the next chapter and broader questions that this research cannot answer, but in whose direction the results point, are also raised.

CHAPTER 5

IMPLICATIONS FOR POLICY FORMULATION ON ELECTRONIC WASTE

The previous two chapters of the dissertation focus mainly on insights for business managers, but this research also has implications and potential insights for environmental policy formulation. Most of these are derived by observing the nature of product flows in the system and the changes in the optimal forward and reverse flows under various legislative scenarios for the case study. First, this chapter discusses the implications of the results of this research for state-level electronic waste (referred to as "E-waste" hereafter) legislation in the U.S. (Section 5.1). This discussion is then expanded to the broader perspective of national and international-level E-waste issues in Section 5.2. This section also looks at some interactions between different realms of public policy. The chapter concludes with a brief summary in Section 5.3.

5.1 Implications for state-level E-waste legislation in the U.S.

The discussion in Section 2.4 shows that a wide variety of legislation on electronic waste is proposed or is currently in force in the United States. Comprehensive federal legislation has not been the driver, resulting in a patchwork of alternative state-level legislative activities. The application of the research model to shed light on state-level E-waste issues is the subject of this section. A few implications follow directly from the results presented in Chapters 3 and 4. However, on the basis of these results, it is also possible to hypothesize about other, more general implications.

5.1.1 Direct implications: The impacts of legislative measures

Expectedly, state-level legislation on electronic waste focuses on meeting various policy objectives of the state (a more detailed discussion on this appears in Section 5.1.2). The intentions of state-level legislators may be good, and the proposed or existing policies may even meet state policy objectives, but it is not immediately clear whether these policies would collectively be effective and have a significantly beneficial effect overall.

As an example, consider a landfill ban on Cathode Ray Tubes (CRTs), such as the one enforced in Massachusetts [64]. The direct objective of this policy is to keep CRTs out of landfills in Massachusetts, and hence to reduce the pace at which the state's remaining landfills reach their capacity, to reduce potential public health risks, and to promote the reuse and recycling of lead and other precious metals contained in CRTs. If it is assumed that the policy is enforced perfectly, then all its objectives have been achieved, and the state of Massachusetts benefits from it.

However, due to the Interstate Commerce Act of 1887 [100], transportation of waste across state boundaries cannot be prohibited directly, and as a result, economic actors (mainly businesses) seeking to maximize their profits can circumvent state laws and manage their end-of-life product flows in a manner that may overall be environmentally "unfriendly." This hypothesis is supported by the changes in product flows that the research results have shown for alternative legislative scenarios. For example, Section

3.4.4 reveals that due to a significant increase in asset disposal costs as a result of the landfill ban on CRTs in Massachusetts, the leasing company finds it more profitable to transport CRTs to Georgia for disposal. If it were cheaper to dispose CRTs by way of putting them into a hazardous waste landfill than by way of recycling their materials (and this is generally the case), then none of these CRTs would be recycled in Georgia. In addition, as discussed in Section 4.3.2, the problem would be further exacerbated if transportation rates were very low. So, has the Massachusetts legislation solved the problem, or has the problem simply been transferred from Massachusetts to another state?

In addition, the costs of running a recycling program (either state-funded or in private hands) are not insignificant and its viability heavily depends on being able to maintain a large and steady volume of waste to achieve economies of scale. Therefore, this transfer of electronic waste across state boundaries also contributes to the reduced viability of recycling programs, which hinders Massachusetts from achieving the policy objective of promoting the reuse and recycling of electronic waste.

Impacts of the imposition of an Advance Recycling Fee (ARF) in a particular state (*e.g.*, California) can be similarly analyzed, but are somewhat harder to predict. An ARF increases asset purchase costs and hence reduces asset purchases in the state. This could potentially lead to a loss of sales tax revenues for the state. In addition, the ARF collected is intended to fund electronics recycling infrastructure, and if asset purchases in the state decrease, so would the collected ARF amount, which leads to detrimental effects on the establishment of an electronics recycling infrastructure. Once again, low transportation rates can exacerbate the problem. However, since an ARF also affects asset disposal costs by making disposal of some kinds of assets cost neutral, it is possible that this measure may encourage recycling of assets that were not profitable to recycle earlier. Hence, it may also counterbalance the negative effect of reduced asset purchases on electronics recycling infrastructure.

5.1.2 More general implications

While Section 5.1.1 discusses policy implications that follow directly from research results, this section presents hypotheses on more general policy implications that can be formulated based on insights obtained from this research. The focus of the discussion remains state-level environmental legislation on electronic waste.

To begin the discussion, it is instructive to list some typical objectives that guide the formulation of E-waste legislation and policies. The list is based on policy documents from the states of Iowa [52], Massachusetts [64] and Washington [75], and can be claimed as sufficiently representative to be generalizable to other states. The primary objectives considered during the formulation of policies appear to be as follows.

