ENVIRONMENTAL IMPLICATIONS OF LEASING

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Environmental Implications of Leasing

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To the students of the Georgia Institute of Technology and my coworkers in the Sustainable Design & Manufacturing group.

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NOMENCLATURE

Chapter 4

A, *B* constants from the equation of energy consumption trends

b build energy (kWh)

c constant used for calculating aging rate

n length of life spans (years)

m slope of energy consumption trend graph (kWh/year)

r initial aging rate

T start year (years)

t model year

V variable energy (kWh/year)

Chapter 5

ΔE is the annual increase in energy, *a* the age, and *r* and *c* are constant values calculated by Johnson to account for losses (*r*=0.045 and *c*=2.5 where used in this study)

Chapter 6

m_i slope of the products annual energy consumption

m_{i+1} slope of energy consumption in following periods

t_i length of time which the product is used in a specific period

t_{i+1} length of time which the product is used in a specific period in following periods

b initial manufacturing energy

SUMMARY

This thesis will investigate the possibility of leasing as a ‘greener’ form of business transaction. With leasing, the customer pays for the service obtained from the product, but does not own the physical asset; ownership remains with the lessor. This has been claimed to increase resource productivity and close material loops. Numerous complications exist, however, such as tax regulations limiting operating leases to terms of 75% of the total product’s life. In addition, no clear pattern has emerged in leasing practices, and in most cases manufacturers approach leasing on an ad hoc basis.

Research has found that usage-phase impacts play a major role in determining the advantages realized by leasing. Products such as vehicles or refrigerators that continually consume energy negatively impact the environment much more during their use than during manufacturing or transportation. Because most lease agreements contain maintenance contracts, the opportunity to upgrade and increase product efficiency during this use-phase is paramount to reducing negative impacts. Remanufacturing also shows potential to further reduce resource requirements. However, if product efficiency is not improving significantly, remanufacturing alone does not make a significant impact. In some cases, such as carpets, remanufacturing is not practical, but recycling can be utilized. Tax regulations require leased terms to be less than that of a product’s designed life, hastening replacement. This has the potential to offset any advantages seen with a lease agreement. Academic work in this area remains very limited and product-specific.

Case study analyses performed in this thesis found that increased product turnover can actually be environmentally beneficial when technology is improving. These gains can be further improved with remanufacturing and optimized product replacement

moderated by lease agreements. If usage energy is significantly less than manufacturing energy, leasing has little value for reducing impacts. Also, leasing may motivate closed material loops, but without improving product efficiencies there is no advantage to optimizing life cycles with lease contracts. The LCA performed on carpet recycling found that although recycling significantly reduces environmental impacts, it is possible for closed material loops to succeed without the presence of lease agreements.

1. Introduction

1.1. Waste Generation

Society's impact on the environment is closely linked with economic activity (Allen L. White, Mark Stoughton, & Linda Feng, 1999b). As economies grow and populations prosper, so does the demand for materials. In 2007 approximately 254 million tons of municipal solid waste was collected, and more than half of this, 54 percent, went directly to landfills (EPA, 2008). Waste from commercial locations accounted for 35 to 45 percent of this waste and volumes continues to increase, as seen in Figure 1 (Agency, 2007). This problem is compounded by the fact that as landfills are filled to capacity and must be closed new ones are not being developed, resulting in a shortage of landfill space. This trend can be seen in Figure 2.

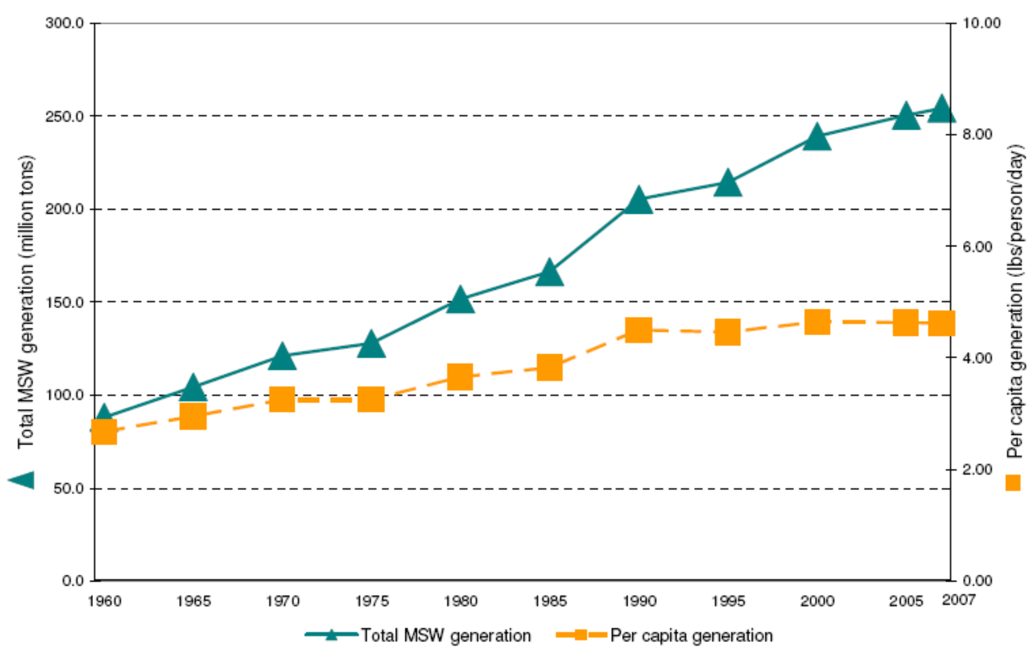

Figure 1. MSW Generation Rates (EPA, 2008)

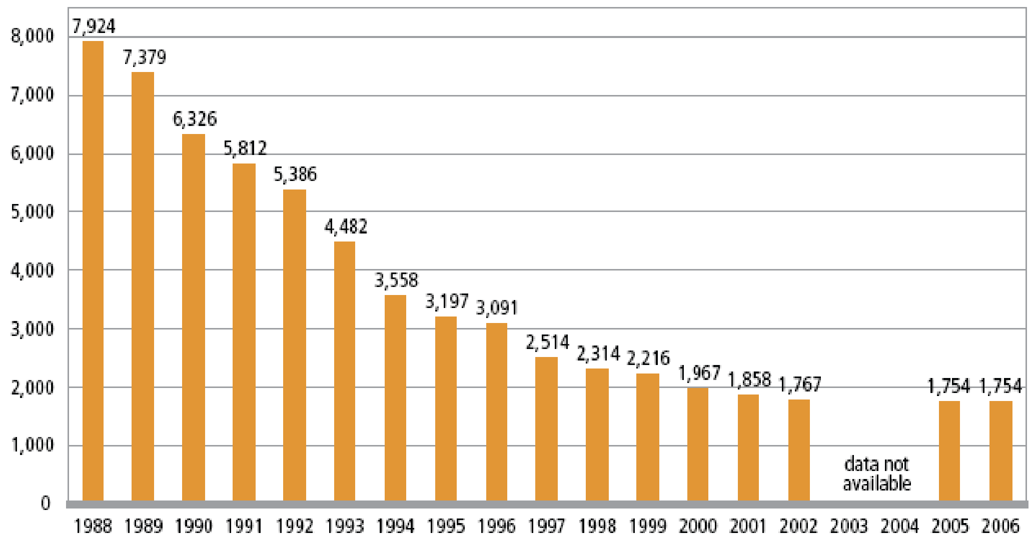

Figure 2. Number of Landfills in the United States , 1988-2006 (EPA, 2008)

These numbers represent more than 25 percent of the world's resources, yet accounts for only 5 percent of the world's population (Fishbein, McGarry, & Dillon, 2000). As China and India's economies continue to grow, their waste generation will also increase.

1.2. Implications with GHG and Climate Change

This large generation of solid waste carries with it severe environmental consequences. Waste is only the final step of a products life which begins with extraction and processing of raw materials, goes on to be manufactured into a product, transported to market, and used by consumers until finally being added to the waste stream. This entire life cycle is beset with energy usage and greenhouse gas emissions.

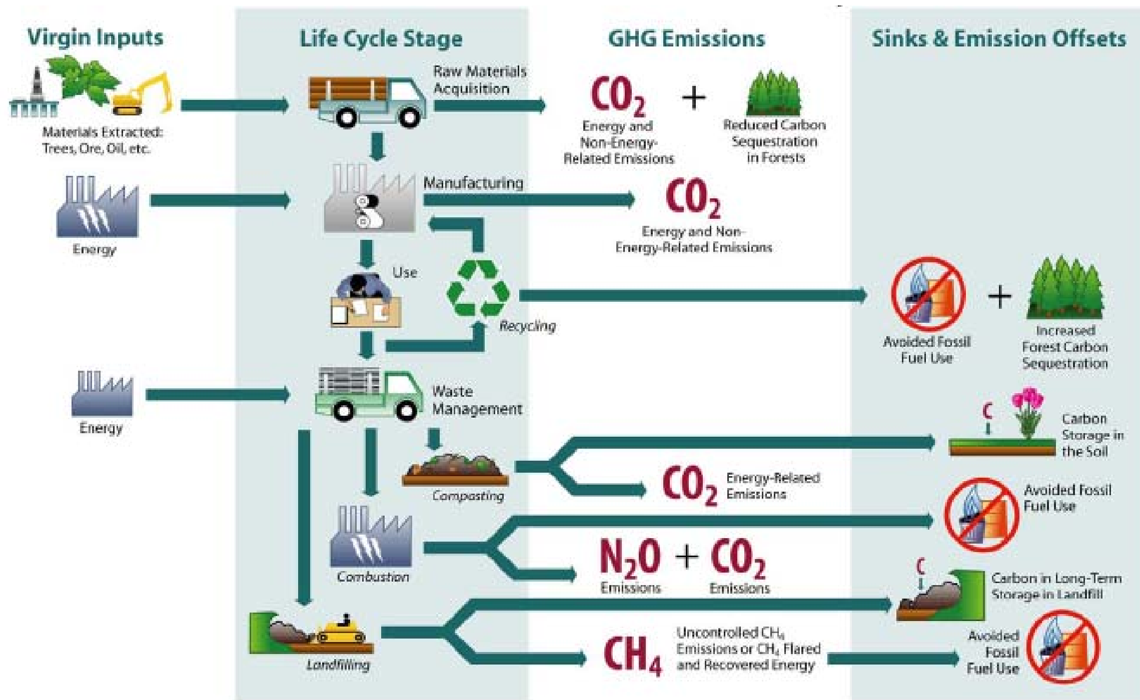

Figure 3. Greenhouse Gas Sources and Sinks Associated with the Material Life Cycle (EPA, 2006)

1.3. End of Life Activities

There are numerous options available when it comes to how to dispose of a product. The most commonly used method is simple disposal in a landfill. However, when other options such as reuse, remanufacturing, and recycling are added, the number of possible disposal options increases, as shown in Table 1.

Table 1. Generic End-of-Life Options (Guidry, 2008)

EOL Options:	Category:	Description
Waste Disposal	Landfill	Dumping of discarded goods in a landfill.
	Landfill w/ Energy Capture	Capturing gas, such as methane, from anaerobic activities in landfill decomposition for conversion into electric energy.
	Incineration	Burning of trash without energy capture.
	Compost	Disposal of bio-materials for anaerobic decomposition.
Reuse	Repurpose	Extended product life through second use phase, no mechanical or chemical processing of product before second use phase
	Remanufacture	Repair or revamping of products for deployment in second use phase defined in same context as first use.
Recycle	Open-Loop	Mechanical and/or chemical processing of a product and/or product materials back into their original form.
	Closed-Loop	Mechanical and/or chemical processing of a product and/or product materials back into a new form.
	Up-Cycle	Mechanical and/or chemical processing of materials into new materials of a greater value.
	Down-Cycle	Mechanical and/or chemical processing of materials into new materials of a lesser value.

1.4. Closing the Material Loop

Depending on which end-of-life (EOL) option is chosen (or combination of these) has a direct affect on a product's material flow. Traditionally, a products life cycle was an open system. Raw material was mined or harvested, transformed, used, and then thrown out. Industrial firms rarely regard a product as part of their system once it has been sold, and therefore put no thought into what happens to the product once it has been sold. When products wear out or are replaced they are usually thrown away (Frosch, 1997). This material flow is illustrated in Figure 4.

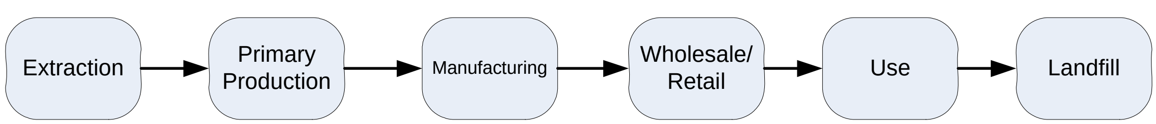

Figure 4. Linear/Open material flow

Utilizing alternative end-of-life options has the potential to close the material loops and avoid disposal, as shown in Figure 5.

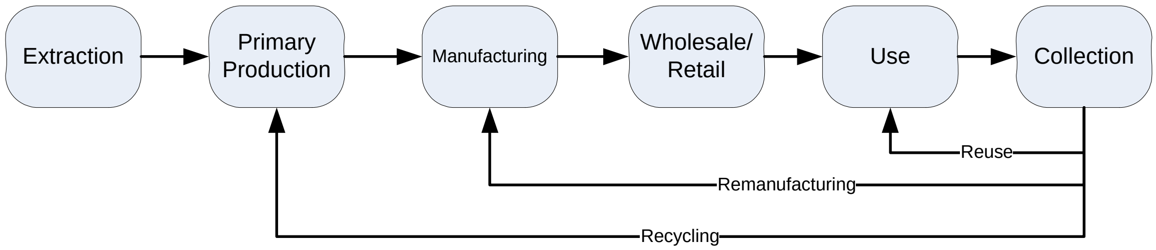

Figure 5. Closed-loop material flow

1.5. Is Leasing Green?

Over the years a growing number of advocates have claimed that adopting leasing as a business model as being more ‘green’. The practice of leasing products, rather than selling them, is a strategy for increasing resource productivity by moving to a pattern of closed-loop material use by manufacturers (Fishbein et al., 2000; O. K. Mont, 2002; Robert et al., 2002). Proponents of leasing claim that by maintaining ownership of the product the manufacturer can successfully put in place a service strategy to preserve end-of-life value and a product recovery strategy consisting of reuse, remanufacturing and recycling.

One may therefore assume that leasing is obviously an environmentally superior option to selling. However, there have also been claims contrary to this, and numerous complications to leasing exist that may hinder its potential environmental improvements (Agrawal, Ferguson, Thomas, & Toktay, 2009; Lawn, 2001; Ruth, 1998). Several issues limiting leasing’s environmental potential are:

- An original Equipment Manufacturer (OEM) may want to prematurely remove old equipment from the market to keep it from cannibalizing the sales of newer, higher margin products, leading to a higher volume of disposal.
- The current US tax regulations for operating leases require a maximum lease term of 75% of the product's expected lifetime. If the product is disposed of, or even recycled, at the end of the lease, the environmental impact could be worse than if the customer used the product for its full lifetime.
- The maintenance, repair, recycling or remanufacturing often associated with leasing can potentially have a greater environmental impact than disposal.

The answer to the question "Is leasing green?" therefore, is not clear cut. There are numerous factors and variables that must be accounted for before such a claim can be made.

Gaining a better understanding of these concepts could benefit a number of groups. Most obviously those involved in public policy can use the findings in this study to direct new material recovery policies similar to those fashioned in Europe, or perhaps judge the success of European laws using similar methods developed here. The issues of product recovery and manufacturer responsibilities will continue to become an integral part of environmental policies at all levels of government, and this research work aims to provide both a methodology for analyzing successful policy and concrete findings to guide future decisions.

Manufacturers and consumers alike can also benefit from this study by learning how product choice affects environmental impacts. Most significantly manufacturers can gain a better understanding of the importance and opportunities available with closed material loops. Understanding how and when leasing may contribute to reduced energy consumption of resource use is vital for businesses to reduce their overall impact. Finally, knowing how certain products characteristics affect the manner in which leasing may influence energy usage is also important.

1.6. Problem Statements

The idea of leasing for the environment is a relatively recent development. The most frequently heard answer to questions about leasing as a means of implementing a product recovery strategy is "it depends…" followed by a number of vague qualitative statements. It is the goal of this thesis to bring some quantitative analysis to the topic and provide a concise decision matrix to determine the possible environmental improvements of leasing depending on product characteristics. The research questions to be answered in this thesis are summarized below.

1. Does the shortened life span stipulated by US tax regulations for leasing negatively impact the environment?
2. Can closed material loops offset the impacts of greater product production volume and increased product turn over?
3. What relationships exist between product characteristics and successful leasing for the environment?

The first step is to gain a solid understanding of leasing practices and how leasing can potentially reduce environmental impacts. A thorough literary review will cover the development of leasing among businesses and why it is often viewed as a green business strategy. Several characteristics of leasing will be highlighted for topics to be further investigated in the research of this thesis. Other issues such as maintenance will also be discussed. Three case studies will be used to provide quantitative data to help answer the research questions.

1.7. Outline of Chapters – Thesis Plan

Chapter 2 is composed of a literature review with a focus on leasing. It explains both why businesses may choose to adopt leasing as a business model and how it promotes extended producer responsibility and a close material loops; two keys to improved environmental practices. This will reveal shortcomings in the current literature. Chapter three will then focus on the methodology used to answer questions and expand the current knowledge base.

The first case study focuses on carpet recycling. Interface, a LaGrange, Georgia based textile manufacturer has experimented both with leasing carpets and carpet recycling to close the material loop and reduce waste streams. Carpet, unlike many other goods, is static, meaning it does not produce any negative impacts during its usage phase. This will provide and interesting comparison to the next case study.

Case study two focuses on white goods and vehicles. These common consumer products are generally bought and used for their maximum useable life, and produce significant emissions during their long usage phase. Leasing is proposed as a means to better manage the life cycle of these products and take advantage of improved technologies.

Computers form the third case study. Unlike the other products discussed in this thesis, computers exhibit the majority of their environmental impacts during manufacturing rather than use. Additionally, computers are extremely difficult to remanufacture or recycle, further complicating the potential for closing the material loop.

Chapter 7 will condense the findings of the case studies to determine the major characteristics that affect the success of leasing for the environment and provide a simple decision matrix.