- To evaluate the feasibility and impacts of legislative measures such as landfill bans, ARFs and Extended Producer Responsibility (EPR).
- To encourage the resale, reuse and recycling of used electronic equipment, while discouraging disposal at the same time.
- To develop and maintain a strong electronics recycling infrastructure. This includes the development of end-of-life markets for electronic equipment and the integration of business incentives into formulated policies.
- To preserve and create local jobs as a result of electronics recycling.
- To establish education programs that enhance understanding and awareness of electronics waste management issues.

It must be noted that these objectives are clearly interrelated. Even though this research cannot possibly examine all the complex interactions between these objectives, it is possible to combine intuition and the research insights to hypothesize about the expected effectiveness of formulated policies with regards to the aforementioned objectives.

Section 5.1.1 already addresses the first point, *i.e.*, the evaluation of expected impacts of E-waste legislation measures such as landfill bans and ARFs. The remainder of this section presents some hypotheses that can be formulated about the additional policy objectives, on the basis of results from this research.

Encouraging resale/reuse and recycling, and the establishment of a strong electronics recycling infrastructure are inextricably linked issues. If there do not exist markets for the resale/reuse of electronic equipment, or if there does not exist infrastructure with sufficient capacity to handle the volume of electronic waste generated, it would not be possible to encourage reuse and recycling.

The value of assets with short life cycles, such as electronic equipment, depreciates very quickly (modeled by an exponential decay curve in this research). Therefore, given the low residual value of used assets, a market for resale and reuse would need to have fairly low transaction costs that do not negate all of the (small) profits that can be made by the resale of an asset. In general, the buyers of used electronic equipment are likely to be individual consumers, schools, charities and small businesses. The sellers are likely to be large businesses, which buy or lease high-end equipment and then upgrade it after three or four years. However, the relative transaction costs for the sellers are likely to be quite high, due to the small size of each transaction with individuals or small buyers.

Similarly, the successful establishment of infrastructure for recycling depends on being able to achieve economies of scale. This requires the collection of a large and steady volume of used electronic equipment. The primary targets for collection have probably been correctly identified by many states as individual consumers and small businesses, who are a lot more likely to store used electronic equipment or dispose of it by other means. States with small populations, or with low use of electronic equipment per capita, may not be able to support a profitable state-wide electronics recycling infrastructure despite steady collection volumes and high recovery rates. They must therefore look to other alternatives, such as forming a coalition with neighboring states for establishing a common infrastructure. However, success is not guaranteed for large states either, because the existence of individual recycling infrastructure in many states creates competition for obtaining used electronic equipment. In addition, the existing legislation in a state may drive E-waste flows out of the state, as discussed in Section 5.1.1. These are possibly the most complex issues to address at the time of state-level E-waste policy formulation. It must be strongly emphasized here that it is impossible for a state to formulate locally effective policy without taking into consideration proposed or existing policy alternatives in other states.

Existence or establishment of a strong electronics recycling infrastructure can quite possibly lead to job creation in the state. According to the Massachusetts policy document on the development of electronics recycling infrastructure [64], repair and resale of used electronic equipment creates the most jobs per unit weight of assets recycled, followed by recycling and disposal (in that order). This is clearly not surprising, given that repair and resale include activities like (non-destructive) disassembly, product testing and software installation. However, repair and resale activities require skilled personnel, and thus labor costs can become quite high. In addition, large companies, such as the leasing company considered in the case studies in this research, incur significant overhead if they carry out repair and resale activities. This is because of the scale of their operations, which amounts to the addition of a completely new division or department in their workforce. In light of this fact, and the fact that according to the model developed in this research, the leasing company would always dispose of assets via the cheapest possible option, formulating policies that lean strongly towards encouraging repair and resale may actually prove ineffective in job creation. It is of course possible to provide subsidies such as tax breaks so as to reduce the costs of resale and repair for leasing companies. This is an interesting topic for further research, but once again, since policies implemented by other states would result in different disposal costs from those in that particular state, it is quite apparent that this issue also requires consideration of policies implemented by other states.

Education programs are clearly important, particularly to encourage households and small businesses to recycle their electronic waste instead of storing or disposing it. In addition, they have fewer options to manage electronic products at end-of-life than do large businesses. Therefore, education programs also make them aware of their options, although education programs regarding the applicability of proposed and existing legislation are important for large businesses as well. Another impact of education programs is to raise awareness of negative environmental impacts of discarded electronic products, which may bring into play market forces regarding “green” market images of electronics manufacturing and leasing firms. Firms that dispose assets in environmentally unfriendly ways could see their market shares reduced. In the mathematical model presented in Chapter 3, increasing the cost of landfilling assets, or introducing a penalty term (for landfilling assets) in the objective function is a possible method of capturing this phenomenon, at least partially. In any case, investigating the effects of education programs and market images of companies are not the primary objectives of this research.