2. Background

The concept of leasing is not new by any means, and has been a long-time part of business transactions. However, leasing as a means to reduce environmental impacts is a relatively new concept. The transition of thinking from leasing as only a business transaction to a ‘green’ concept follows a complex line of debate that will be summarized in this section. Understanding how leasing has become the focus of environmental discussion requires the reader to be familiar with the motivations of businesses utilizing leases and the resulting affects.

This paper begins with a review of early works focusing on leasing strategies. The motivation of these papers is strictly economics, with little in the way of environmental discussion. Although initial research focused on tax benefits to explain the growth of leasing, it becomes evident there are numerous other incentives that are more likely to fuel to growth of the leasing industry. The review will then investigate how the growing adoption of leasing (and aspects associated with leasing) can change market transactions, primarily through supply chains, remanufacturing and material recovery. This leads to the concept of closing material loops and reducing waste with potential for environmental improvements. The review will then discuss the foreseen advantages and disadvantages of adopting such a strategy for the environment.

This review is not meant to be an exhaustive list of all the work that has been done on the subject areas but to touch on major topics and research in the area, and give the reader the proper context to understand the motivations of this paper and the questions that still need to be addressed.

2.1. Work focusing on economic viability of leasing

Early research work on leasing focuses on explaining the possible motivations and reasons for growth in the practice. Tax incentives were once considered the only possible advantage to leasing, as will be evident in the first papers discussed. Eventually, however, the academic community begins to broaden the possible incentives to explain the growing leasing industry as evident in more contemporary research.

2.1.1. Taxes as motivation for leasing

An excellent review for evaluating the economic advantage of leasing is provided by Bower (Bower, 1973). Several ad hoc approaches to the leasing decision are examined and weighed, as well as developing a hybrid approach based on differing strategies to determine if leasing is economical. Bower finds that there is very little agreement among decisions made using an ad hoc approach, and that the final decisions are best left to managers in charge. Myers et al. continue the development of a coherent formula for evaluating the lease or buy decision (Myers, Dill, & Bautista, 1976). A comprehensive formulation on determining the economic advantage of leasing is developed which also incorporates tax advantages into the theory. In fact, Myers et al. conclude that the only advantage to leasing over buying can be found in the tax rates. The primary savings made from leasing result when accelerated depreciation on goods is allowed for tax purposes or when interest rates are high. However, the paper admits that given the growing use of leasing in business practice warrants a more thorough look at the leasing industry. The difficulty in generalizing the lease or buy decision is reflected by Lewellen et al. (Lewellen, Long, & McConnell, 1976). Tax conditions also play a large role in the analysis of leasing in this paper, ending with similar conclusions found in Myers. Given the complexity of conditions between lessors and lessees tax rates and deductibles on leased items are the only discernable factor that determines the profitability of leasing versus buying. Miller and Upton examine the decision to lease from several points of views, such as an economist's approach versus an accountant's, to determine what motivates the decision (Miller & Upton, 1976). Miller and Upton reach conclusions similar to those already discussed; stating that it's difficult to generalize the decision of leasing and that it must be determined on a case-by-case basis. This paper also downplays the importance of taxes on the decision, suggesting that firms can be rearranged or specialized to take advantage of taxes and maintain profitability. These early articles reached similar conclusions that would seem to disprove any tax advantages to leasing, suggesting other motivations must be in place for the growth of leasing.

More resent work by Eades and Marston briefly focuses on the possibility of tax arbitrage as a motivation for leasing. If an owner of an asset faces higher marginal tax rates than a firm that desires the use of the asset, the owner can minimize tax liability by acting as a lessor rather than selling the asset. This is because the owner places a higher value on depreciation tax shields (Eades & Marston, 2002). Lease goods may also lower information cost and other contracting costs, thereby reducing the cost of capital (Eades & Marston, 2002). Operating leases can also be treated as overhead rather than a purchase, and can therefore be written off immediately (Fishbein et al., 2000). This allows cost to be shifted to the operating budget from the capital budget, saving cash and preserving credit lines.

Leasing has become a significant aspect of business transactions in today's competitive world. In 2005 $791 billion was spent by businesses on competitive assets, $213 billion, or 27%, of which was acquired by leasing ("State of the Industry Report," 2005). 80% of all US companies now lease some or all of their equipment (Fishbein et al., 2000). This number continues to grow each year, and more and more manufactures are offering leasing programs and additional services that introduce a new revenue stream for companies. This growth cannot be explained by the marginal tax benefits covered thus far. Alternative incentives are motivating business to adopt such business practices. Contemporary consensus among research papers it that other advantages aside from leasing are driving the growth of leasing in today's industry. The next section of this review will therefore focus on the alternative explanations to the growth of leasing.

2.1.2. Alternative to tax incentives

Smith and Wakeman explore numerous alternative advantages to leasing (C. W. Smith & Wakeman, 1985). Looking outside of tax-based incentives this paper finds leasing to be economically attractive when: (1) use and maintenance decisions have a minor affect on the value of the asset; (2) the asset is not specialized to a single firm; (3) the lease term is significantly shorter than the asset's life cycle; (4) "if corporate bond contracts contain specific financial policy covenants"; (5) provisions exists that provide payoffs depending on the return of invested capital; (7) the lessor has substantial control of the market; and (8) the lessor has substantial control on asset disposal. The paper concludes that non-firm specific assets take greatest advantage of leasing, rather than firm-specific assets.

Grenadier investigates another aspect of leasing, building a complex method to evaluate the economic uncertainty of leasing for individual value-maximizing firms (Grenadier, 1995). Grenadier expands on this with a follow-up paper which primarily focuses on the equilibrium credit spread of leases subject to default risk (Grenadier, 1996). These two papers do not consider the motivation of tax credits as has been done the previous papers, but uses a real-options approach to analyze leasing with great thoroughness. These papers, however, seek to model existing leasing agreements rather than find the motivation for firms to lease goods.

Grenadier also notes the significant increases of leases in the last few decades (Grenadier, 1995). Despite initial research findings that suggest very little incentive existed for leasing, it's obvious corporations found otherwise. According to the article, "the dollar amount of rental expenses was more than 40% of the dollar amount of interest expenses for all active companies reported in COMPUSTAT," and in addition, "in 1991 one-third of new equipment was leased." Obviously, significant incentives must exist for such large volumes of leasing to occur.

2.1.3. Why leases exist in industry

In an effort to uncover what drives leasing practices in the real world Eades and Marston examine the largest 100 lessees and lessors in the U.S. (Eades & Marston, 2002). Contrary to the earlier literature, Eades and Marston determine that access-to-capital and taxes are not the primary reason firms choose to lease. The results of the paper suggest that the primary motivation factors are "the flexibility afforded the contracting parties and other asset-specific attributes rather than from tax arbitrage or reduced cost of capital". The paper also finds that companies with higher-than-average credit quality (when compared to the S&P population) tend to practice leasing more than others. Another interesting pattern found among these 100 firms is that along with being the largest lessors they are also the largest lessees. The primary driving force for leasing is the ability to purchase, renew, sublet or cancel leases. Eades and Marston also note that leasing at this level results in a secondary markets for use of the assets and the end of the lease terms. This will prove important when closed-loop supply chains and sustainable design are considered later.

The lease contract itself also offers advantages appealing to lessors. Leasing ensures continued revenue from consumers through contracts. Smith and Wakeman explain that a lease contract guarantees a firm constant payments from customers for an agreed time period (P. Desai & Purohit, 1998). Lessors benefit from lease contracts because they are only responsible for financing the capital costs of a product, which is often cheaper than finance options when buying (P. Desai & Purohit, 1998). There is also the aspect of flexibility that is introduced with a leasing contract. The lessor is generally obliged to perform maintenance on leased goods as part of the lease contract. This is advantageous because the lessee, who is often the product manufacturer, retains special knowledge of its products and is in the best position to make repairs. Miller and Upton add to this, explaining that the lessor obviously benefits from having the service available to make repairs (Eades & Marston, 2002). Many lease contracts also provide a cancellation policy, or have the option to renew or buy at the end of a lease period. This gives the lessee greater flexibility to abandon the asset after a relatively short period of use. This is especially significant when technology products such as computers are leased, which tend to become obsolete only after a few years. Additionally, if the lessor develops new technology the lessee can choose to cancel the lease on the old generation and upgrade to the new model at a relatively low cost (Eades & Marston, 2002).

2.1.4. How leasing affects the market

Market focus begins to shift from focusing on products to focusing on services as leasing becomes more prevalent. This has continuing consequences in how the market and industries behave.

Desai and Purohit address this and investigate how leasing affects market demand (P. Desai & Purohit, 1998). The primary focus of this paper is determining “the long-term implication of leasing to some customers and selling to another set of customers”. A distinction is made between the secondary markets of ex-leased goods and used goods. The advantage of an ex-leased good versus a good that was bought and then re-sold as a used product is that an ex-leased good remains in control of the firm. This allows a firm to be in the secondary market that would otherwise be occupied exclusively by third parties. Their findings suggest that a combination of selling and leasing is the best option for a firm. This allows a firm to reach two levels of the market, the high-level buyers and the secondary used market. Doing so also gives a firm control over the secondary used market that may otherwise be occupied by third parties. Similar conclusions are found by Bulow (Bulow, 1982). Bulow finds that if a monopolist firm sells a product rather than leases it stands to make less money because “he has the ability to reduce the capital value of the outstanding stock of durables and no way of guaranteeing that this power will not be used.” In addition, a monopolist seller does not have the flexibility of choosing its production technology independent of the product demand.

In addition to supporting previous findings, Desai and Purohit also recognize the importance of durable goods (P. S. Desai & Purohit, 1999). As a product's life cycle increases it becomes more profitable to lease, an important distinction in leasing strategies. Reisken et al. also find support in favor of leasing (Reiskin, White, Johnson, & Votta, 2000). The term servicizing is used to describe this transition from product to service based enterprise. The paper notes the many hidden costs of purchasing materials that is often overlooked by management. The "procurement, delivery, inspection and inventory," are all costly results of purchasing materials. Transportation may be the most costly depending on the nature of the material due to numerous safety regulations. Companies focused on producing a product often overlook these secondary costs of maintaining their material supply. Servicizing the material handling can relieve companies of these additional costs. Doing so also puts control of possible hazardous materials in firms specialized to handle such items. Although Reiskin et al. focus on chemical supply chains, these issues can be applied in numerous other industries.

2.1.5. External Factors on Leasing

In the introduction of this thesis government legislation was briefly discussed as a major factor in influencing the transition to services. These external influences and the resulting industry behavior are examined in the following papers.

Webster and Mitra examine how take-back laws influence companies to change their business models and product designs (Webster & Mitra, 2007). Consumer electronics are under pressure to improve sustainability with the European Union's adoption of the Directive on Waste Electrical and Electronic Equipment (WEEE) which sets new requirements for manufacturers to take back their products. Webster and Mitra develop a two-period model to predict how companies can adjust to the new restrictions, and if the adjustments can also be economical as well as environmental. Three main conclusions are determined. First, a manufacturer can actually profit more from revenue associated with a remanufacturing operation than by operating as a monopolist. Second, the WEEE take-back law can simultaneously lead to increases in manufacturer profitability and reduce the tax burden on society. Third, the WEEE take-back law provides incentive for structural changes in industry that result in the introduction of remanufactured products. These findings show that government enactments can have positive effects, despite industry concerns to the contrary.

Gerrard and Kandlikar study how the European Union's end-of-life vehicle (ELV) Directive has impacted the automobile industry (Gerrard & Kandlikar, 2007). The research found that the ELV legislation improved recycling processes, such as shredder residue separation techniques. However, numerous factors exist that prevent automobile manufacturers from fully embracing remanufacturing in their design stages. Vehicles, like many consumer products, rely on customization for customer appeal, and this greatly restricts the amount of remanufacturing design that can be applied to the vehicles. The delayed payback associated with long vehicle lifetimes has kept management from increasing efforts for eco-design as well. These examples show that numerous roadblocks exist in real-world studies, and that each industry will be faced with its own unique problems.

2.2. Supply Chain and Remanufacturing

Once a lease period has ended, the lessor maintains ownership of that product, and it is generally returned to the manufacturer. This maintained product ownership increases the probability a product will be reused, remanufactured, or recycled (Fishbein et al., 2000). Disposal costs and value of materials are major incentives for companies to regain as much value from their products as possible. What results is a closing of the material loop. This is supported by research conducted by INFORM, which argues that leasing can be used to manage the reverse logistics involved with remanufacturing (Fishbein et al., 2000). The report on leasing found that leases "can increase the probability that a company will own and be responsible for managing its products at the end of life and internalize the costs of doing so." Leasing both provides a motive for product take-back, and provides a structure to aid in the logistics involved with closed material loops.

2.2.1. Managing quality of returned goods

Most literature focusing on supply chains and remanufacturing have assumed product returns to be an exogenous process, meaning the company has no control over the quality and quantity of returned products. One of the first papers to investigate the accuracy of this assumption is by Guide et al (V. Daniel R. Guide & Wassenhove, 2001). Guide et al. argue that companies can actively manage product returns, rather than accepting them passively. Successfully controlling the quality of products returned can be done using a market-driven approach. The assertion is expanded on a follow up paper (V. Daniel R. Guide, Teunter, & Van Wassenhove, 2003). In this follow up a framework is developed for determining optimal prices and the corresponding profitability when a firm can proactively influence product returns. The novel market-driven recovery system supported by Guide et al. allows firms to optimize the profitability of a remanufacturing system. This is because an active recovery system allows the firm to control the quality of returned product by offering incentives for retailers or brokers to collect high-quality used goods. Rather than receiving unknown quality of products if they were returned through the waste stream, active recovery ensures control over the quality of goods that are returned. This reduces the cost to remanufacture and increases the price that can be demanded for the goods. However, Guide et al. use a fairly narrow example of a cellular phone recovery company for their model. It's claimed that this can be carried over to other products actual case studies remain to be completed. Once a product has been returned there are numerous stages a product must undergo; the primary ones being disassembly, remanufacturing, and reassembly. This creates a logistical challenge that is addressed in earlier paper by Guide and Srivastava (V. Daniel R. Guide & Srivastava, 1998). This paper discusses the possible management scenarios surrounding a remanufacturing process in an effort to determine the ideal method that minimizes waste and increases productivity. It is found that the flow of materials can be controlled using buffers between the major processing points of a remanufacturing operation. Showing that complex flow of materials in remanufacturing are manageable is important, proving it is a viable business option. This particular paper, however, does not address the economic impact the various buffering methods may incur. Some methods may prove cost prohibitive for certain firms.

Fleischmann discusses numerous topics concerned with closed-loop supply chains, and provides numerous case studies that show the economic and environmental possibilities available with such strategies (Fleischmann, 2001). Fleischmann stresses the importance of good Reverse Logistics models and emphasizes the need for supply control. This requires a company to have an active role in returns, making part of management practice which Fleischmann claims can be done thanks to ever improving information technology allowing more accurate modeling. This contradicts the industry belief that the return flow of products is external to the company and cannot be actively controlled

Following this theory, Denizel et. al. develop a model similar to a production planning problem, but with the focus on returning products on remanufacturing operations (Denizel, Ferguson, & Souza, 2008). In particular, the article is concerned with how the quality of the primary material, or cores, affects the economic viability of remanufacturing. The model "determines the quantity of cores of each quality grade that should be remanufactured, held in inventory for a future period, or salvaged each period in a finite horizon planning horizon." The model results show that the greatest factor, as far as profits are concerned, is the relationship of the product cost and core quality, the salvage value of the core, and the cost of grading each core as it is returned. Other major cost factors are storage and backlogging costs of cores.

The importance of determining the quality of returning materials is applied to a case study by Ferguson et. al. (M. Ferguson, Guide, Koca, & Souza, 2008). In this paper a grading system is developed to help with tactical production planning for remanufacturing. If properly applied, a grading system can help expedite the remanufacturing process, and it is found that firms tend to remanufacture at a rate equal to the demand in production. Doing so also results in an increase of profits. There is such a thing as too aggressive of a grading system, and Ferguson et. al. stress that approximately five different quality level are optimum when designing a grading scheme. Any more over complicates the procedure, and too few grades may make proper remanufacturing difficult.

2.2.2. Economic viability of remanufacturing

Of course determining if remanufacturing is even economically viable is important, and Fleischmann discusses using Economic Value Added (EVA) analysis to assess the potential profitability of remanufacturing. EVA is robust enough with minimal information to indicate whether or not a firm should consider remanufacturing. A general overview of the use of EVA is provided by Young (Young, 1997). EVA provides a simple way of determining a company's net profits with debt and equity capital included in the equation. When concerned with leases an EVA analysis treats leases "as a rent expense, and the asset acquired through the lease is not capitalized."

Savaksan et al. seek to develop mathematical models for determining the profitability of supply chains with remanufacturing (Savaskan, Bhattacharya, & Wassenhove, 2004). Focus is on the relationship between "pricing decisions in the forward channel and the incentives to collect used products under different reverse channel structures." In doing so appropriate closed-loop supply chain structure for OEMs are created. The assumptions used in this paper may be too broad, however. Of note is the assumption that no distinction exists between new or remanufactured products. Given the large number of uncertainties and varied industries developing appropriate models is extremely difficult. Another approach to forecast returns is given by Toktay et al (2003) (Toktay, van der Laan, & de Brito, 2004). Using data collection on returns Toktay et al. develop a model for forecasting returns. The data from historical sales are used to predict the future product returns, enabling a company to better prepare for inventory and remanufacture. Several methods are developed to accommodate varying time points and product volumes.

Competition also has a large affect on the profitability of remanufacturing, particularly if one considers remanufactured products to cannibalize a company's sales of new products. Ferguson and Toktay focus on this phenomenon (M. E. Ferguson & Toktay, 2006). This paper expands on Desai and Purohit (P. Desai & Purohit, 1998), and investigates the effects remanufacturing has on the sale of new products, a reason many firms have chosen not to remanufacture their products. Ferguson and Toktay develop a model to determine which conditions are necessary for remanufacturing to be profitable, despite the possible loss of sales of new products. Agreeing with Desai and Purohit, it is determined that it is more profitable to enter the remanufactured products market, as this acts as a deterrent for new entrants into the used goods market. Failing to do so may allow third parties to enter the remanufactured goods market, resulting in loss of revenue for the original equipment manufacturer (OEM). Also, the lower cost remanufactured goods can open a secondary market for buyers not willing to pay for full-priced new goods. Perhaps most interesting, Ferguson and Toktay find that "when collection is the major portion of the total remanufacturing fixed and/or variable cost, the OEM is better off remanufacturing." An investigation on the effects of competition on remanufacturing is done by Majumder and Groenevelt (Majumder & Groenevelt, 2001). Numerous scenarios are considered in this paper. The most general results agree with previous work; supporting the argument for remanufacturing as a means of increasing a firms revenue by opening new secondary markets.

Debo et al. discuss the factors that influence the remanufacturing environment, focusing on the managerial importance (Debo, Toktay, & Wassenhove, 2005). Debo et al. continue the discussion of the affect of manufactured goods on the sale of new goods. The term market segmentation is used to describe this. Numerous important factors are taken into account in this model including; consumers preference of new over used goods, market competition and third party remanufacturers, and the OEM’s control over the products design for remanufacture. Several factors were ignored, however, that may increase the profitability of remanufacturing. The goods are assumed to exist through one remanufacturing cycle only, and that the cost to do so is constant over time. With proper designing a good can be made to be reused numerous times and improved technology can make remanufacturing less costly over time as well. Given this analysis the argument for remanufacturing is very strong.

Several hypotheses using a model designed by Thurston et. al to assess the relationship between various lease terms and the economic and environmental impacts (Thurston & de la Torre, 2007). Most significantly, the authors found that longer lease periods “are associated with an improvement in environmental impact,” as well as cost (Thurston & de la Torre, 2007). However, as the lease terms increase, the reliability of products decreases, as would be expected. In support of related research the authors also find that leasing agreements are vital for the manufacturer to control the incoming feedstock.

2.3. Focus on environmental benefits of leasing

In addition to the financial advantages seen with leasing, and the remanufacturing often associated with it, some have argued that leasing is beneficial from an environmental standpoint. Servicizing, as found by the Tellus Institute, often results in three situations that suggest a reduction in environmental impacts: (1) results in internalizing use or disposal costs, (2) is driven by the economic value of the end-of-life good, (3) reconstitutes the product as a cost rather than a profit center (White et al., 1999b).

The first two cases are closely related. With leasing the manufacturer is often responsible for the product disposal, which incurs costs. Additionally, the product may contain valuable materials that also embody energy, labor and capital that went into its construction. This value is lost when a product is simply disposed of. For these reasons, economic incentives exist for a company to try and regain the value of these materials through recycling or remanufacturing, which also has the added benefit of reduced disposal.

As can be seen from the progression of these articles over time, the question of remanufacturing and its implications for the environment have been raised. It was not until fairly recently, however, that this has been thoroughly investigated. The following articles look into leasing and its environmental impacts as a result of changing business practices.

2.3.1. Is Leasing Better for the Environment?

Nasr and Thurston see remanufacturing as a necessary step towards product system sustainability. Although the advantages to recycling are noted as well, remanufacturing is seen as a more efficient means of material recirculation (Nasr & Thurston, 2006). The paper finds three major objectives companies should strive for to become sustainable. These are proposed as laws, and are given as (1) Minimize material and energy resources needed to satisfy product function and consumer demand, (2) Maximize usage of expended resources, (3) Minimize or eliminate the adverse impacts of waste and emissions. Following these laws will naturally lead to a closed-loop material stream and the utilization of reuse, remanufacturing, and recycling. Nasr and Thurston believe that given the limited resources available in the world, sustainable products and business models will gain significant market advantage.

A report by INFORM was compiled to determine if leasing increases resource efficiency, particularly if it meets Europe's extended producer responsibility (EPR) strategy (Fishbein et al., 2000). EPR's goal is to increase producer responsibility by requiring manufacturers to "take back their products when consumers discard them, manage them at their own expense, and meet specified recycling targets." INFORM's report uses personal computers as a case study on the effects of leasing on waste disposal. The report finds that leasing does increase the probability that a company will be responsible for a product at the end of its life, but that this is often limited to the type of product being leased. Also, leasing alone does not meet the EPR guidelines, as doing so does not require a company to offer a take-back program to prevent products from being dumped in landfills. It is determined that design for end of life and remanufacture is economically viable primarily for goods that retain significant material value after it's initial use. In the case of personal computers this is often difficult because of the rate at which equipment becomes obsolete. This characteristic, as with all consumer electronics, may make it seem as though these products are not suited for leasing. However, the report finds that leasing "can result in more rapid return of equipment to product recovery channels, avoiding prolonged equipment storage and increasing resale and reuse opportunities." With computers, different customers have different computing needs. A customer with lower performance needs can be leased cheaper, older equipment recovered from a customer that has higher performance needs. This greatly increases the products life. Once systems no longer meet the performance requirements of any customers the leasing firm can recycle much of the raw materials in computers, and properly dispose of the components that cannot be reused. This makes computers, as well as many consumer electronics, an appealing industry for leasing. Although leasing alone cannot meet stringent guidelines like those set by the EPR, leasing does promote increased product life which can then be furthered encouraged through government incentives and regulations. The report finds, as with many others, designing the products for reuse and remanufacture will also greatly increase the cost effectiveness of leasing.

Similar work by Sharma investigates how leasing goods with short life cycles, such as computers, can still be economical and environmentally beneficial given efficient reverse logistics (Sharma, 2004). Sharma developed a mixed integer linear program to model product flows. Using the model relationships between costs of transportation and disposal are highlighted. In support of the leasing strategy, it is found that rebuilding is a profitable activity. As mentioned in earlier works, this profitability increases as the durability of the product increases. Important insight into the effect environmental legislation has on product flow is also developed. Sharma finds that legislation at the state level to prohibit the disposal of hazardous materials, such as cathode ray tubes (CRTs) is not necessarily effective from an environmental standpoint. This is because waste across state boundaries is not prohibited. Rather than pay significant fees for disposal, firms find it more cost effective to transport their waste to neighboring states with less stringent disposal laws. The end result is that environmental legislation creates gaming behavior in leasing companies, which leased to efficiency losses, as well as negating the environmental improvements the laws set out to create. The conclusion that must be drawn is that uniform legislation across all states is necessary for the laws to be effective.

An extremely simple and generalized method for determining the environmental load that results on company decisions is developed by Goedkoop et al (Goedkoop, van Halen, te Riele, & Rommens, 1999). This paper was commissioned by the Dutch ministries of Environment and Economic Affairs and aims to create a method of determining the environmental load of company and government decisions in a way that is easy enough for large firms to interpret yet broad enough to cover numerous industries. This new tool, called the E2 (Economy-Environment) vector, is graphical way of relating environmental load to economic value. The term ‘product service systems’ is used to describe this combination of economic and environmental business assessment. Two important considerations that are often overlooked despite their obviousness are also discussed by Goedkoop and associates. First, the customers may respond negatively to a shift in services rather than products. Obviously, if customers are not interested in purchasing a service, but prefer the product, there will be little incentive for a firm to lease. Secondly, the paper considers changing behavior patterns. This is an extremely difficult variable in determining environmental impacts best illustrated with an example; suppose a consumer purchases a hybrid vehicle. This is environmentally advantageous because of the lowered emissions and increased gas mileage. However, this decrease in cost may encourage the owner to drive more often, when he/she would normally have walked or taken public transportation. If other hybrid owners follow this trend the end result may be an increase of vehicles on the road, and an increase in congestion, negating any positive effects owning a hybrid vehicle may have had. This is an extremely difficult to predict, but remains an important consideration when developing environmentally conscious business practices.

Mont continues this work on servicizing, here referred to as product service systems (PSS) and focuses on the feasibility of such systems (O. K. Mont, 2002). Mont determines that PSS would reduce the negative impact on the environment, but like many other studies, finds numerous barriers in adopting this across all industries. Successful adoption of PSS would require significant changes in current societal, human, and organizational infrastructure. However, few comprehensive case studies exist to support it. The system may remain viable for certain niche markets or industry, but would require a case-by-case assessment.

Stahel clearly argues that what’s necessary for improved environmental practices is higher resource efficiency, which can only be gained from a servicizing economy (Stahel, 1997). Stahel claims that recycling alone does not “reduce the flow of material and energy through the economy,” and what is really needed is the reduction of resource flow through the economy. Leasing, it is claimed, would effectively close the resource loops and improve resource efficiency. The steps necessary to make organizational changes from a traditional business strategy to one that focuses on leasing is also outlined. Although Xerox is often cited in this article as an example, the article remains purely theoretical, and therefore does not account for market complexities.

The importance of extended producer responsibility and the work of Stahel is expanded by Lowe (Lowe, 2005). Lowe relates the effects of leasing on company business practices and the characteristics of sustainable economic practice. Countries such as Germany, Japan, and China have all set new standards in environmental restrictions which can often put strain on company practices. Lowe argues that by leasing products, and adjusting a company's focus to services rather than goods, the incentives are already in place to meet the increasing environmental restrictions on companies. In other words, the same benefits from increased legislation can be gained, through economic incentives, by companies transitioning to services rather than goods.

The Tellus Institute generated a report that focuses on servicizing and its effects on extended producer responsibility (EPR), as well as drivers and challenges facing companies looking to switch to selling a service rather than a product (White et al., 1999b). The article finds that servicizing does, in theory, promote EPR to varying degrees, which often result in closed material loops. These economic drivers are: internalization of use or disposal costs, recovery of economic value of an en-of-life good, and transformation of the product into a cost rather than a profit center. However, market barriers exist that may prevent firms from successfully transitioning to a servicizing focus, or that a company's products may not be well suited for leasing. The report also finds that leasing does generally reduce material waste, but it is not always the case. Consumers of durable or semi-durable goods tend to expect relatively new equipment, and this can cause the average product age to decrease over time as companies cannot lease older equipment when clients demand newer models for their lease. This could result in faster turnover of products, effectively increasing the number of units that are moved in and out of the market. Unless a used product market exists to absorb the increased number of products, more waste will be generated with leasing.

The effect of these changes in business is that reclamation activities increase, reducing the amount of material extracted and disposed of over the lifecycle of a product. Nasr and Thurston outline three “laws” necessary to achieve sustainability: (1) Minimize material and energy resources, (2) maximize usage of expended resources, and (3) minimize or eliminate the adverse impacts of waste and emissions (Nasr & Thurston, 2006). The significance of following these rules in hopes of achieving sustainability is that they inherently close the material loop, implying that sustainability and remanufacturing are connected. An illustration of the closed loop material flow that would result by following these laws is seen in **Figure 6**. Where once a product has been used it can be reused, remanufactured, or recycled. Remanufacturing is typically a more efficient means of material recirculation than recycling, and reuse is more energy and resource efficient than remanufacturing (Nasr & Thurston, 2006). Each of these processes carries with it various complications and environmental burdens of their own, however. The general consensus is that these burdens are small compared to raw resource extraction. Nasr and Thurston believe that companies that adopt sustainable products and business models “will gain a significant market advantage” (Nasr & Thurston, 2006).

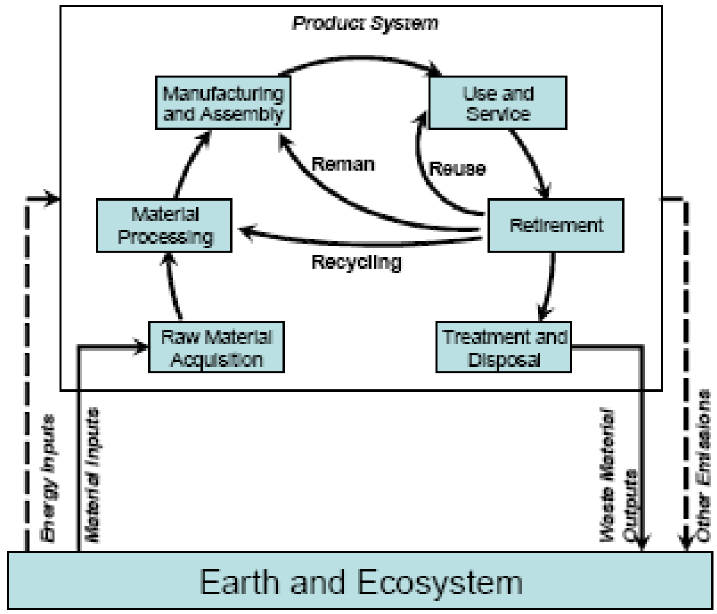

Figure 6. The Closed loop material flow (Debo et al., 2005)

The argument can then be made that under leasing the ownership of a product at the end of a product's lease term remains an asset to the OEM, whom is now responsible for its disposal, creating a closed-loop life cycle of the product (Fishbein et al., 2000; O. K. Mont, 2002). OEMs therefore have an incentive to recover the end-of-life value from its products, usually with refurbishing or remanufacturing a product and leasing it again. Research has shown that the probability of equipment being reused, remanufactured, or recycled is greater if it is returned to the manufacturer at the end of life (Fishbein et al., 2000). Throwing a product away would simply be throwing valuable materials and parts away. Because of this diversion away from landfills and reduced reliance on raw materials, it is believed that leasing may result in fewer tons of discarded material in the world's landfills.

An article by Agrawal et al. develops a model to investigate the optimal recovery and disposition strategy for a firm under leasing and selling. The model draws several connections between leasing and the environment. Although it finds that choosing to sell rather than lease does not necessarily indicate a greater environmental burden, it does find that "in the cases where the firm prefers to lease, we find that the environmental impact is always lower than or equal to that under selling" (Agrawal, Ferguson, Thomas, & Toktay, 2007). The article finds that when salvage values of products may be profitable, leasing is always more profitable than selling because the firm does not need to persuade customers to return the used goods.

2.3.2. Roadblocks to Leasing for the Environment

The Tellus Institute report also has some contradictions that undermine many of the arguments it attempts to make. A point is made about use-related environmental impacts, which can significantly be reduced with product design, increased turnover, and operations enhancement. Increased product efficiency has the obvious environmental benefits. But, this has a tendency to encourage businesses to rotate their models more frequently, to have access the latest technology (White et al., 1999b). When leasing durable goods, customers expect relatively new items. Increasing turnover rate gives a lessee more opportunities to pull outdated equipment out of the loop and replace it with newer, more efficient models. This trend reduces the average age of a product in service. Production and remanufacturing operations are increased, resulting in greater energy and resource usage. The argument made here essentially claims that rapid turn-over is advantageous when considering product efficiency improvement, but this also means a reduction in product life times, and a shorter life-cycle. This is an obvious disadvantage when concerned with sustainability because it increases consumption of limited resources, even though more efficient products are being produced. The resulting contradiction has not been thoroughly studied, and numerous arguments for either side have been made in literature without an in-depth investigation. Performing a quantitative analysis of this and expanding on the theoretical research that has been done is a primary goal of this thesis.

There are other factors affecting product life-spans as well, as noted by Fishbein et al. Current US tax regulations for operating leases require a maximum lease term of 75% of the product's expected lifetime, and in addition to energy consumption for recycling or refurbishing materials and products, can affect the overall environmental impact of leasing a product. The present value of the lease payments must also be less than 90% of the fair market value of the product (Fishbein et al., 2000). The law is designed to protect lessees from being leased over-used and damaged goods, but this also prevents a leased product from being utilized for its complete life cycle in a single lease term. Goods are essentially returned to the manufacturer prematurely. Even if a company recycles or remanufactures its product, it would do so at a greater rate than if only take-back incentives were offered at the end of a product's full life. Leasing in this case effectively shortens a products life-cycle.

In a study focusing on the US metals sector, Ruth finds that the numerous variables involved in industry can make it very difficult to determine energy usage and efficiency, and that these factors often negate any foreseen advantages (Ruth, 1998). Many metals have seen reduced production over the years, a result of increased metal recycling and from alternatives to metals, such as plastics and ceramics. The overall reduced production result is significant reductions in CO_2 emissions, but only within the steel industry. The introduction of plastic or ceramic competition could easily outweigh any benefits from reduced metal production (Ruth, 1998). Ruth notes this is just one of many variables that can affect what, on the surface, appears to be a straightforward measurement. New technologies, new production methods, and new competition can all offset any industry improvements when measured on a global scale.

Fishbein et al. expand on the dangers of over-generalizing the benefits of leasing across industries. The leasing infrastructure in place varies between industries and businesses. Some original equipment manufacturers (OEMs) may sell their products to independent leasing companies. If this is the case, then when a product's lease has ended, it will not return to the manufacturer. Leased products, upon termination of their leases, may also be sold to secondary markets, preventing the return of the product to the manufacturer (Fishbein et al., 2000).

Desai and Purohit found that a company would only lease all its products if it were a monopoly, but in cases where competition is involved it is detrimental to rely on leasing alone (P. S. Desai & Purohit, 1999). This is because a pure leasing strategy leaves room for competition in a market.

Agrawal et al. also discuss how companies may respond with the introduction of leased products to the market. Offering used products to consumers may be lucrative to leasing firms as consumers who cannot afford new products may be able to purchase a used or remanufactured product. But, doing so would compete with the manufacturer's new products, essentially cannibalizing the new equipment market. As a result, firms may be motivated to remove used equipment prematurely from the market, increasing the volume of product disposal rather than reducing it (Agrawal et al., 2007).

The validity of the “Leasing is Green” argument is investigated by (Agrawal et al., 2009). For a variety of conditions under which leasing can be environmentally superior and profitable or where selling may benefit both dimensions. This paper also includes disposal costs, an important factor financially as landfill costs continue to increase and is often overlooked by other works. Several comparisons are made for both profitability and environmental impact of leasing versus selling, which various results. The main drivers for profitability and environmental impact are found to be the magnitude of disposal cost, the differential in the disposal costs faced by the firm and consumers, and the environmental impact profile of the product. The primary results found by this work are; (1) leasing may be less green than selling despite full remarketing and green despite premature disposal, (2) selling may be more profitable and even a win-win for high non-use impact products, (3) leasing may be more profitable but less green by driving up volumes, (4) leasing can be a win-win choice for high use-impact products and, (5) leasing is hard to sell.

It is clear that the effects leasing has from an environmental standpoint needs further investigation. Although some research has been done on the connection between leasing and environmental impacts, the studies remain strictly theoretical and limited. Many claims of the benefits to the environment are based solely on anecdotal data, and the concerns that are raised complicate the issue.

2.4. Product Characteristics to Benefit Leasing

Kumar and Putnam develop a thorough study of the difficulties and opportunities in closing the supply loop across three industry sectors (automotive, consumer appliances and electronic), and investigate if lessons learned in one sector are transferable to others (Kumar & Putnam, 2008). The authors site both external regulations and increasingly scarce resources as the primary motivators for industries to attempt and close the material loops. Kumar and Putnam find results along the same lines and Webster and Mitra, finding regulations like the WEEE can be successfully followed if industries adjust appropriately.