5.2 Extensions to national and international issues

Many issues discussed in Section 5.1 also apply to the broader perspective of national and international policies on electronic waste. Some of these issues are analogous to those experienced at the state level, but the complexity of the links between various issues increases dramatically. Clearly, since this research does not focus on the formulation of national and international policy, it would be able to provide insights on only a few of these complex issues. However, failing to mention the other issues would leave this discussion incomplete. Therefore, the other issues are discussed briefly, but with an implied understanding that further research is required to make additional substantive statements about them.

Section 5.2.1 illustrates how decentralized (state-level) policy formulation on E-waste can create inefficiencies and impose negative externalities on other realms of policy. Section 5.2.2 generalizes this discussion by discussing “gaming” situations that arise as a result of decentralized policy. Section 5.2.3 discusses other closely related issues that are important, but which this research is unable to address definitively.

5.2.1 Creation of inefficiencies and policy tradeoffs

The discussion in this section starts with a specific demonstration of the creation of logistics inefficiencies due to different E-waste legislation in different geographic areas. It then moves up to a more general level and discusses policy tradeoffs in general.

As shown in Section 4.3.2, the strong interactions between changes in transportation costs and changes in asset purchase and asset disposal costs due to environmental legislation affect product flows greatly in the case study. In a case where transportation costs are low and environmental legislation is enacted in both Massachusetts and California (Scenario 11, Table 4.1), large flows of assets from Massachusetts to Georgia and California (for disposal) are observed. Clearly, this transportation would have been unnecessary had asset disposal costs been the same in all three locations, as Table 4.11 shows no change in relative percentage of asset disposals in the three locations under "No legislation" scenarios, even with a huge variation in transportation costs. Thus, different environmental legislation in different geographic areas is observed to create an artificial demand for transportation. For the case study, Table 5.1 shows the potential increase in total transportation costs as a result of legislation.

Since the costs in the system are assumed to depend only on distance, a relative increase in transportation costs implies an identical relative increase in the total item-miles. The results from various scenarios in Table 5.1 show that if transportation rates are low, differences in environmental legislation at the three warehouse locations could result in a 25% increase in total item-miles. This is by no means a trivial increase. Scaled up and added over all similar equipment leasing businesses, the number of additional item-miles created by legislation could turn out to be very large. Together with the discussion in Section 5.1, this implies that having different E-waste legislation across states in the U.S. would not only have failed to achieve the desired objective of environmentally friendly disposal of E-waste, but would additionally create logistics efficiencies, which imply more pollution and more congestion!

Table 5.1: Total transportation costs ($ million) under various scenarios of transportation rates and environmental legislation for the case study

	No legislation	**ARF in CA**	**Landfill ban in MA**	**Both ARF and landfill ban**	**Maximum % increase due to legislation**
Base case transportation rates	8.95	9.04	9.15	9.24	**3.17%**
Transportation rates 0.1 times base case	1.61	1.74	1.91	2.03	**25.48%**
Transportation rates 10 times base case	77.30	77.30	77.30	77.30	**0.00 %**

This discussion leads to a broader question about formulation of public policy in general. Just as interactions between various costs in the system are observed, there are also interactions between the various realms of public policy. For example, transportation policies have pollution reduction and congestion reduction as some of their primary objectives. However, in this case we see that formulation of (potentially inappropriate) environmental policy has negated gains made in the transportation realm. Given the huge geographic size of the U.S., the increase in item-miles resulting from state-level environmental policies is potentially very large, and hence these negative externalities imposed on transportation policy could be quite significant. On a global scale, this particular effect could be mitigated due to several factors, such as higher transportation costs for international shipping, use of less polluting transportation modes (typically hazardous electronic waste would be shipped by sea) and most importantly, the Basel convention (discussed in Section 5.2.3). However, on a global scale, the number of policy issues involved is much higher, which leads to an exponential increase in the number of possible policy interactions, and therefore the potential for the inadvertent imposition of negative effects of one policy realm on another is ever larger.

5.2.2 "Gaming" as a result of decentralized policy formulation

While Section 5.2.1 specifically shows how transportation inefficiencies are created as a result of decentralized legislation, the creation of inefficiencies is not restricted to transportation alone. This section discusses how decentralized legislation can lead to "gaming" behavior by firms and policy makers, thus exacerbating inefficiency.