The authors make the important note that the design stage of products is the most important stage where remanufacturing and environmental progress can be made. Unfortunately, industry has traditionally not taken a systems approach to integrating environmental management, but doing so can make significant improvements (Kumar & Putnam, 2008). The conclusion found by the authors is given the complexities of industry sectors they are rarely similar. Few models that have been developed are transferable across numerous industries for end-of-life studies. It is concluded that many appealing models exist, but no model is broad enough to support numerous industries, and each industry may be required to develop its own model unique to the industry's characteristics.

2.4.1. Determining when Leasing Can/Should Be Done.

The optimal end-of-life strategy for dealing with products is dependent on numerous characteristics of the item in question. Some items are durable enough to be reused with only minimal refurbishing, while other products may require significant remanufacturing and updating. Remanufacturing may be impractical altogether, and recycling is the best possible option. Understanding how aspects of a product's design and composition effect the end-of-life processing is important to determining leasing opportunities as well. Leasing may be viable with remanufacturing, but not with recycling. Or, a certain category of products may be very well suited to leasing only when recycling it utilized. The impact to the environment is related to the processes chosen, and it is therefore important for manufacturers to choose the proper end-of-life options for leased products. Design for environment is the common terminology used to describe the process of developing new products while using its desired end-of-life processing as a design constraint.

Rose et al. perform a survey of consumer products and use case studies to determine the common end-of-life processes used in the industry based on product characteristics (Rose, Ishii, & Masui, 1998). This paper divides the numerous product characteristics into four main factors; external factors (such as wear-out life and technology cycle), material factors, disassembly factors, and inverse supply chain factors. Rose et al. are able to break down these factors and determine what characteristics facilitate either reuse, remanufacturing, or recycling, as shown in Table 2.

Table 2. Characteristics for End-Of-Life Processes (V. M. Smith & Keoleian, 2004)

Reuse	Remanufacture	Recycle
Short Wear-out Life	Long Wear-out Life	Long Wear-out Life
Short Technology Cycle	Short Technology Cycle	Long Technology Cycle
Easy separation of components	Easy separation of components	Low separation of components
Moderate number of common materials	Moderate number of common materials	High number of common materials
High Modularity	High Modularity	Moderate Modularity

Rose et al. (2009) follow this with continuing work to develop an on-line design tool for determining the feasibility of end-of-life strategies based upon significant product characteristics (Rose, Beiter, & Ishii, 1999). Rose et al. (2002) expand their survey of case studies in yet another paper to further improve the design tool (Rose, Ishii, & Stevels, 2002).

Numerous other works have been carried out to determine how product characteristics affect end-of-life strategies. Mangun and Thurston develop a model for a decision tool to aid in determining when a product should be taken back, and if it should be reused, remanufactured or recycled (Mangun & Thurston, 2002). This approach highlights the importance of considering the products disposal process in the early design stages. Sundin and Bras also emphasize the importance of design for environment and remanufacturing (Sundin & Bras, 2005). The study concentrated on remanufacturing facilities for household appliances and automotive parts. Looking into greater detail than the previous works mentioned, the paper examines specific factors in the product and processes, such as ease of separation. These factors play a large role in the economics of remanufacturing, as well the difficulty in implementing a recovery strategy. The major factors in ease of remanufacturability were found to be ease of access, ease of handling, ease of separation, and wear resistance (Sundin & Bras, 2005).

There is little work drawing a connection between remanufacturing and leasing, and therefore no studies have been done to connect product characteristics that are advantageous for leasing and specific EOL scenarios. The final goal of this thesis will be to provide a basic framework to determine what conditions are necessary for leasing and

EOL processes to minimize environmental impacts depending on several basic product characteristics.

2.4.2. Existing Case Studies

A variety of case studies have been performed relating to the work in this thesis. The majority of case studies summarized here focus on performing life cycle optimizations on household appliances. Other case studies focus on vehicle engines and computers.

2.4.2.1. Carpet

Olivia and Quinn summarize the history of Interface's attempt to lease carpeting using the Evergreen Services Agreement (Oliva & Quinn, 2003). This report for the Harvard Business School recounts Interface's attempts to promote leasing of carpet and reasons for its unpopularity. Caroline Guidry developed a LCA for carpet recover and recycling based on Interface's model primarily for broadloom carpets (Guidry, 2008). This work found that recycling significantly reduces overall emissions compared to manufacturing. However, the analysis does not include newer recycling methods developed for processing nylon 6,6 face fibers of modular carpet tiles. The life cycle inventory values from this report provide much of the data for a similar LCA provided in this thesis.

2.4.2.2. Refrigerators

Kim et al. calculated the optimal replacement policy for refrigerators based on historic data and future forecasts for efficiency improvements ranging from 0% to 2% (Kim, Keoleian, & Horie, 2006). Findings from this paper are also supported by Horie's thesis work (Horie, 2004). Rudenauer and Gensch perform similar assessments on various types of refrigerators (Rudenauer & Gensch, 2005b). In these works the replacement intervals vary because the rate of efficiency improvements slows dramatically during the course of the period examined. Not surprisingly, the rate at which refrigerators should be replaced depends on the rate at which efficiency gains are made, and no single life span is optimum. Analysis on optimum replacement cycles for minimizing cost and other emissions are also studied. In all studies the replaced refrigerator is recycled.

2.4.2.3. Clothes Washers

A life cycle optimization on clothes washers is performed by Rudenauer and Gensch (Rudenauer & Gensch, 2005a). Numerous variables are found to complicate the analyses such as water temperature, spin cycle, and load size. Recycling is considered the only EOL process. In general five years was found to be the optimal time period between purchases of new machines. Factors other than energy were also examined including global warming potential and cost.

2.4.2.4. Dishwashers

Chalkley et al. develop a simplified method to find the optimum life span from energy consumption data (Chalkley, Billett, Harrison, & Simpson, 2003). Because the rate of improvements is not consistent, the length a dishwasher should be kept in service depends on the year it was purchased. The appliance is assumed to be landfilled after use, with no resulting energy consumption. In general, however, 8.1 years was found to be the optimum replacement cycle.

2.4.2.5. Automobiles and Engines

Smith and Keoleian develop an LCA on restoring an automotive engine to like-new condition, finding that significant resource savings can be made (V. M. Smith & Keoleian, 2004). If remanufacturing improves fuel efficiency by 1%, the life-cycle energy savings can be doubled. This paper finds strong support for the remanufacturing process of internal combustion engines, both from an environmental and economic standpoint. Remanufacturing reduces the use of all resources, from energy to chemicals, and of course reduces material consumption and landfill waste. An economic savings of 30% to 53% can also be realized. The model used by Smith et al. was modeled after a typical machine shop facility. Facilities such as the one used to build the model have fairly low remanufacturing volume and further investigation is necessary to determine if the savings determined in this paper can scale up to mass-remanufactured volumes.

This work is continued with a case study of complete automobiles by Kim et al (Kim, Keoleian, Grande, & Bean, 2003). The paper examines the validity of vehicle scrappage programs aimed at removing older, less efficient vehicles from the road. Several minimization objectives are studied with 18 years found to be the optimum vehicle lifetime when minimizing energy and driving less than 12,000 miles a year. These findings are also in agreement with a paper by Spitzley et al (Spitzley, Grande, Keoleian, & Kim, 2005).

Kim et al. expand these findings to perform an analysis on fleet vehicle replacement (Kim, Ross, & Keoleian, 2004). The optimum replacement intervals are complicated by varying regulations, and may differ greatly depending on what is being minimized. Accelerated scrapping may reduce regulated emissions, but at the expense of slightly higher greenhouse gas emissions.

2.4.2.6. Computers

The computer industry presents another challenging supply-chain scenario, and with such large volume and short product life time the environmental impact is huge. Rosen et al. look at the economic characteristics that influence how a firm leases computers with a focus on transaction cost economics (TCE) (Rosen, Bercovitz, & Beckman, 2001). TCE is used to explain “how buyers and sellers govern their economic transactions with one another.” This paper addresses many important issues, but offers few concrete explanations as to the cause-relation of environmental decision making.

Choi et al. produce a thorough LCA with the help of Simapro and data collected from Korean national database (Choi, Shin, & Hur, 2006). Simapro produces numerous metrics, but for simplicity this work focuses only on energy consumption. Therefore, the results found by Choi et al. are not necessarily comparable to the work here. Similar to numerous other works, design for environment is found to be a vital step when attempting to reduce product impacts. Perhaps most interesting, Choi et al. find that 46% of computer components can be recycled. Although one may intuitively assume that recycling more is better for the environment, Choi et al. find this not to be true. Given the intense energy and chemical requirements to recycle many computer components, it is actually more detrimental to the environment to attempt to recycle 100% of the computer with current technology.

Neto and Bloemhof focus on computer remanufacturing in terms of both environmental impact and economic viability (Neto & Bloemhof, 2009). The study uses cumulative energy demand (CED) as its metric. The paper claims remanufacturing to be an effective way to reduce energy consumption during a computer's life cycle, but does not define what processes are involved in remanufacturing. It is assumed that remanufacturing computers is equivalent to refurbishing or upgrading; replacing outdated or failed components with new hardware.

Kiatkittipong et al. develop a simple mathematical model for determining when it is environmentally beneficial to purchase new electronics equipment (Kiatkittipong, Wongsuchoto, Meevasana, & Pavasant, 2008). Specifically, the study compares the use of an existing CRT monitor to the purchase of a new LCD. The paper notes the important relationship between usage energy and life span and how that can affect replacement strategies.

Thurston and de la Torre take the concept of remanufacturing and closed loops and combine it with leasing specifically focused on computer components (Thurston & de la Torre, 2007). A constrained optimization model for product design that considers leasing programs and their impact on cost, reliability and environmental impact is thoroughly developed. Several interesting results are obtained by this analysis.

1. The longer the lease period, the lower the annual cost for each market segment and for each life cycle
2. The longer lease periods are associated with an improvement in environmental impact and a worsening in reliability.

3. Longer lease periods are associated with improvements in cost and environmental impact.

2.5. Background Summary

It is clear at this point that significant research has been done both on the motivations for leasing and the resulting impacts on business practices and associated environmental impacts. Additionally, it should now be clear that work remains to be done in understanding under what conditions leasing may actually benefit the environment, if at all. The contradictions reported in works by the numerous others including the Tellus Institute, Agrawal et al., and Fishbein et al, clearly expose an area where a more in-depth study is needed. Work done by Rose et al, Mangun and Thurston, and Sundin and Bras on connecting how product characteristics affect end-of-life processes has been more thoroughly studied, but has not been connected with leasing.

These areas of uncertainty are the primary motivator for the goals of this research outlined in chapter 1. The issues outlined in section 2.3.2 (Roadblocks to Leasing for the Environment) are obvious areas lacking thorough analysis, but no systematic model or case study has been done to study how well founded these arguments are. The case study modeling outlined in Chapter 3 and performed in Chapters 4 through 6 will provide some quantitative analysis to the issues found with leasing and product life cycles. These case studies will also provide a context to which the product characteristics can be connected the impact and motivation for leasing.

3. Methodology

3.1. Research Methods

Given the complexities in real-world situations it is suggested that a mix of research and modeling methods are needed (Perry, Riege, & Brown, 1998). Adding to the difficulty is the immaturity of the research field. Drawing a connection between the environment and leasing is a new and evolving research field, and because leasing occurs at the proprietary level, data is difficult to obtain. For these reasons this research examines leasing and its impact from various angles.

The literature survey provided an explanation for the ‘leasing is green’ concept. Leasing internalizes costs to OEMs, motivating them to recover value from their products after use which leads to recycling or remanufacturing. This seemingly simple concept is complicated by many factors, such as tax regulations and product characteristics. Section 1.6 posed the major questions focused on in this thesis. Questions 1 and 2 are primarily concerned with shortened life spans resulting in increased product turnover and production volumes. Question 3 aims to find a connection between product characteristics, leasing, and reduced environmental impacts. Literature exists on connecting product characteristics to remanufacturing, but leasing has not yet been included in this relationship.

Questions 1 and 2 can best be answered by performing life cycle optimizations (LCO). Life cycle optimization is a calculation method to determine replacement intervals while accounting for technology improvements of new models and impact factors from all stages of a products life. If LCO results indicate shorter life spans than are currently practiced by consumers it is clear that increased product turn over could be environmentally beneficial. If the results indicate longer life spans than are common, it's obvious products should be replaced less often.

Question 3 is investigated using several techniques. Life cycle analyses (LCA) take into consideration all aspects of a product's life from obtaining raw materials, manufacturing, use and disposal. LCAs are used in this research to determine impacts of new recovery efforts with closed material loops of carpet recovery efforts. This can be used to answer question 3 by gaining a better understanding of how products characteristics relate to environmental impact.

Several scenario analyses are also used to better understand the connection between leasing, product characteristics and environmental impacts. Scenario analysis is a process of analyzing possible results by considering alternative possible outcomes. This will be used to pose several 'what if' cases to better understand how factors such as maintenance or product energy consumption impact environmental factors.

Combing the knowledge gained in the literature survey with the case studies utilizing the techniques mentioned will provide a more complete picture of the leasing for the environment argument with real-world conditions. Using the diverse techniques described with a variety of products, it is hoped that more linkages can be drawn between what characteristics products exhibit and how the can be beneficial or detrimental to leasing and reducing environmental impacts.

Ideally, a decision model can be obtained to help aid manufacturers determine if leasing can be successfully used to reduce environmental impact on products based on a small number of vital characteristics. Although a nearly infinite number of products exist, it is not necessary to do a thorough evaluation of each. All products share a few significant characteristics, and these will be the focus of the studies to determine if and how they impact the viability of leasing in conjunction with a variety of end-of-life processes. Determining which specific characteristics are important factors in the success of leasing while reducing environmental impacts is a primary goal of this research.

The case studies used in this research were chosen based on availability of data and diversity of product characteristics. The case studies chosen were modular carpet tile, white goods, vehicles, and computers.

3.1.1. Carpet – LCA

Modular carpet tile presents an interesting case study because leasing has been attempted in the industry as a way to reduce environmental impacts. Interface created the Evergreen Services Agreement (ESA) attempting to lease carpet, which included a maintenance service, rather than the traditional business model. The concept was touted as a ‘green’ business transaction. However, given the shorter life cycle of the carpets under leasing and the difficulties in recycling the carpet material, the benefits are not clear. An LCA is used to determine the full environmental impacts of the carpet based on a variety of possible life cycles and end-of-life scenarios.

Much of the work done on the carpet LCA here is a continuation of the work by Caroline Guidry. Guidry performed an LCA on various carpet types and end-of-life processes. However, Interface has recently developed a more efficient recycling process and has reassessed their leasing scenario. The LCA conducted here aims to update previous work done with a recently developed process for recycling nylon 6,6. The LCA standards are based on those set by the International Organization for Standardization

(ISO) in the ISO 14040 series (ISO14040, 2006). The affects of leasing or selling scenarios can then be assessed using these results.

As part of the lease agreement, carpet maintenance would be included as part of the operating lease. Carpet maintenance is modeled in a scenario analysis to calculate where the possible break-even points may be between extended carpet life and offsetting maintenance emissions. This will offer insight to the impact of product maintenance and how product life-cycle energy usage relates to this.

3.1.2. Consumer Goods – Life Cycle Optimization

White goods and vehicles, unlike carpet, have the significant characteristic of high usage-energy, meaning they consume significant amounts of energy during the usage phase of their life. This increases their environmental impact, but also offers more opportunities to reduce energy. Life cycle optimization (LCO) finds the replacement intervals that minimize energy usage based on the efficiency improvement trends of new product models. This will address the issues of increased product turn over that may result from leasing. Life cycle optimizations are performed on several common consumer products, but unlike previous LCOs, remanufacturing is included in place of manufacturing for comparison purposes. Remanufacturing is significant because, as shown in chapter 2, it is a result of the closed material loop that is often created with leases.

3.1.3. Consumer Electronics / Computers

Consumer electronics offer an interesting contrast to the other products discussed thus far. These products have a large usage phase similar to appliances, but their life cycles are much shorter due to rapidly advancing technology and consumer preference. As a result, the vast majority of the life cycle energy use comes during manufacturing rather than use. This combined with a rapid technological obsolescence makes for a difficult combination of product characteristics to deal with when considering leasing.

Desktop computers are the primary focus of this case study. Scenario analyses are used to pose several what if cases to determine what conditions are necessary for computers to benefit from LCO or remanufacturing and recycling and investigate if these conditions can be reasonably obtained with leasing. It will be determined what efficiency improvements are necessary to offset manufacturing energies when a computer is replaced.

3.1.4. Terminology

A variety of terminology is used in relating research. For clarity some of the commonly used terms are defined here.

3.1.4.1.Manufacturing

Manufacturing is the process of producing a material good. The boundaries of what constitutes manufacturing can very between literature, but unless otherwise stated here it will include all processes starting with mining raw materials to the final product leaving the factory.

3.1.4.2.Remanufacturing

Remanufacturing is often times confused with other product recovery processes such as reconditioning or refurbishment. The act of remanufacturing is based on the process utilized. Gray and Charter concisely define remanufacture as “recapturing the value added to the material when a product was first manufactured" (Gray & Charter, 2008). At the very least remanufactured equipment should meet the performance specifications of the OEM. Most remanufactured products contain a 'core' which is used to describe the component or product that is retained through the remanufacturing process. The core is usually highly durable with other components of the products being replaced around it, replacing the pistons while reusing the engine block being for example. This also provides the opportunity to upgrade vital components that are still compatible with basic core, increasing the value of the product beyond its original manufacturing specifications. This is an important aspect of remanufacturing that will be discussed to a much greater extent later in this thesis.

Two major forms of remanufacturing firms exist; third-party remanufacturers and OEM remanufacturers. Third-party remanufacturers, also known as independent remanufacturers, do not manufacture the original product. Remanufactured products are usually sold to replacement parts stores or are contracted by OEMs to remanufacture replacement parts and act as suppliers for OEMs who sell remanufactured items through their existing dealer networks (Bras, 2007). This paper is concerned only with OEM remanufacturers. OEMs possess detailed knowledge about their products often putting them at an advantage over third-party firms. Using OEM remanufacturers in this paper will simply scenarios as material return streams can be demonstrated with a single return stream rather than to potentially complex third-party organizations. OEMs are also positioned to design products for intended remanufacturing and shift to a service focus business model claimed to be motivated with leasing (Bras, 2007).