Section 5.1.1 clearly illustrates the gaming behavior of firms when different environmental legislation exists in different states. In order to try and maximize their profits, firms could circumvent state laws and engage in environmentally unfriendly practices. In fact, it is quite possible that many electronic product OEMs and leasing companies would actively lobby their respective state governments to try to block any moves towards centralized legislation on electronic waste. In addition, it is also possible to envisage electronics recycling companies engaging in this kind of behavior. For example, an ARF collected in California may be used to subsidize the setting up of electronics recycling infrastructure. However, in Massachusetts, individual consumers and businesses pay disposal fees to an electronics recycler at end-of-life for proper disposal of electronic equipment, and this fee is expected to provide the majority of funding for an electronics recycler to set up operations. In such a scenario, it is conceivable that the "recycler" could collect assets (and the accompanying fee) in Massachusetts, transport all these assets to California and use his ARF-subsidized operations to increase profits substantially. In an even worse case, these assets could be transported to Georgia for landfilling, and therefore, not recycled at all! The landfilling problem could be partially avoided because many large businesses demand proof that their assets have actually been recycled. However, the potential for gaming remains very high, and it is possible to think of other actors and other situations where such gaming takes place.

In fact, why should gaming behavior be restricted to individual actors? Is it not possible that state legislators could use the gaming behavior by individual actors to further their state policy objectives? For example, California legislators could turn a blind eye to malpractices by a recycler located in their state, because a large recycling operation in the state creates tax revenues and additional employment. Another situation where gaming might take place is one where states that currently have no legislation on electronic waste design their electronic waste policies. They could take into account the actions of other states and then design their own system so as to make it as efficient as possible, but at the same time imposing negative externalities on other states.

This discussion leads one to believe that there is a serious need to re-think the strategy of leaving the formulation of E-waste legislation up to the states. An alternative that imposes some uniformity is strongly needed.

A recent proposal aimed at increasing legislative uniformity in the United States is a bill introduced in the House and referred to the Ways and Means Committee. This is the Tax Incentives to Encourage Recycling Act of 2004 (TIER Act of 2004), and proposes to give tax credits to electronic equipment manufacturers who recycle their equipment [90]. For the model in Chapter 3, this can be viewed as a uniform reduction in the recycling costs across all warehouse locations. However, state-level legislative activities on E-waste will continue even if it is enacted, and it is still possible that there would exist significant differences in legislation between different states. Therefore, this tax break initiative may encourage more recycling, but is not likely to reduce the aforementioned inefficiencies significantly.

A few other alternatives could increase the uniformity of E-waste legislation in the U.S. One alternative is the formulation of regional E-waste legislation, such as one based on the U.S. EPA Regions 1 through 10. Some of these regions, such as Regions 1 and 2, are geographically too small to provide sufficient uniformity. However, even if states across regions form a coalition and reduce the number of effective regions, the larger problem would still not be solved. This is because most large U.S. corporations operate on a national and international basis, and the possibility of circumventing regional legislation remains intact. Another related alternative is the tabling of the E-waste issue in the National Governors Association (NGA) [73], an organization through which governors discuss and resolve issues of public policy related to the states. The NGA is a powerful lobbying organization in Washington and has the ability to influence major policy decisions. The E-waste issue has not been discussed in the NGA so far, but this would be a very good forum for states to discuss ideas and solutions for the growing E-waste problem.

Finally, federal legislation on E-waste could be imposed in the U.S. Perhaps a discussion of the E-waste issue in the NGA would ultimately lead to this solution, if the governors are unable to reach a consensus, or if they determine that state-level legislation without a strong federal guideline would leave open too many opportunities for system gaming. In this regard, the U.S. can draw upon the European example, whereby a stringent EU-wide E-waste Directive exists and member states are required to formulate national legislation that is at least as stringent, or more stringent than the general EU Directive (Section 2.4).

It must be noted that much shorter transportation distances and higher transportation costs in the EU make the situation more favorable for avoiding the aforementioned inefficiencies that region. In addition, almost all the developed EU member states have ratified the Basel Convention [12], so that hazardous waste cannot be transported across national boundaries.

Countries like Taiwan and Japan can also avoid inefficiencies by virtue of their uniform national legislation, small geographic size and high transportation costs. However, consumers of electronic goods (purchased before October 2003) pay high end-of-life disposal fees under the Japanese system (Section 2.4), which could encourage storage instead of recycling. In addition, Japan has not ratified the Basel Convention and Taiwan is not a party to this treaty, so there is a potential for some firms from these countries to export hazardous electronic waste to third-world countries. In fact, there are indications that this activity is actually taking place [11]. The export of hazardous waste is a very serious international issue, and is discussed in the next section.

5.2.3 Other important E-waste issues

All the state-level issues mentioned in Section 5.1.2 also apply to the formulation of national legislation. However, there are also additional considerations that transcend national boundaries. Some of these are as follows.