3.1.4.3.Recycling

Recycling returns a product to raw material form which can be used again in the manufacturing process. No part of the product is retained in its manufactured form.

3.1.4.4.Maintenance & Repair

If a product is broken repair is used to make it operational again. The primary goal of maintenance is to ensure a product remains operational and is usually used as a preventative measure for failure. Often times maintenance replaces components that are known to wear out, such as bearings or transmission oil. The goal is continued use and therefore the product may not perform like a new product, and components are not upgraded with new technology.

3.1.4.5.Disposal

Disposal in the context of this paper refers primarily to landfill disposal. Aside from transportation, landfilling is assumed to have no further energy usage or emissions. Depending on the material properties of a product there is always the potential for toxins to seep out of landfills or gases to be emitted during decomposition, but due to the difficulty to measure these values and the primary focus in this paper on energy consumption these situations are not focused on.

4. Carpets Case Study

Interface, the LaGrange, Georgia based textile company, has made numerous strides to reduce their environmental impacts and improve sustainability. In 1995 Interface debuted their Evergreen Service Agreement (ESA) (Oliva & Quinn, 2003). Rather than simply selling carpet, ESA was meant to be a shift to providing long-term flooring services. This transition, often called servicizing, is aimed to closing the material loop and minimize material flowing into landfills (Eades & Marston, 2002). The primary motivation for this move was Interface's push to recycle carpet. Leasing was seen as a reliable means to retrieve used product at its end-of-life and be recycled into new carpet, avoiding landfill disposal. Unfortunately, slow sales resulted in Interface canceling the service and abandoning the ESA. Despite this failing, Interface has continued to advance their recycling capabilities in hopes of achieving improved sustainability.

Interface's carpet tile face fibers are made from nylon 6,6; an extremely durable material but also very difficult to recycle. The only material that could be recovered from the tile during the ESA trial was the PVC backing, which could be reused to make new tile backing using a series of processes licensed by Interface as 'Cool Blue'. The nylon face fibers contained significant contaminants making recycling difficult and was discarded. Over the last several years Interface has developed new technology to successfully recover the nylon with minimal contaminates, allowing much easier recycling into new carpet fibers. This process, given its recent development, has not been fully investigated to determine the environmental impacts that results from the additional processing steps. Regardless, Interface is touting its new technology as a significant step towards sustainability.

4.1. Goal

In this chapter an LCA will be performed on modular carpet tile through a variety of end-of-life processes, including a process meant to approximate the new nylon 6,6 recycling procedure developed by Interface. A standard linear material flow with carpet ending in a landfill will be equivalent to the standard business model for carpet sales. A scenario that includes material recovery will be equivalent to the intended outcome for the ESA lease agreement. This will determine if environmental benefits exist under this recovery situation. The low durability of carpet material and the inability for carpet to be remanufactured add to complications with a leasing case, and the unsuccessful outcome of the ESA lease will be discussed in relation to the viability of leasing with similar products.

For the LCA this paper will first look at the end-of-life (EOL) options for used carpet tiles. This involves transportation, landfilling, and recycling of the primary carpet materials. The paper will then examine carpet maintenance and the impacts of vacuuming and cleaning the carpet.

4.2. Scope

A comparative assessment is conducted from the perspective of a carpet manufacturer who assumes the responsibility of post-consumer carpet (PCC) tile collection, processing, and disposal of all materials. Much of the LCI data was collected for work conducted by Caroline Guidry (Guidry, 2008). The functional unit is a kilogram of PCC-tile. The scenarios examined in this study are outlined in **Table 3**.

Table 3. Scenarios Examined in Study

Scenarios	Component	Process
Case 1	Nylon	Disposed - Replaced with new material
	PVC	Disposed - Replaced with new material
	Filler	Disposed - Replaced with new material
Case 2	Nylon	Disposed - Replaced with new material
	PVC	100% of material is recycled
	Filler	Disposed - Replaced with new material
Case 3	Nylon	100% of material is recycled
	PVC	100% of material is recycled
	Filler	Disposed - Replaced with new material
Case 4	Nylon	75% Recycled, 25% New material
	PVC	85% Recycled, 15% New material
	Filler	Disposed - Replaced with new material

The first scenario is the most common case where material is simply dumped in a landfill after being removed from a building, as illustrated in Figure 7.

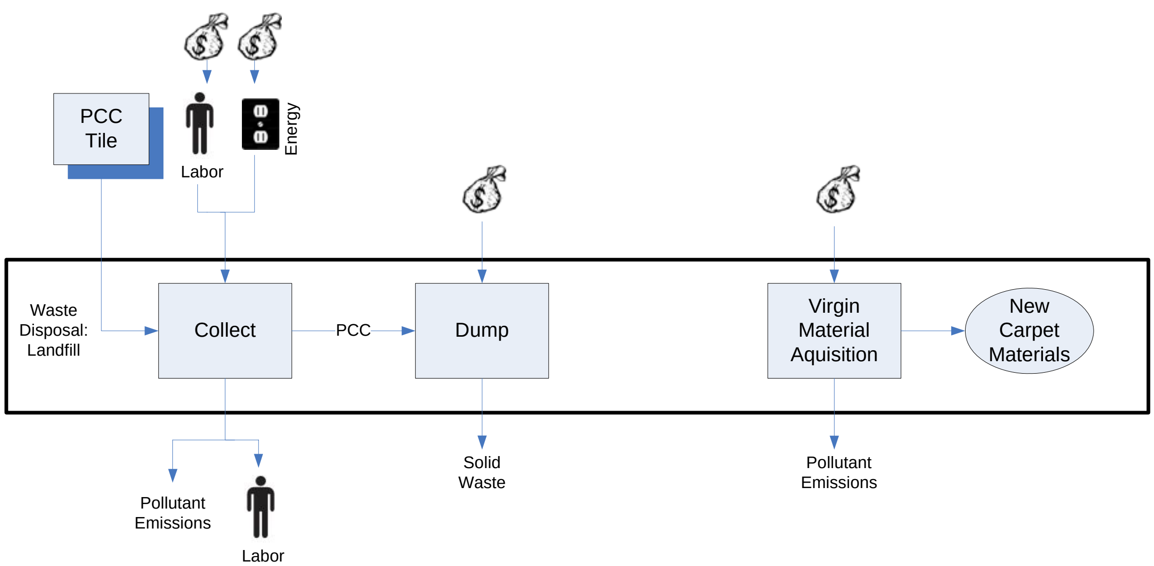

Figure 7. PCC-tile Direct to Landfill Disposal

In the second case the PCC-tile is recovered and brought to the LaGrange recycling facility. A series of mechanical operations are performed to separate the nylon and PVC and remove contaminants and other materials found in the carpet's construction. The PVC material is then pelletized and returned to the manufacturing facility to be used in new carpet backing. The nylon face fibers are disposed of in a landfill. This is the current process that Interface is using with much of its product, illustrated in Figure 8.

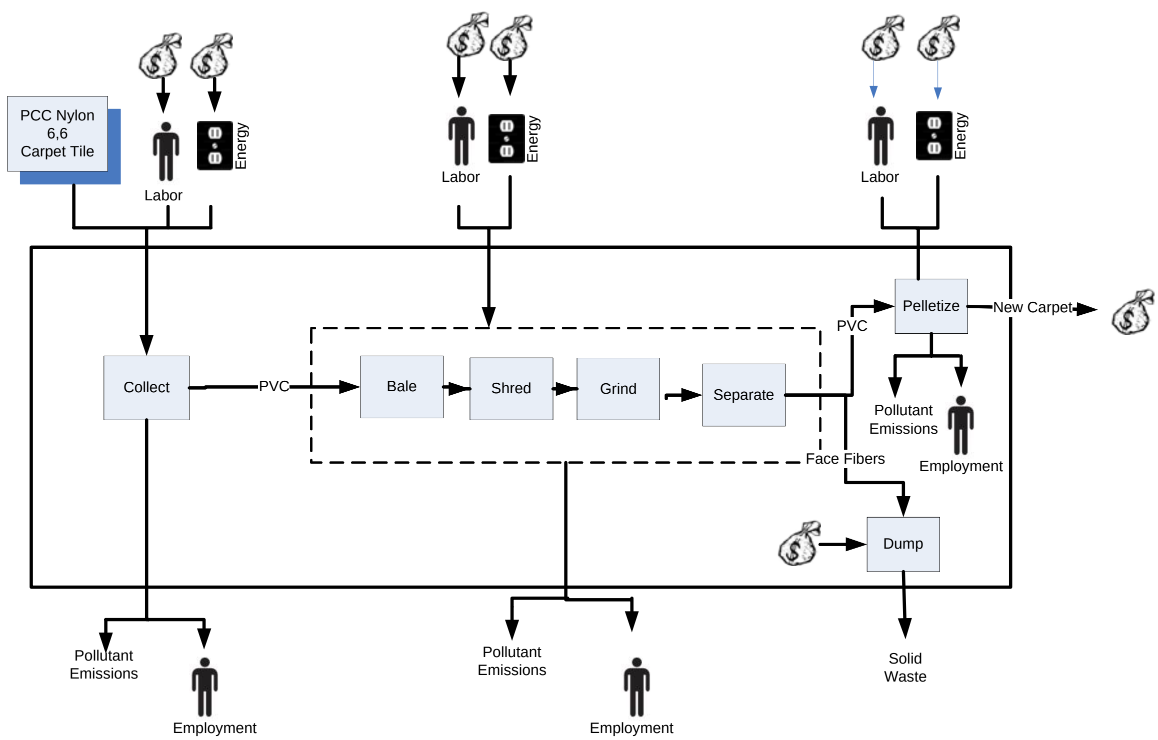

Figure 8. PCC-tile Collection and PVC Recycling

The third case examines what Interface hopes to integrate in the near future. PCC-tile is again collected and transported to the LaGrange facility. The PVC and nylon materials are separated first. The backing then undergoes a similar process used in the second scenario. The nylon, rather than being dumped, is processed and recycled into nylon thread to be used in new carpet, as shown in Figure 9.

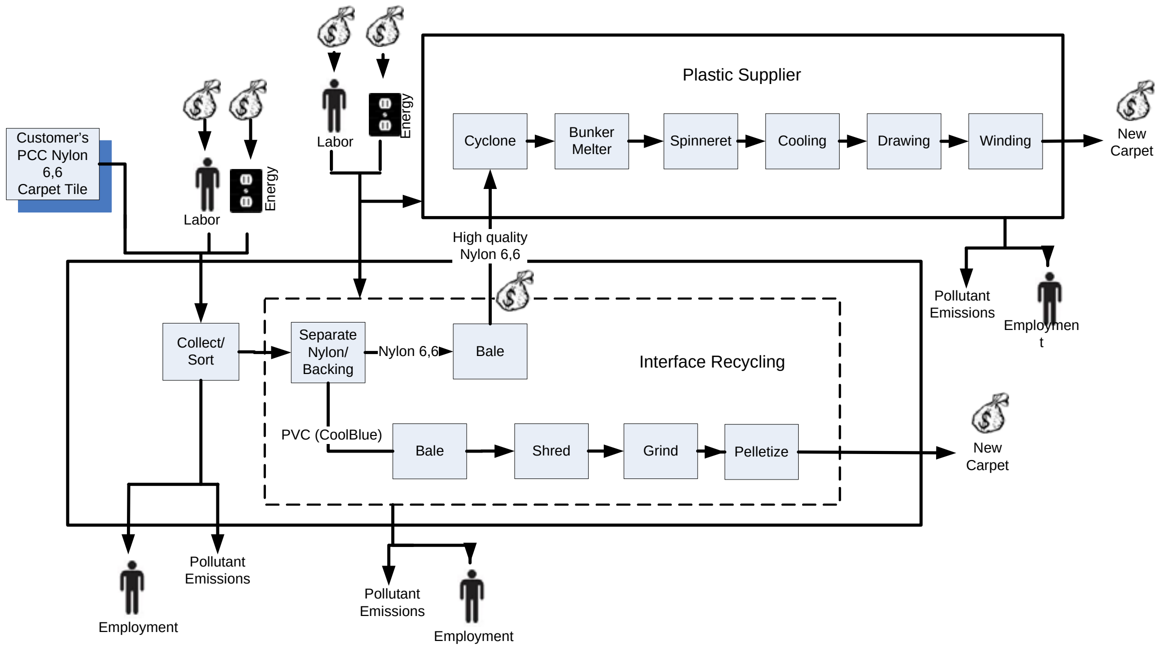

Figure 9. PCC-tile Collection and Recycling

Case 4 is identical with the system illustrated in Figure 9 except that virgin material is added to the recycled material as well, resulting in slightly higher environmental impacts that will be shown in detail later in this study. This is the scenario Interface intends to use with its new nylon recycling technology.

4.3. Impact Categories

4.3.1. Energy Usage

There are numerous metrics which can be used to assess environmental impacts. Unfortunately, many of these metrics are difficult and time consuming to determine. One aspect that can fairly easily be investigated in all cases is energy consumption. With the exception of manual labor just about every manufacturing process requires energy, and each topic in this study has energy values. Although in the carpet case pollutant emissions will primarily be focused on due to their availability in this case, energy values will also be given for easier comparison with the other studies in this thesis.

4.3.2. Pollutant Emissions

Pollutants fall under three categories: Greenhouse gases, criteria pollutants, and additional pollutants.

4.3.3. Solid Waste

Solid waste specifically refers to PCC-tile that is landfilled. This material is limited to the material contained in the PCC-tiles, primarily nylon or PVC, but also additional fillers such as calcium carbonate.

4.4. Product Inventory Estimates

The PCC-tile estimates are based on county populations for the thirteen counties comprising the Atlanta metropolitan region. Based on a ten year life span for carpet, the Carpet and Rug Institute estimates approximately 21 to 31 pounds (9.5kg – 14.1kg) of carpet per person in the Atlanta region ("CRI," 2009). Approximately 10% of carpet is of the tile variety studied here. Therefore, the annual availability of PCC-tile is 4.3 million to 5.2 million kilograms (Guidry, 2008). In this study, an average value of 4.8 million kilograms is used in calculations.

The amount of PCC-tile that is available and will be recovered from specific regions is proportionally related to population. **Table 4** lists the total kilograms of carpet that is assumed to exist in each county based on population.

Table 4. Carpet Tile Inventory by County (Guidry, 2008)

County	10kg/person/year	14kg/person/year	Average
Cherokee	135,169	199,535	167351.9
Clayton	225,293	332,575	278934
Cobb	578,910	854,581	716745.2
Coweta	84,981	125,449	105214.85
DeKalb	634,266	936,297	785281.35
Douglass	877,999	129,609	503804
Fayette	86,932	128,328	107630.1
Forsyth	93,737	138,576	116156.35
Fulton	777,282	1,147,416	962348.65
Gwinnett	560,523	827,438	693980.35
Henry	113,678	167,810	140743.65
Paulding	77,802	114,850	96326.15
Rockdale	66,784	98,586	82684.7

4.5. Carpet Tile basics

There are two major categories of carpet; broadloom and modular or carpet tile. Broadloom carpet is what’s most commonly found in households, and is produced in large rolls to be custom cut to fit in rooms. Carpet tile, or modular carpet, is most commonly found in commercial buildings and is the focus of this study. Carpet tile, unlike broadloom, is manufactured into evenly sized square sections and laid down much like tiles. It also has a much shorter face fiber making it more durable and able to withstand heavy traffic.

The most common manufacturing method for commercial carpet is tufting. Tufting uses specialized multi-needle sewing machines to stitch hundreds of rows of pile yarn tufts through a primary backing ("CRI," 2009). The needles push yarn through the primary backing fabric, where a loop holds the yarn in place to form a tuft as the needle is removed. The fabric is then sandwiched in place with a secondary backing, usually composed of polyvinyl chloride (PVC), as illustrated in Figure 10. The face fiber used in carpet tiles is nylon 6,6, chosen for its high durability.

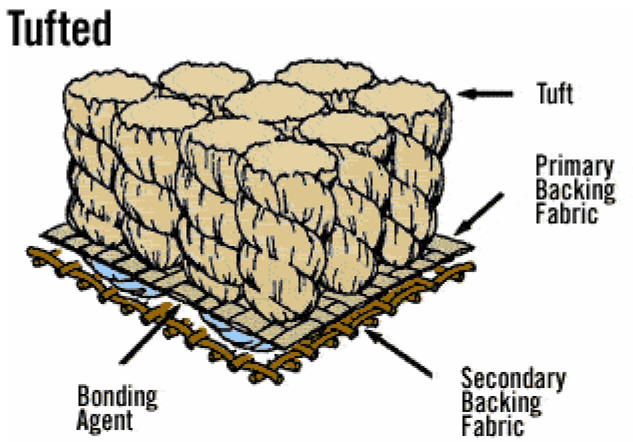

Figure 10. Tufted Carpet (CRI)

The material composition of carpet tile varies depending on the information source. Table 5 through Table 7 give the material compositions from different sources.

Table 5. Carpet Tile Material Composition (InterfaceFLOR, 2009)

Layer	Component	Material	Availability	Mass %	Origin
Wear Layer	Face Cloth/yarn	Nylon 6,6 Virgin	Fossil resource, limited	11.12%	US
		Nylon 6,6 Post Industrial Recycled	Recycled material, abundant	3.36%	US
		Nylon 6,6 Post Consumer Recycled	Recycled material, abundant	1.06%	US
Tufting Substrate	Primary	Polyester	Fossil resource, limited	2.28%	US
Precoat Bonding Layer	Latex	EVA	Fossil resource, limited	4.88%	US
	Filler	CaCO3	Mineral resource, non renewable, abundant	14.37%	US
	Foamer	Soap	Fossil resource	0.28%	US
Glass Stabilization	Fiberglass	Silica	Mineral resource, non renewable, abundant	1.52%	US
Structural Backing	GlasBacRE Backing	Post Consumer recycled vinyl	Post Consumer recycled material, abundant	60.85%	US

Table 6. Carpet Tile Material Composition (M. D. Realff, 2004)

Material	% Composition	Function
Nylon 6	15%	Face fiber
PET	3%	Primary backing
Fiberglass	1%	Primary backing reinforcement
PVC	5%	Secondary backing material
Poly(methylacrylate-co-vinyl chloride)	7%	Backing additive
EVAC copolymer	6%	Adhesive
Diisoheptyl phthalate	12%	Backing additive (for flexibility)
CaCO3	50%	Backing filler

Table 7. Carpet Tile Material Composition (Nelson, 2008)

Material	% Composition
PVC Resin	17%
Plasticizer	17%
Coal Fly Ash	47%
Additives/Colorants	4%
Nylon 6,6 Face Fiber	15%

Because of this variability, some assumptions must be made regarding material composition. Numerous components exist as fillers and additives, many of which have no existing LCA calculation in any packaged software such as Simapro. All carpet tile is composed of three major components; the face fiber, the backing, and filler or padding. The face fiber varies depending on the pile height, but in this case the average material composition of nylon 6,6 is taken to be 16%. The tile backing is primarily PVC (approximately 0.5 kilograms of face fiber per $0.5m^2$), but is also composed of various plasticizers to make it flexible. Thankfully, these additives do not need to be removed before recycling occurs (Nelson, 2008). This is because these additives are also needed in the manufacturing of new carpet backing, and can therefore remain in the material as it undergoes the recycling process. Determining the composition of the chemical additives in the PVC backing is difficult with the data provided. The value from Table 5 is the most recent value published, and therefore the value of 61% backing material is used in this study. This value is assumed to include numerous fillers, which are not accounted for individually. Numerous materials also exist to provide padding and sound dampening elements for the carpet. Although numerous fillers may exist, the majority of these fillers are found to be calcium carbonate ($CaCO_3$), and therefore the remaining carpet material is assumed to be composed of $CaCO_3$. The resulting carpet tile composition used in this study is outlined in Table 8.

Table 8. Assumed Material Composition Values

Material	% Composition
Nylon 6,6 Face Fiber	16%
PVC Backing	61%
$CaCO_3$ filler	23%

4.6. Life Cycle Inventory

4.6.1. Energy Requirements

With the exception of transportation, each processing step requires an energy input. Because the recycling facility is located in Georgia the state power mix is used to determine emissions from electrical consumption. Information on power generation and emissions were calculated using data provided by the EPA eGRID database (eGRID, 2006). Aggregated annual emissions rates are used to estimate the pollution emitted per kilowatt-hour. Table 9 shows the mix of power generation in Georgia, and Table 10 shows the resulting emissions.

Table 9. Georgia State Energy Composition

Georgia Power Mix	% State Output
Bituminous Coal	47.12%
Nuclear	26.63%
Subbituminous Coal	18.36%
Natural Gas	4.37%
Water	2.22%
Black Liquor	1.23%
Wood Solids	0.03%
Residual Oil	0.03%
Landfill Gas	0.01%
Distillate Oil	0.00%

Virginia's power mix was also investigated because the primary supplier for nylon fiber is located in Virginia, where the nylon fiber bales are shipped for processing back into nylon fiber. The Virginia power mix was also found to be composed primarily coal power and for simplicity purposes the power emission for Virginia are assumed to be equivalent to Georgia's power mix ("Electric Power and Renewable Energy in Virginia," 2007). Therefore, the emissions shown in **Table 10** for the Georgia state power mix will also be used for the Virginia state power mix.

Table 10. Georgia Power Emissions

Weighted Emission Rates				
	CO2 Output Rate (g/kWh)	SO2 Output Rate (g/kWh)	NOx Output Rate (g/kWh)	Hg Output Rate (g/kWh)
Bituminous Coal	420.67	3.54	0.62	6.73E-06
Nuclear	0.00	0.00	0.00	0.00E+00
Subbituminous Coal	183.23	0.57	0.13	0.00E+00
Natural Gas	24.84	0.00	0.01	0.00E+00
Water	0.00	0.00	0.00	0.00E+00
Black Liquor	0.48	0.02	0.01	0.00E+00
Wood Solids	0.00	0.00	0.00	0.00E+00
Residual Oil	0.37	0.00	0.00	0.00E+00
Landfill Gas	0.00	0.00	0.00	0.00E+00
Distillate Oil	0.00	0.00	0.00	0.00E+00
TOTAL	629.58	4.13	0.77	6.73E-06

4.6.2. Vehicles

Heavy duty diesel vehicles (HDDV) with a model year of 2008 are assumed to be used for all transportation. The fuel economy of the HDDVs is assumed to be five miles per gallon (0.425 km/liter) (Guidry, 2008). A class HDDV-3 vehicle is with a 75% total load is assumed for all transportation. This means the that each truckload can carry 1,361kg of carpet waste (Guidry, 2008). Table 11 shows the resulting emissions from HDDV transportation options.

Table 11. HDDV Emissions (Guidry, 2008)

	Greenhouse Gases (g/km)			Criteria Pollutants (g/km)				Additional Pollutants (g/km)				
Class	**CO2**	**CH4**	**N2O**	**SO2**	**NOx**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SOx**
2A	438.223	0.0032	0.0030	0.0055	2.65	N/R	10.26	N/R	N/R	0.86	0.07	N/R
3	487.446	0.0032	0.0030	0.0061	3.06	N/R	11.87	N/R	N/R	1.00	0.08	N/R
4	568.91	0.0032	0.0030	0.0071	3.45	N/R	13.37	N/R	N/R	1.12	0.09	N/R
5	582.766	0.0032	0.0030	0.0073	3.61	N/R	14.00	N/R	N/R	1.17	0.09	N/R
6	668.357	0.0032	0.0030	0.0084	4.62	N/R	17.91	N/R	N/R	1.50	0.12	N/R
7	792.973	0.0032	0.0030	0.0099	5.80	N/R	22.46	N/R	N/R	1.88	0.14	N/R
8A	882.502	0.0032	0.0030	0.011	6.52	N/R	25.26	N/R	N/R	2.12	0.16	N/R

HDDV-8A is also used in a single case when nylon recycling is occurring. An HDDV-8 with 100% capacity is assumed to be used to transport nylon material from the LaGrange recycling center to a nylon recycling facility run by Universal Fibers in Bristol, Virginia. This vehicle is chosen because it is the common vehicle used for long distance trucking, and it is reasonable to assume that the vehicle would not make the trip without a full load. The associated hauling capacities of these vehicles classes are shown in Table 12.

Table 12. HDDV Capacity (Guidry, 2008)

Vehicle Class	Capacity [kg]
HDDV-2B	680
HDDV-3	1,814
HDDV-4	906
HDDV-5	1,587
HDDV-6	2,947
HDDV-7	3,175
HDDV-8A	12,247

4.6.3. Distances

Transportation distances will vary depending on the collection and processing scenario. The base case examined in this study is simply hauling all PCC-tile to the nearest landfill. Because carpet tile is primarily used by businesses, the distance from county seats to nearest landfills are calculated using Google Maps. County seats are generally business centers where carpet tile would be removed from offices, schools, or government facilities. The distances from county seats to nearest landfills are shown in Table 13. Data on landfill locations is provided by the University of Georgia's Agrosecurity annex database (Savaskan et al., 2004) and county seat locations were found from the Georgia state website (Bower, 1973).

Table 13. Distances from County Seats to Nearest Landfill

County	Nearest Landfill	County of Landfill	to Landfill [km]
Cherokee	Ballground	Cherokee	21
Clayton	Lovejoy	Clayton	11
Cobb	Ballground	Cherokee	56
Coweta	Newnan	Coweta	8
DeKalb	Conley	DeKalb	19
Douglass	Atlanta	Fulton	34
Fayette	Atlanta	Fulton	63
Forsyth	Ballground	Forsyth	31
Fulton	Atlanta	Fulton	8
Gwinnett	Buford	Gwinnett	21
Henry	Ellenwood	DeKalb	29
Paulding	Atlanta	Fulton	48
Rockdale	Lithonia	DeKalb	11

When carpet is being collected for recycling it is assumed that there are collection centers located around the greater Atlanta area. Carpet from the local area can be brought to a centralized collection center to then be moved to the recycling facility in LaGrange, Georgia. Again, these collection centers are assumed to be located within the county seats. The value of the distance from each county seat to LaGrange, Georgia is shown in Table 14.

Table 14. Distances from County Seats to LaGrange, Georgia

County	County Seat	to LaGrange [km]
Cherokee	Canton	166
Clayton	Jonesboro	100
Cobb	Marietta	134
Coweta	Newnan	50
DeKalb	Decatur	121
Douglass	Douglasville	103
Fayette	Fayetteville	84
Forsyth	Cumming	172
Fulton	Atlanta	108
Gwinnett	Lawrenceville	159
Henry	McDonough	134
Paulding	Dallas	146
Rockdale	Conyers	138

Additional waste that may result during recycling processes at the LaGrange facility will also need to be transported to a landfill. The LaGrange landfill is located 12.1km from the recycling facility and this is used as the transport distance of all waste generated at the recycling facility.

4.6.4. Virgin Material Acquisition

Whenever a material is disposed of it is assumed that new material is needed to replace the landfilled product. Therefore, anytime PCC-tile or any material component is landfilled, the emissions required to produce replacement plastics from virgin material is considered. **Table 15** lists the energy requirements to produce material for each carpet tile.

These values are the energy values include raw material acquisition such as mining to usable material before product production begins.

Table 15. Energy Requirements for Material Production

Material	Energy Requirements [kWh/kg]	Production Energy [kWh/PCC-tile]	Source
Nylon 6,6	38.508	7.702	(Boustead, 2005)
PVC	17.167	13.090	("Idemat 2001," 1998)
CaCO3	0.020	0.006	(M. D. Realff, 2004)
Total		20.797	

The data shown in Table 16 for the virgin emissions of producing PVC are an average value from a variety of software packages and sources (Guidry, 2008).

Table 16. Virgin PVC Pollution Emission Rates per kg of PVC (Guidry, 2008)

Greenhouse Gases (g/kg-PVC)			Criteria Pollutants (g/kg-PVC)				Additional Pollutants (g/kg-PVC)				
CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
2015	10.27	0.0007	12.12	8.43	0.001	4.03	0.002	3E-05	1.4	1.47	10.43

These values are for the production of one kilogram of PVC. However, the functional unit in this study is one kilogram of carpet tile, which contains less PVC. Each carpet tile weighs approximately 1.25kg, and the PVC backing would compose 61% of this mass. Table 17 gives the values of emissions that result for the production of virgin PVC that is needed to produce one kilogram of carpet tile.

Table 17. Virgin PVC Production Emissions per kg of PCC

Greenhouse Gases (g/kg-PCC)			Criteria Pollutants (g/kg-PCC)				Additional Pollutants (g/kg-PCC)				
CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
1229.2	6.265	0.000	7.393	5.142	0.001	2.458	0.001	1.8E-05	0.854	0.897	6.362

Similarly, the data shown in Table 18 for producing nylon 6,6 are also an average value of data sources (Guidry, 2008).

Table 18. Virgin Nylon 6,6 Pollution Emission Rates per kg of Nylon (Guidry, 2008)

Greenhouse Gases (g/kg-nylon)			Criteria Pollutants (g/kg-nylon)				Additional Pollutants (g/kg-nylon)				
CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
6681	42.09	0.74	21.6	17.85	2E-06	6.27	0.08	4E-06	3.89	2.11	0

Table 19 shows the values adjusted for the production of one kilogram of carpet tile.

Table 19. Virgin Nylon Production Emissions per kg of PCC

Greenhouse Gases (g/kg-PCC)			Criteria Pollutants (g/kg-PCC)				Additional Pollutants (g/kg-PCC)				
CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
1069	6.7344	0.1184	3.456	2.856	3E-07	1.0032	0.0128	6E-07	0.622	0.3376	0

The emission values for CaCO3 production were obtained using SimaPro, a packaged LCA assessment software tool. The values for the production of one kilogram of CaCO3 are shown in Table 20.

Table 20. Emissions from CaCO3 Production per kg of CaCO3

Greenhouse Gases (g/kg-CaCO3)			Criteria Pollutants (g/kg-CaCO3)				Additional Pollutants (g/kg-CaCO3)				
CO2	CH4	N2O	SO2	NOx	PB	CO	VOCs	Hg	HC	PM	SOx
6.1501	0.01042	0.000136	0	0.01295	2E-06	0.0053	0.0085	2E-07	6E-05	6E-05	0.024

Table 21 contains the values adjusted for the production of one kg of carpet tile.

Table 21. CaCO3 Production Emissions per kg of PCC

Greenhouse Gases (g/kg-PCC)			Criteria Pollutants (g/kg-PCC)				Additional Pollutants (g/kg-PCC)				
CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
1.4145	0.0024	3.14E-05	0	0.00298	4E-07	0.0012	0.002	4E-08	1E-05	1E-05	0.006

4.7. Unit Processes

4.7.1. Landfilling

No processing occurs in this case other than transportation to the landfill. Because the carpet material used is completely inert, no emissions result in any reasonable amount of time (Guidry, 2008). The only factors that result in emissions is therefore the transportation of PCC-tile from the collection centers to the landfill, and the production of virgin material for new carpet.

4.7.2. PVC Recycling

The recycling process outlined here is based on work performed by Guidry. The PVC recycling consists of mechanical processes to turn carpet tile backing into usable pellets for reuse.

4.7.2.1.Baling

To minimize the space material occupies during transportation and storage the PCC-tile is bundled into 1450kg bales. The machine specifications used for this process come from a vertical Conquest 180-100S HI GRADE baler (Guidry, 2008). The process flow for baling can be seen in Figure 11, where M is the motor power and T is the throughput rate.

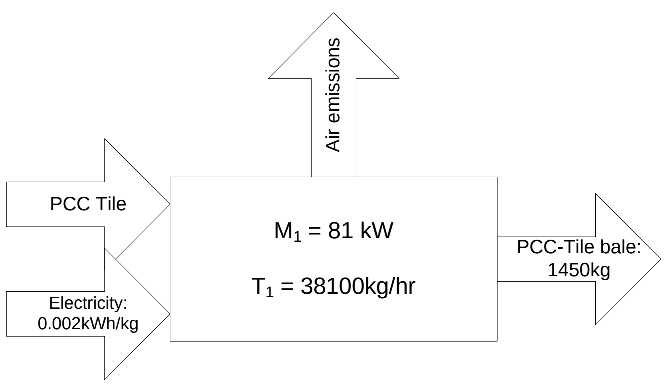

Figure 11. Baling Process Flow (Guidry, 2008)

4.7.2.2.Shredding

Shredding reduces the size of the baled carpet material into approximately 6.35cm pieces. Energy and throughput estimates are determined by averaging performance and machine specifications of several Carpet America Recovery Effort (C.A.R.E.) recommended machines (Guidry, 2008). The process flow is shown in Figure 12.

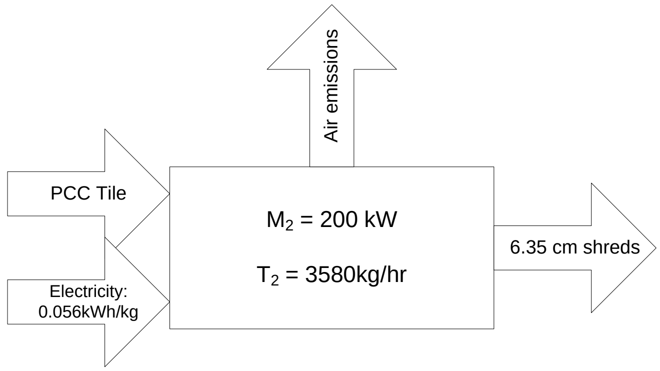

Figure 12. Shredding Process Flow (Guidry, 2008)

4.7.2.3.Grinding

Further size reduction is carried out during the grinding process, reducing the carpet material size to approximately 0.95cm. Machine specifications used are for a HiTorc Grizzly material grinder, with process values shown in Figure 13 (Guidry, 2008).

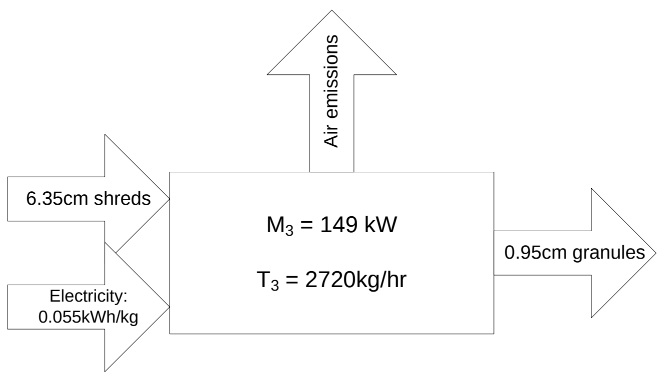

Figure 13. Grinding Process Flow (Guidry, 2008)

4.7.2.4.Material Separation

The carpet material is separated using a centrifuge. Machine specs used here are for a Bird Humboldt Censor Three-Phase Centrifuge, with process values shown in Figure 14 (Guidry, 2008).

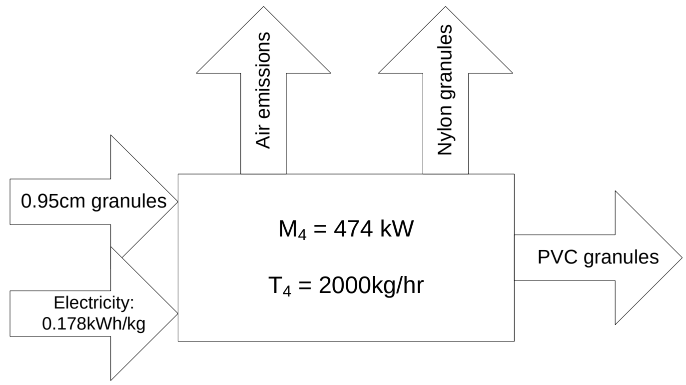

Figure 14. Material Separation Process Flow (Guidry, 2008)

4.7.2.5.Pelletizing

This step is strictly for the PVC material that is being recycled back to making carpet backing. The PVC granules from the grinder processes are melted and formed into pellets for easy material handling and aides in uniform melting during manufacturing. This process is actually composed of three separate steps. The first step creates the pellets by melting, extruding, and cutting the material. The second phase transports the pellets to a dryer. The last step dries the pellets using a centrifugal system. The resulting process values are shown in Figure 15 (Guidry, 2008).