- To prevent the export of electronic waste to third-world countries.
- To determine and allocate responsibility for the environmentally friendly disposal of electronic waste at end-of-life.
- To phase out the use of toxic materials (*e.g.*, heavy metals) in the design and manufacture of electronic equipment.

Section 2.4 also mentions the export of electronic waste from the U.S. to third-world countries, where the method of handling in general is not only environmentally unfriendly, but also presents very serious health hazards to people involved in the activity. The Basel Convention (1989) [12], along with the Basel Ban Amendment (1995) [12] prohibits the transportation of hazardous waste across national borders. However, the U.S. has not ratified this treaty (the only developed country not to have done so), and it is estimated that approximately 50 to 80 percent of the E-waste received by U.S. recycling firms could potentially be exported to third-world countries [10]. This can be viewed as a generalization and extension of the impact of different legislative measures in different geographic regions. It is shown in Section 4.3.2 that low transportation costs combined with large differences in asset disposal costs across geographic locations dramatically alter end-of-life product flows, and the existence of these two conditions can be shown here.

Transportation costs are considered first. E-waste is transported to third-world countries by sea, in shipping containers. Ocean freight is the most economical mode of transportation for long distances, and the cost for full container-loads is the lowest among all categories of ocean freight (of the order of a few cents per pound [74]). In addition, another important factor that drives down this cost further is the direction of ocean freight flows. If one looks at the volume of containerized cargo at two largest ports on the U.S. west coast (Los Angeles and Long Beach), it is observed that the export volume is much lower than the import volume (less than one-third) [96]. This implies that container ships sail in to the ports fully loaded, but may not be fully loaded on backhauls. Therefore, shipping companies would be happy to get any value that they can for this perishable capacity, and may offer deeply discounted rates on backhauls to Asian countries like China, India and Pakistan.

Second, labor rates in third-world countries are very low, *e.g.*, approximately $1.50 per day in China [10]. In addition, there might exist demand for used electronic products in third-world countries, and a "recycler" in the U.S. could collect revenue from end-of-life disposal fees in the U.S., and then again by exporting this material. This leads to disposal costs being much lower (and perhaps negative) in a third-world country as compared to those in the U.S.

Other related factors that drive the end-of-life flows of electronic equipment to third-world countries are the demand for raw materials (such as ferrous and non-ferrous metals) from burgeoning manufacturing operations, and loosely enforced or non-existent environmental regulation in third-world countries.

Expanding manufacturing operations in third-world countries have fuelled the demand for raw materials used in production processes. For example, there has been a sharp increase in copper demand in China, particularly for metal used in power cables and wires. Chinese demand for ferrous metal scrap from the U.S. is also expected to increase [17]. Recycling of electronic waste is one of the sources that feeds ferrous and non-ferrous metals as inputs into production processes.

Finally, environmental legislation has been weak or non-existent in most third-world countries, who have focused primarily on economic growth. The potentially harmful effects of E-waste processing on the environment and on human health have not been widely recognized. These stark differences in environmental legislation between developed countries and third-world countries have resulted in third-world countries becoming “dumping grounds” for electronic waste [91][101]. However, there are positive signs, which indicate that concerns about E-waste have mounted significantly to galvanize some third-world countries into action. For example, China has banned the imports of scrap electronic goods, effective November 1, 2004 [24]. In India, the Central Pollution Control Board has set up a task force to assess the activities of small E-waste recycling units. One organized E-waste recycling company in India has also announced the setting up of a scientifically managed E-waste recycling plant near Bangalore [101].

It is understandable that environmental legislation has not been a priority for third-world countries so far. However, it is important for developed countries to aid third-world countries in focusing on and developing effective environmental policies, not only for electronic waste, but also for other environmental issues. This argument is not based solely on ethics and morality, but on broader global environmental issues such as Environmental Justice (EJ) [26] and the existence of the empirical Environmental Kuznets Curve (EKC), which is an inverted U-shaped relationship between national per capita income and pollution levels. For obvious reasons, no further discussion is included in this dissertation, but the interested reader is referred to Davidson and Anderton (2000) [30], Turner and Wu (2002) [92], Grossman and Krueger (1995) [39] and Yandle, Bhattarai and Vijayaraghavan (2004) [105].

Allocation of responsibility for the environmentally friendly disposal of electronic waste at end-of-life is potentially a very difficult issue to handle, because it involves the re-distribution of wealth. For example, proposals about the implementation of Extended Producer Responsibility (EPR) are vehemently opposed by manufacturers, who are consequently held responsible for the management of their equipment through its complete life cycle. On the other hand, the collection of visible ARFs from customers imply that manufacturers have virtually no responsibility to ensure that their product life cycles are as environmentally friendly as possible. Landfill bans accompanied by end-of-life disposal fees place the entire burden on consumers of electronic products, and once again, none of the actors has an economic incentive to be environmentally friendly. This issue has been widely debated as a part of the NEPSI initiative [72] and is not discussed further.