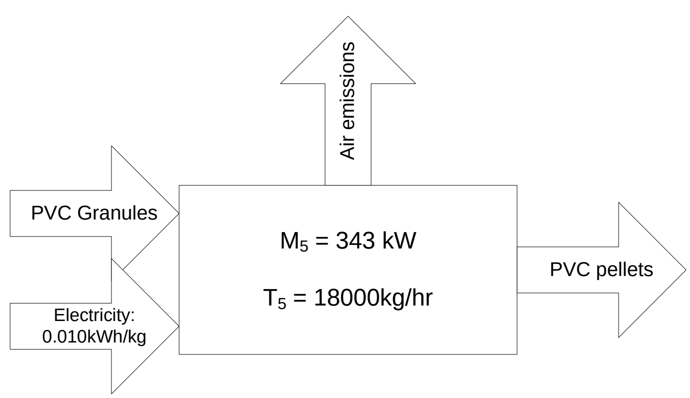

Figure 15. Pelletizing Process Flow (Guidry, 2008)

A summary of the energy requirements for each kilogram of material processed is provided in Table 22.

Table 22. PVC Recycling Process Energies (Guidry, 2008)

Process	[kWh/kg-PCC]
Baling	0.002
Shredding	0.056
Grinding	0.055
Material Sep	0.178
Pelletizing	0.010
Total	0.301

4.7.3. Unit Processes – Nylon Recycling

Determining the process used by plastic suppliers for Interface was difficult to determine because the process is considered proprietary and is not publicly available. Although nylon 6,6 recycling processes previously existed, they usually required depolymerization of the plastic, which is an energy intensive process requiring toxic chemicals. The system examined here is advantageous because it uses only mechanical processes (Nelson, 2008). Once the nylon face fibers have been separated from the tile it is baled and shipped to plastic suppliers for recycling. The plastic suppliers require only air cleaning of the nylon fluff to remove enough contaminants to allow the material to be pushed through extruders (Nelson, 2008).

4.7.3.1.Cyclone Air Separator

Figure 16 shows the process flow a cyclone air separator which is the most likely air cleaning method used (M. Realff, 2009). The solid waste that is removed consists of dust and other small particulate matter that is accumulated in carpets during use. This is generally believed to be about only 1-2% of the total mass moving through the process (Nelson, 2008).

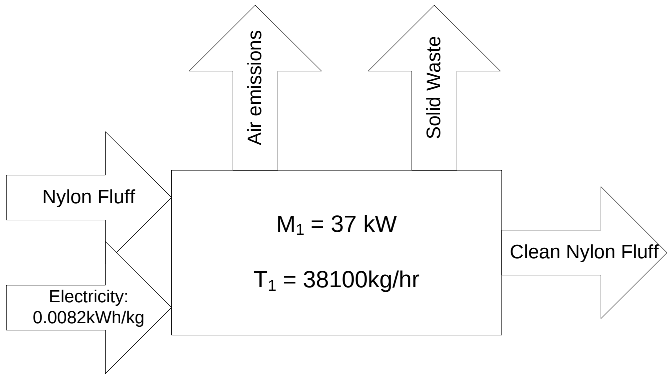

Figure 16. Cyclone Air Separator Process Flow

Theoretically, the nylon fluff should be free of enough contaminants to be recycled back into nylon thread. The remaining steps were taken from the nylon manufacturing process outlined in Brown et al (Brown et al., 1996).

4.7.3.2.Bunker Melter

A bunker melter is used to transform the nylon fluff back into a liquid state. The process flow for this is shown in Figure 17.

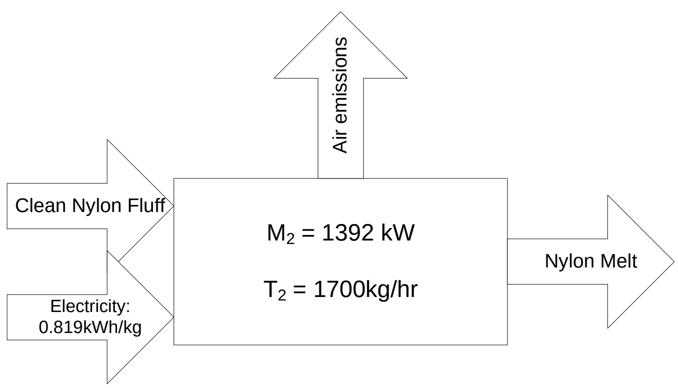

Figure 17. Bunker Melter Process Flow

The melted nylon is then passed through a spinneret so that nylon fiber is formed, shown in Figure 18.

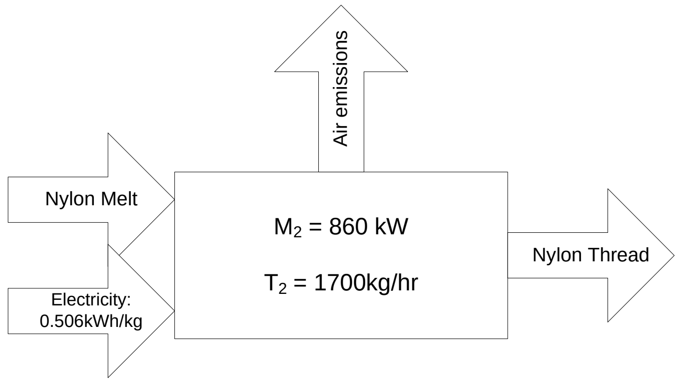

Figure 18. Spinneret Process Flow

4.7.3.3.Air Cooling

An air cooling process is used to solidify the newly formed nylon thread. The process flow for this is shown in Figure 19.

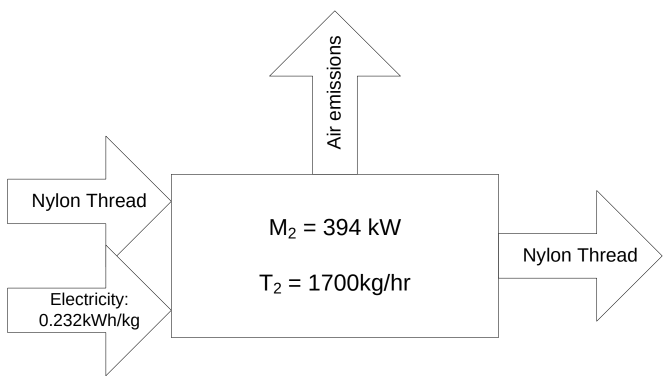

Figure 19. Cooling Process Flow

4.7.3.4.Drawing

An additional drawing process is done to obtain the desired dimensions for the nylon thread, shown in Figure 20.

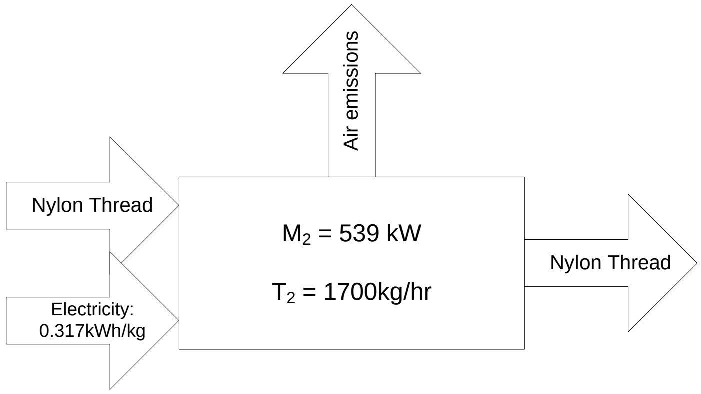

Figure 20. Drawing Process Flow

4.7.3.5.Winding

Finally, the thread is wound for easy handling. This process is outlined in Figure 21.

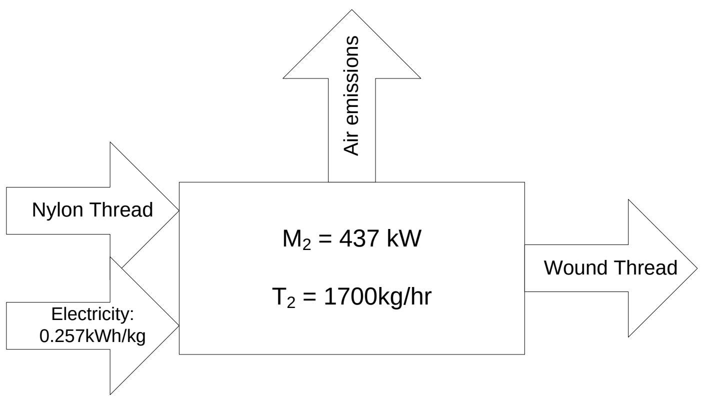

Figure 21. Winding Process Flow

The required energy for performing each of these processes for each kilogram of material is summarized in Table 23.

Table 23. Nylon 6,6 Recycling Process Energies (Brown et al., 1996)

Process	[kWh/kg]
Cyclone	0.004
Bunker Melter	0.819
Spinneret	0.506
Cooling	0.232
Drawing	0.317
Winding	0.257
Total	2.134

4.8. Additional Assumptions

Several assumptions that are not mentioned in detail elsewhere in this study are listed here.

- The number of times nylon fiber can be processes in the manner described is not known. However, this study assumes that the nylon fiber can be recycled indefinitely.
- Because the recycling process used is only mechanical and does not include any chemical processes, the dye that is used to color the face fibers is not removed. Therefore, the recycled carpet fibers can only be dyed darker colors when reused. This also means that lighter-colored carpets are preferred over dark colors. The effect of dyes is not considered in this study, and it is assumed that all carpet fibers can be recycled without regard to color.

4.9. Calculations

4.9.1. Case 1: Direct to Landfill

The direct-to-landfill scenario calculations were completed first to provide a base case to which the other scenarios could be compared. Transportation data was calculated starting with the estimated PCC-tile inventory for each county seat. The total kilograms of carpet in each county seat is divided by the load capacity of the HDDV-3 vehicles. This provides the number of trips necessary to haul of the carpet to the landfill annually. These values were then multiplied by the distances from each county seat to the nearest landfill. The values were doubled to account for the vehicles requiring round trips to and from each landfill. The production values for new materials are also used to account for new carpet production. The final calculated values are shown in Table 24, with the total emissions resulting from the direct-to-landfill scenario being listed at the bottom.

Table 24. Resulting Emissions from Landfillling Scenario

	Emissions (g-pollutant/kg-PCC tile)											
	Greenhouse Gases			Criteria Pollutants				Additional Pollutants				
	CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
Transportation	18.41	0.0001	0.0001	2E-04	0.116	0	0.448	0	0	0.038	0.003	0
PVC Production	1229.15	6.26	0.0004	7.393	5.142	6E-04	2.458	0.001	2E-05	0.854	0.897	6.362
Nylon Production	1068.96	6.73	0.12	3.456	2.856	3E-07	1.003	0.013	6E-07	0.622	0.338	0
CaCO3 Production	1.41	0.0024	3.1E-05	0	0.003	4E-07	0.001	0.002	4E-08	1E-05	1E-05	0.006
Total	2318.14	13.0016	0.11897	10.85	8.118	6E-04	3.917	0.016	2E-05	1.514	1.237	6.368

Because no recycling processes occur in this scenario, the energy usage comes only from the production of new materials and the process energies for manufacturing new materials. The manufacturing energy is the same regardless of the scenario and can therefore be excluded in the comparison. This is because carpet tile utilizes recycling in the closed loop cases, which returns material to its remanufacturable form, but still requires the standard manufacturing processes to return to a completed product. This leaves only the raw material acquisition energy and transportation in the disposal case, shown in Table 25.

Table 25. Carpet Disposal Energy Requirements

Process	Energy Consumption [kWh/kg-PCC]
Transportation	0.08
Nylon 6,6 Production	38.51
PVC Production	17.17
CaCO3 Production	0.02
Total	55.77

4.9.2. Case 2: PVC Recycling

The next scenario recycles the PVC, but still landfills the nylon. The collection values are calculated the same was as in the landfilling case. However, the number of trips is multiplied by the distances from the county seats to LaGrange, rather than the nearest landfill. As can be seen in Table 26, the resulting collection transportation emissions are larger due to the greater travel distances required. Transportation also occurs when hauling the nylon material that is not recycled to a landfill located in LaGrange only 7.5 miles (12.1km) away. The emission values for the PVC recycling process are calculated by finding the total energy required in kWh/kg described in detail in the unit processes. This number is then multiplied by the resulting power emissions for the Georgia power grid.

Table 26. Resulting Emissions from PVC Recycling Scenario

	Emissions (g-pollutant/kg-PCC tile)											
	Greenhouse Gases			Criteria Pollutants				Additional Pollutants				
	CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
Collection	91.37	0.001	0.001	0.001	0.574	0	2.224	0	0	0.187	0.014	0
PVC Recycling	144.50	0	0	0.95	0.18	0	0.00	0	0	0.00	0.00	0
Nylon Transport	0.69	4.5E-06	4.2E-06	8.7E-06	4.4E-03	0	1.7E-02	0	0	1.4E-03	1.1E-04	0
Nylon Production	1068.96	6.7344	0.1184	3.456	2.856	3E-07	1.0032	0.013	6E-07	0.6224	0.3376	0
CaCO3 Production	1.41452	0.0024	3.1E-05	0	0.003	4E-07	0.0012	0.002	4E-08	1E-05	1E-05	0.01
CaCO3 Transport	0.20054	7.2E-07	6.8E-07	3E-06	0.0015	0	0.0057	0	0	0.0005	4E-05	0
Total	1,307.1	6.7	0.1	4.4	3.6	0.0	3.3	0.0	0.0	0.8	0.4	0.0

The avoidance of producing new PVC material reduces the overall emissions, showing that material recycling has potential to reduce emissions. Table 27 shows the corresponding energy requirements for this scenario. The disparity between the recycling energy for PVC and the raw material production for nylon can easily be seen.

Table 27. PVC Recycling Energy Requirements

Process	Energy Consumption [kWh/kg-PCC]
Transportation	0.35
Nylon 6,6 Production	38.51
PVC Recycling	0.30
CaCO3 Production	0.02
Total	39.18

4.9.3. Case 3: PVC & Nylon Recycling

The collection pattern for the third case is the same as for case 2. Instead of nylon being dumped in the landfill, however, it is recycled following the process flows described earlier. Additional transport of the nylon fluff to the Universal Fibers facility in Bristol, Virginia is also considered. Only travel from LaGrange to Bristol is considered because transport back to LaGrange occurs in all cases for new plastic materials and does not change between scenarios. In addition, the recycling of PVC and nylon results in no virgin material energy needed, greatly reducing the total emissions shown in Table 28.

Table 28. Emissions from Nylon and PVC Recycling Scenario

	Emissions (g-pollutant/kg-PCC tile)											
	Greenhouse Gases			Criteria Pollutants				Additional Pollutants				
	CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
Collection	91.371	0.0006	0.0006	0.0011	0.574	0	2.224	0	0	0.187	0.014	0
PVC Recycling	144.50	0	0	42528	11745	0	0	0	0	0	0	0
Nylon Transport	7.3096	2.6E-5	2.5E-5	9E-05	0.054	0	0.209	0	0	0.018	0.001	0
Nylon Recycling	268.66	0	0	1.763	0.330	0	0	0	3E-6	0	0	0
CaCO3 Production	1.4145	0.0024	3.1E-5	0	0.003	4E-07	0.001	0.002	4E-8	1E-05	1E-05	0.01
CaCO3 Transport	0.2005	7.2E-7	6.8E-7	3E-06	0.0015	0	0.006	0	0	0.001	4E-05	0
Total	513.45	0.0030	0.0006	42529	11745	4E-7	2.440	0.002	3E-6	0.205	0.016	0.01

It is clear that recycling the material results in a dramatic improvement in emissions. Recycling PVC provided an emissions reduction over landfilling the PCC-tile, and with nylon recycling the emissions are further reduced. These significant savings can also be seen when only energy is examined, as shown in Table 29. Eliminating raw material acquisition and production significantly reduced energy requirements. These energy values are proportionally much larger than the emission values for the same system. This is most likely the result if discrepancies between sources. The energy values for raw material acquisition and emissions values come from separate sources, and therefore may not necessarily agree on input or output values. LCA programs such as Idemat do not show how their emission values are calculated so a careful comparison is difficult.

Table 29. Nylon & PVC Recycling Energy Requirements

Process	Energy Consumption [kWh/kg-PCC]
Transportation	0.36
Nylon 6,6 Recycling	2.13
PVC Recycling	0.30
$CaCO_3$ Production	0.02
Total	2.81

4.9.4. *Case 4: PVC & Nylon Recycling with New Material Added*

These cases have all assumed that 100% of the PVC backing and nylon face fibers can be successfully recycled. In reality the recycled material needs to be mixed with new material, also known as sweetening, to allow for adequate performance and machining. This means despite recycling the major components of the carpet tile, virgin material production is still included. For this final case, it is assumed that 15% virgin PVC and 25% virgin nylon is added to the recycled plastics. These were the values determined necessary for desired quality and manufacturability (Nelson, 2008). The resulting emissions are shown in Table 30.

Table 30. Emissions from Recycling Scenario with Sweetening

	Emissions (g-pollutant/kg-PCC tile)											
	Greenhouse Gases			Criteria Pollutants				Additional Pollutants				
	CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
Collection	91.37	0.0006	0.0006	0.0011	0.5740	0	2.224	0	0	0.187	0.014	0
PVC Recycling	98.2583	0	0	0.6449	0.1207	0	0	0	1E-06	0	0	0
Nylon Transport	7.30963	2.6E-05	2.5E-5	9E-05	0.054	0	0.2092	0	0	0.0175	0.0013	0
Nylon Recycling	161.196	0	0	1.058	0.1979	0	0	0	2E-06	0	0	0
PVC Production	184.373	0.93971	6.4E-5	1.109	0.7713	9E-05	0.3687	2E-04	3E-06	0.1281	0.1345	0.954
Nylon Production	267.24	1.6836	0.0296	0.864	0.714	8E-08	0.2508	0.003	2E-07	0.1556	0.0844	0
CaCO3 Production	1.41452	0.0024	3.1E-5	0	0.003	4E-07	0.0012	0.002	4E-08	1E-05	1E-05	0.006
CaCO3 Transport	0.20054	7.2E-07	6.8E-7	3E-06	0.0015	0	0.0057	0	0	0.0005	4E-05	0
Total	811.36	2.63	0.03	3.68	2.44	0.00	3.06	0.01	0.00	0.49	0.23	0.96

The total emission values shown indicate that the more recycling that occurs the lower the overall impact. This is due to the large emission contributions that result from raw material manufacturing. Examining only CO_2 equivalencies for the sake of comparison, case 1 results in approximately 2,620 grams of CO_2 equivalent emissions per kilogram of carpet tile produced. When recycling is utilized in case 3 this number drops to 432 grams of pollutant per kilogram of carpet; a significant reduction. When 'sweetening' occurs, the amount of CO_2 equivalents released increases to 868 kilograms, still significantly smaller than case 1. In all cases the amount of $CaCO_3$ transported and disposed remains the same, and is a very small contributor to the overall emissions. Table 31 shows the relating energy requirements. The addition of raw material production for sweeteners increased the energy requirements, but remains lower than product disposal in case 1 or PVC recycling in case 2.