Product redesign for elimination of toxics is closely linked to the allocation of responsibility. If there exists a separate legislation such as RoHS in the EU (Section 2.4), this issue can be handled somewhat independently, but even so, responsibility for the environmentally friendly disposal of electronic equipment does drive product redesign. If manufacturers were absolved of all responsibility, they would have little incentive for the elimination of toxic substances in their products. Product redesign is also linked to issues regarding the resale and reuse of electronic equipment. It has been mentioned in Section 5.1.2 that resale and reuse activities are likely to be hampered by the high costs of disassembly and testing. However, product redesign initiatives, such as modular design, Design for Disassembly (DfD) and Design for Environment (DfE) can potentially reduce these costs and make it possible to reap the benefits of resale and reuse of electronic equipment. In fact, this argument is supported by the research result in Section 3.4.3, whereby it is observed that refurbishment is a profitable activity for expensive assets, because the benefits from reuse outweigh the costs of disassembly and testing.

In summary, this section extends the policy discussion in Section 5.1 to national and international policy issues in the end-of-life management of electronic products. A few interesting and important insights, such as the tradeoffs between various realms of policy and the incitement of gaming behavior by individual actors due to differences in environmental legislation across states, are provided on the basis of the case study results obtained in this research. Other important issues are briefly discussed as well. The next section concludes and summarizes this chapter.

5.3 Summary and conclusions

This chapter presents insights that this research can provide to environmental policy makers, both at state and national levels. Also discussed are other important issues that cannot be addressed directly, but provide interesting topics for extended research.

It is first argued that based on the specific case study results obtained for this problem, it is possible to evaluate the expected impacts of alternative state-level environmental legislation such as landfill bans and ARFs. For example, the research results show a landfill ban in one state may lead to outward end-of-life flows of assets from that state, hence defeating the primary policy objective of keeping hazardous waste out of landfills and eroding the economies of scale required for the establishment of a strong electronics recycling infrastructure. An ARF may also lead to the erosion of economies of scale, but could also encourage recycling of certain kinds of assets, which is a counterbalancing effect.

The case studies also provide helpful additional insight for an informed discussion of other complex state-level policy formulation issues. For example, due to high transaction and labor costs, policies focused strongly on encouraging repair, resale and reuse of electronic equipment may be ineffective in achieving that objective as well as in job creation. Also, establishment of a strong electronics recycling infrastructure is not only dependent on the economies of scale achieved by collection of a large and steady volume of electronic waste collected in the state, but is also greatly affected by the competition for obtaining used electronic equipment by similar existing infrastructure in other states.

The research results are also useful in the discussion of national and international issues in the management of electronic waste. For example, it is shown that the effectiveness of formulation of E-waste legislation at the state level is questionable, because it leads to public policy formulated in one realm imposing negative impacts on that in other realms. In this case, state-level E-waste legislation is found to create an artificial demand for transportation, hence impacting transportation policies negatively. It also incites gaming behavior among individual actors and possibly even legislators, and hence exacerbates inefficiencies in the system.

Finally, for the sake of completeness, other important national and international issues in E-waste management, that this research does not address, are also discussed. One of the most important ones is the Basel Convention, which prohibits the export of hazardous waste across international boundaries. Other important issues are the allocation of responsibility for the environmentally friendly disposal of electronic waste and product redesign issues like Design for Disassembly (DfD) and Design for Environment (DfE).

For obvious reasons, public policy formulation is not the focus of this dissertation, but the insights obtained herein should lead to policy-makers engaging in somewhat more critical evaluations of their policies. Admittedly, policy formulation is a very complex task, but given the pervasive nature of the repercussions of policy, it is necessary to dedicate considerable thought to all possible effects that implemented policies might have, including secondary effects that are not always clearly observable. The new analytic model formulated in this dissertation provides a tool to develop insights into the analysis of E-waste policies. It is hoped that similar research in the future would make further contributions to this activity, especially by revealing policy effects that may not become immediately apparent from the more conventional approaches to policy analysis.

CHAPTER 6

SUMMARY, CONTRIBUTIONS AND EXTENSIONS

6.1 Summary and conclusions

In summary, this dissertation examines the relationships between key logistical and environmental issues in electronic equipment leasing. Given the significant portion of business assets financed through leasing, short lifecycles of electronic equipment and increasingly strict environmental legislation on electronic waste, it is necessary to address these issues simultaneously. A majority of the analysis has been carried out from the point of view of an electronic equipment leasing company that would like to make simultaneous decisions on lease lengths, use of logistics facilities and legally acceptable end-of-life management of assets. In addition, the effects of alternative environmental legislation in different geographic regions are also highlighted.

A literature review (Chapter 2) of the various fields relevant to this problem reveals that even though there is an abundance of published literature on each of the individual fields, there does not currently exist an analytical framework that simultaneously incorporates reverse logistics, parallel asset replacement and environmental legislation.

Subsequently, a mathematical model for the problem addressed in the research is presented in Chapter 3. The model is a deterministic, multi-period, mixed integer linear program (MILP), whose strengths and limitations are also discussed in the chapter. The

MILP reduces to a linear program (LP) under certain cost conditions (and the LP version is used to derive all the subsequent computational results). A deterministic case study with industry representative data validates the approach and demonstrates the utility of the model in answering key research questions. Interesting tradeoffs between various costs in the system are revealed, such as those between asset purchase costs and transportation costs for forward product flows, and between asset disposal costs and transportation costs for reverse product flows. It is also shown that rebuilding is a profitable activity for high-end assets, because rebuilding costs are typically much smaller than asset purchase costs, and thus compensate for the lower revenue yields obtained from rebuilt assets. The last part of the case study presented in the chapter demonstrates, by using CRT monitors as a specific example, that the presence of alternative environmental legislation in different geographic areas can significantly change end-of-life flows of assets.

Chapter 4 presents a more realistic situation and extends the analysis by conducting a detailed examination of the effects of uncertainty in problem parameters. Key research uncertainties are identified as uncertainties in transportation costs, and uncertainties in asset purchase and asset disposal costs because of environmental legislation. The interactions between these sources of uncertainty are presented in the form of a schematic diagram.

The next section of this chapter discusses a robust optimization approach for addressing the key research uncertainties. The objective of the leasing company is to make robust decisions about lease lengths. It is found that the dominance of the effects of uncertainty in transportation costs on the robust objective function value lends itself to the use of intuition and simple empirical methods for making near-robust decisions, without the need for a standard robust optimization framework and the associated theoretical and computational effort.

The remainder of the chapter is devoted to an in-depth examination of the effects of key uncertainties, and their interactions thereof, on product flow and lease length decisions. Intuitive hypotheses about these effects are first formulated and then verified computationally and statistically. Transportation costs significantly affect all these decisions. Lease length decisions are not greatly affected by changes in asset purchase and asset disposal costs due to environmental legislation. However, changes in asset purchase costs are quite significant for asset purchase decisions and forward product flows. Changes in asset disposal costs are very significant for asset disposal decisions and reverse product flows. In addition, there exist very strong interaction effects between the uncertainty in transportation costs and the uncertainty in asset disposal costs.

Chapter 5 examines the problem from the perspective of environmental policy-makers rather than leasing companies. Several interesting policy insights can be obtained from the research results. The first set of insights is for state-level legislators. It is argued that the existence of different electronic waste legislation in different states is unlikely to achieve the primary objective of such legislation. It is also possible to comment on the expected effectiveness of the legislation in achieving its other objectives such as the encouragement of reuse and recycling of electronic equipment, and the creation of jobs in the state.

The next set of insights concerns national and international policy on electronic waste. The research results show that the existence of different E-waste legislation in different states can impose significant negative externalities on other policy realms, such as on transportation policies in this particular problem. In addition, differences in environmental legislation can invoke gaming behavior in leasing companies, other individual profit-maximizing actors and even in state legislators. This gaming behavior leads to further efficiency losses. Therefore, there appears to be a dire need for effective uniform E-waste legislation in the U.S. Finally, some other important international E-waste issues are briefly discussed.

6.2 Research contributions

This dissertation analyzes an interesting real-life problem that lies in the intersection of the fields of reverse logistics and equipment replacement. However, even though there is plenty of published literature on each of these individual fields, there do not currently exist any known analytical approaches for this problem. Asset replacement literature does not generally include logistical and environmental issues, and there has been no known reverse logistics research that incorporates asset management. Therefore, this dissertation bridges a gap in existing literature.

In addition, this dissertation shows that ignoring logistical and environmental issues while making asset management decisions can lead to profitability decreases for a leasing company. For example, increases in transportation costs can reduce profits significantly, and so can disregarding the option for refurbishment/rebuilding activities (particularly for high-end assets). The use of industry representative data for all case studies ensures that these insights would be useful to a leasing company that faces a similar situation.

Furthermore, the examination of the effects of key logistical and environmental uncertainties provides novel insights. Uncertainty in transportation costs is shown to significantly affect forward and reverse product flows as well as lease lengths. Even more interestingly, it is shown that there exist interactions between uncertainty in transportation costs and uncertainty in asset purchase and asset disposal costs due to environmental legislation, and these interactions are sometimes very strong.

Finally, this dissertation provides insights not only for leasing business managers, but also for environmental policy makers, and therefore, the contributions of this work lie in the realm of environmental policy as well. The research results allow policy makers to foresee some of the expected outcomes of E-waste policies and to make comparisons with their intended objectives. The most important policy contribution of this dissertation, however, is the insight on potentially deleterious effects of the existence of different environmental legislation in different states in the U.S. The resulting imposition of negative externalities on other policy realms (transportation policies in this case) and the invocation of gaming behavior in businesses, other profit-maximizing individual actors and even in state environmental legislators are not trivial effects, and need to be taken into consideration at the time of environmental policy formulation. They also indicate that there is perhaps a dire need for consistent national legislation on E-waste in the U.S.

6.3 Extensions and future research directions

Results from this dissertation raise new questions for several potential directions for further research. Since logistical and environmental issues have not been considered simultaneously with asset management in the published literature so far, there is great potential for further research based on the groundwork laid by this dissertation. The possible extensions span the realms of both operations research (OR) and public policy.

The first extension in the OR realm is the development of solution methodologies for larger and even more realistic versions of the problem addressed in this dissertation. The case study solution of the mathematical model formulated in Chapter 3 is relatively fast in terms of solution time, but large in terms of the number of variables and constraints, which can lead to memory exhaustion for solution on individual personal computers (PCs). The formulation uses continuous variables for almost all decisions, but it is perhaps possible to reformulate the problem by using more binary variables. Although this would increase the solution time, perhaps the number of variables and constraints could be reduced. In any case, once the problem size becomes prohibitively large, it would be necessary to develop efficient solution techniques.

Another extension concerns model implementation. As discussed in Chapter 3 (Section 3.3), the model in its current form would likely be implemented via a “rolling horizon” approach, which does not guarantee optimality over a time horizon greater than the one initially used to solve the model, and also has potential “end-effects.” A dynamic multi-stage solution approach could address these limitations, and it would be interesting to see how the solutions differ between the two approaches. This comparison would offer more interesting insights into the problem.

Yet another extension in the OR realm, and this is a very important one, is the examination of other kinds of uncertainty along with the ones considered in this dissertation. As the results from this dissertation show, there may exist strong interactions between various sources of uncertainty, and therefore, it is not necessary that the effects of uncertainty in other problem parameters like demand, asset residual values, etc., would be limited only to decisions expectedly affected by these uncertainties. For example, uncertainty in demand may not only affect inventory and asset purchase decisions, but also end-of-life decisions. In addition, uncertainty in demand would likely have strong interactions with uncertainty in asset prices, which in turn could be affected by market forces, environmental legislation, etc. A related research topic concerns the derivation of analytical robustness results in the presence of one dominant uncertainty. The computational results in Chapter 4, in particular the regular parabolic shapes of the data series in Figure 4.2 seem to suggest some interesting research directions.

This dissertation makes important contributions in providing policy insights, but the formulation of public policy is understandably not its focus. Therefore, policy insights from this dissertation are simply hypotheses about expected outcomes of E-waste policies, formulated with a limited amount of information about the objectives and exact forms of existing or proposed environmental legislation. In reality, policy formulation involves more complex issues than those that can be considered in this dissertation. Therefore, there is considerable scope for future research in the policy realm. At least two important future research directions can be imagined.

The first is the development of detailed analytical methodologies to evaluate E-waste policies more specifically. The mathematical model presented in this dissertation does not incorporate sufficient policy detail to provide an objective comparison between different E-waste policy alternatives. In order to compare alternatives, a model would need to incorporate economic variables (such as supply and demand), other market conditions, more specific details of alternative policies, and the policies and electronics recycling infrastructure existent in surrounding geographic regions. One could then compare the outcomes of E-waste policies against their intended objectives and rank various policy alternatives by their expected effectiveness.

The other research direction is the study of the inadvertent imposition of negative externalities from one policy realm to others. The result in Chapter 5 (Section 5.2.1) showing that the existence of different environmental legislation in different states creates an artificial demand for transportation is happenstance and was not a planned outcome for the research. Models that are more explicit are required to examine this issue with greater specificity. Both these research directions would involve inter-disciplinary research, requiring domain knowledge from OR, economics and public policy, at the very least. However, they are likely to provide some highly novel and very interesting insights.

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VITA

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He received his Master of Science in Industrial Engineering from the Georgia Institute of Technology, Atlanta, GA, in May 2002. His primary area of interest is the modeling and analysis of practical logistics problems, but he also has strong interests in policy, which led to a minor in Environmental Public Policy as a part of his Ph.D. requirements.

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