Table 31. Recycling and Sweetening Energy Requirements

Process	Energy Consumption [kWh/kg-PCC]
Transportation	0.36
Nylon 6,6 Recycling	1.60
Nylon 6,6 Production	9.63
PVC Recycling	0.26
PVC Production	2.58
CaCO3 Production	0.02
Total	14.44

4.10. Validation

As a check for accuracy, these values were compared with similar work done by Guidry (Guidry, 2008). Although Guidry's work focused primarily on broadloom carpets and does not include nylon 6,6 recycling, similar calculations on PVC were carried out. The results calculated here on PVC production and recycling are similar to the values found by Guidry. Although some variation exists the numbers in all cases are at least within the same order of magnitude.

4.11. CO_2 Equivalent Comparisons

Numerous emission factors are considered in this study, but this can make comparisons difficult. To be able to make some basic comparisons between the scenarios the CO_2 equivalents were calculated from the greenhouse gas contributions using the EPA greenhouse gas equivalency calculator, and these values were used in the following graphs ("Greenhouse Gas Equivalencies Calculator," 2009). It should be noted that the following figures do not account for the criteria or additional pollutant values shown in the previous tables, and is done merely as a tool for comparisons. Figure 22 through Figure 25 illustrate how various components contribute to the total greenhouse gas emissions for cases 1, 2, 3, and 4 respectively.

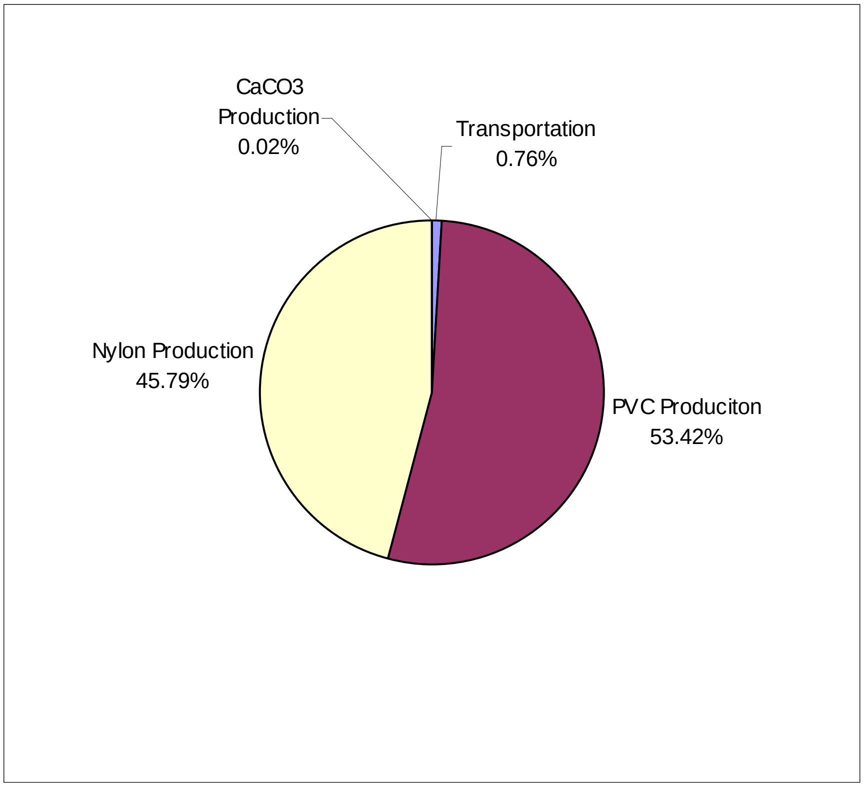

Figure 22. CO2 Contributors to Case 1

When PCC is landfilled without any material recovery, as is the case with Figure 22, it can easily be seen how material production contributes to the vast majority of emissions during the carpet life cycle. Transporting the carpet material to landfills close to county seats contributes less than one percent of the total emissions. If significant emissions savings are to be made, material production offers the best opportunity to make an impact.

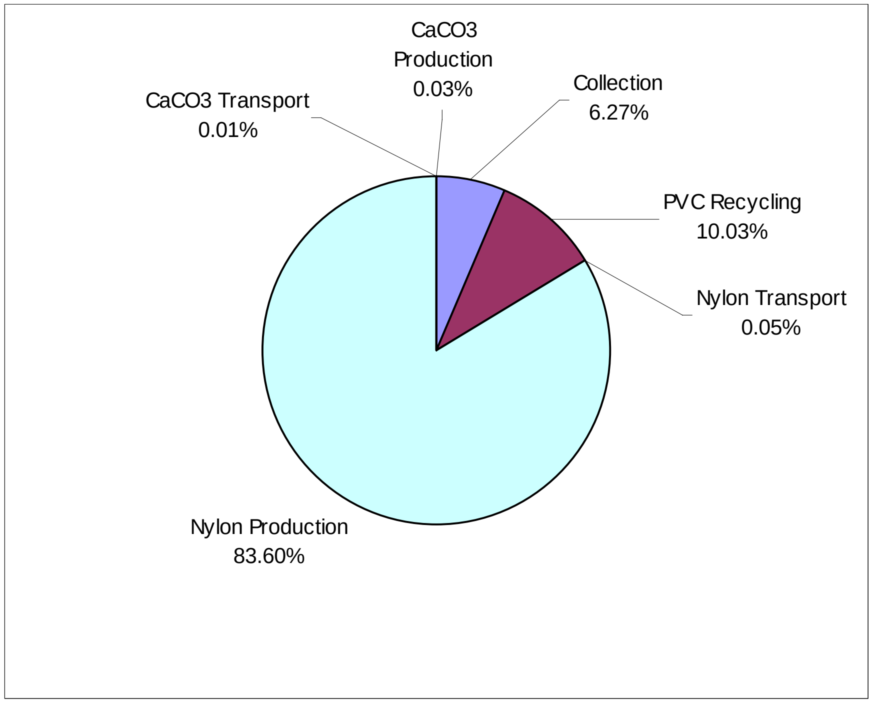

Figure 23. CO2 Contributors to Case 2

Figure 23 shows the results when PCC is transported back to LaGrange, and PVC is separated and recycled, while the remaining material is landfilled. Recycling of PVC saves a significant amount of energy, and here nylon production remains as the major contributor of pollutants. It should also be noted the greater factor that transportation becomes with the increased travel distances to LaGrange, although still not significant compared to material production.

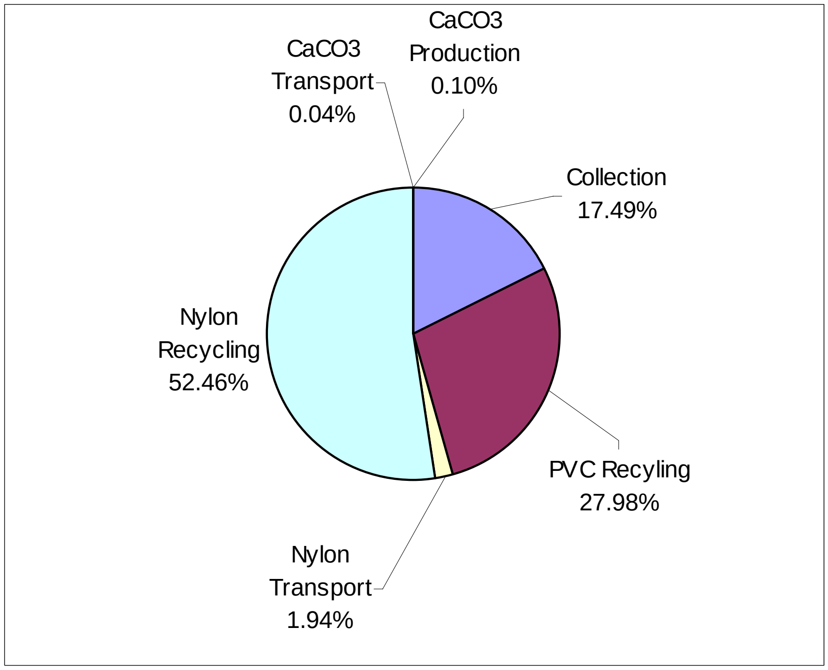

Figure 24. CO2 Contributors to Case 3

When both PVC and Nylon are recycled, the major factors contributing to emissions are shown in Figure 24. Nylon recycling is the greatest emissions contributor. Although nylon composes only 16% of the total carpet material, the recycling process was determined to be more energy intensive than PVC recycling. The greater energy requirements for nylon recycling outweigh the smaller volume of material that is processed. Calcium carbonate contributes only a fraction of the emissions during carpet production. Even if $CaCO_3$ composed the majority of material, as some material sources suggest, it would still be a small amount of the total production emissions.

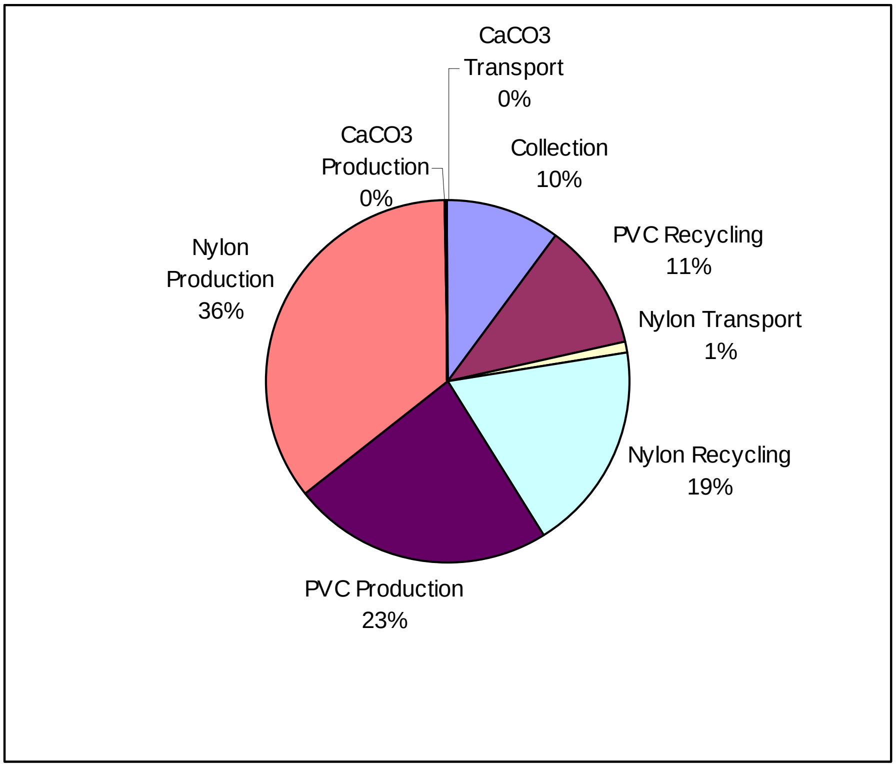

Figure 25. CO2 Contributions to Case 4

If virgin material is mixed in with the recycled materials, as is most likely the case, the resulting emission contributions are shown in Figure 25. This shows an important comparison to the environmental impacts of virgin material production versus recycling. Although only 25% of the nylon and 15% of the PVC is new material, both these processes emit great amounts of pollutants than their respective recycling processes for the majority of the material. Again it can be seen that despite the majority presence of PVC material in carpet tile, nylon contributes the greatest amount of emissions due to energy intensive production and recycling.

It is clear that producing the raw materials for carpet tile is by far the greatest contributor to GHG emissions. Transportation, on the other hand, has very little effect on the total emissions. In all cases transportation and $CaCO_3$ production were the smallest contributors to GHGs.

4.12. Carpet Maintenance

One of the major aspects of servicizing is providing the maintenance needed so that the primary function of the carpet (aesthetics, acoustics, etc.) can be met. Therefore carpet maintenance was part of the ESA agreement, with Interface providing the service (Oliva & Quinn, 2003). Carpet maintenance is potentially an important aspect in extending the life of a carpet, reducing the frequency it needs to be replaced. Unfortunately, vacuuming and extensive cleaning also consume power and resources. The analysis of carpet maintenance impact is also made extremely difficult by the lack of information available on the topic. The extent a carpet's lifespan is lengthened by regular maintenance is not known, and much of the carpet's life is based on aesthetics rather than fiber quality. Also, in a leasing situation the life of the carpet is limited and may never reach its full designed life span, further reducing the environmental benefits. This next section is concerned with the environmental impacts that arise from carpet maintenance.

Two primary forms of carpet care are investigated. The first is conventional care which involves only vacuuming at regular intervals. The second is a deep cleaning which involves application of a cleaning solution, cylindrical agitation, and hot water.

4.12.1. LCI

Data on cleaning equipment comes from work done by Overcash et al. (Overcash, Lu, & Realff, 2008). The work by Overcash et al. composes several cleaning scenarios based on office and building layout. The model used in this study is the generalized commercial building layout.

4.12.1.1. Equipment

Vacuum cleaners are assumed to be Carpet and Rug Institute (CRI) Green label Approved (Overcash et al., 2008). Deep cleaning requires the use of an agitator, extractor, and hot water. No fan drying is included in these values. Table 32 shows the energy consumption for vacuuming and the combined energy consumption for the agitating, extracting, and hot water generation for deep cleaning (Overcash et al., 2008). Values are given for both meters squared and kg per PCC-tile. The weight of PCC-tile is approximately 5kg/m^2 (Guidry, 2008).

Table 32. Carpet Cleaning Equipment Energy Use (Overcash et al., 2008)

Electrical Energy Used (MJ/m^2)		Electrical Energy Used (kWh/kg-PCC)	
Vacuum	Deep Clean	Vacuum	Deep Clean
1.20E-05	2.08E-04	6.64E-07	1.16E-05

Emissions resulting from these energy values use the same emission values for Georgia state power used in the previous section. The resulting emissions from power generation are shown for a single application of vacuuming and deep cleaning in Table 33 and Table 34 respectively.

Table 33. Vacuum Emissions for Single Application

Greenhouse Gases [g-pollutant/kg-PCC-tile]			Criteria Pollutants [g-pollutant/kg-PCC-tile]				Additional Pollutants [g-pollutant/kg-PCC-tile]				
CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
4.18E-04	0	0	2.75E-06	5.14E-07	0	0	0	4.47E-12	0	0	0

Table 34. Deep Cleaning Emissions for Single Application

Greenhouse Gases [g-pollutant/kg-PCC-tile]			Criteria Pollutants [g-pollutant/kg-PCC-tile]				Additional Pollutants [g-pollutant/kg-PCC-tile]				
CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
7.28E-03	0	0	4.78E-05	8.94E-06	0	0	0	7.78E-11	0	0	0

4.12.1.2. Cleaning Solution

The deep cleaning process includes cleaning solution added to the carpet to remove stains and aid in removing dust and other particulate matter. The specific cleaning product considered here is Racine Industries HOST Carpet Cleaning System. This particular solution uses a Green Seal-certified bio-based cleaning agent and a mixture of water and recycled organic fibers (Guidry, 2008). Emissions data for this solution was provided by the BEES4.0 database under Building Maintenance: Cleaning Products: Carpet Cleaners (NIST, 2007). The resulting emission for producing the cleaning products is shown in Table 35. Although HOST carpet cleaner is technically a dry cleaner, and does not require water to be applied before extraction, it will be used as an approximation for general carpet cleaners. HOST carpet cleaner is the only carpet cleaner found with environmental impact data existing. BEES4.0 also contains an anonymous carpet cleaner solution, but no additional data (such as function unit used in the database) is provided, making proper analysis difficult.

Table 35. Emissions Value for Production of HOST Carpet Cleaner

Greenhouse Gases [g-pollutant/kg-HOST]			Criteria Pollutants [g-pollutant/kg-HOST]				Additional Pollutants [g-pollutant/kg-HOST]				
CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
6112	15.89	0.01	47.67	7.43	0	3.67	14.71	0.001	1.3	4.57	0

These values are converted to align with the functional unit of this study. 4.25kg of HOST carpet cleaner are needed to clean 92.9m^2 of carpet. The energy requirements to produce cleaner is given in Table 36, and the resulting amount of pollutants per kilogram of PCC-tile is shown in Table 37.

Table 36. Energy Requirements for Cleaner Production

Electrical Energy Used [kWh/kg-PCC]
Cleaning Solution
1.02E-03

Table 37. Emissions for Producing HOST cleaner per kg PCC-Tile

Greenhouse Gases [g-pollutant/kg-PCC-tile]			Criteria Pollutants [g-pollutant/kg-PCC-tile]				Additional Pollutants [g-pollutant/kg-PCC-tile]				
CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
104	0.27	0.0002	0.81	0.13	0	0.06	0.25	2E-06	0.02	0.09	0

4.12.2. Maintenance Impacts

The act of vacuuming only requires electrical energy, and therefore the emissions that result from vacuuming a kilogram of carpet (0.2m^2 of carpet) are the emissions for generating the power to vacuum that segment, shown in Table 38, which is equivalent to the values given in Table 26.

Table 38. Vacuuming Emissions for Single Application

Greenhouse Gases [g-pollutant/kg-PCC]			Criteria Pollutants [g-pollutant/ kg-PCC]				Additional Pollutants [g-pollutant/ kg-PCC]				
CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
4.18E-04	0	0	2.75E-06	5.14E-07	0	0	0	4.47E-12	0	0	0

Deep cleaning emissions are the sums resulting from the power consumption of the agitator, extractor, water heating, and production of the cleaning solution for a single application, shown in Table 39.

Table 39. Emissions from Deep Clean for Single Application

Greenhouse Gases [g-pollutant/ kg-PCC]			Criteria Pollutants [g-pollutant/ kg-PCC]				Additional Pollutants [g-pollutant/ kg-PCC]				
CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
1.04E+02	0.27	0.0002	8.10E-01	1.30E-01	0	0.06	0.25	2.00E-06	0.02	0.09	0

Obviously, deep cleaning is a much more environmentally costly procedure than vacuuming. Despite this difference, deep cleaning would be performed with less frequency than vacuuming. According to the Carpet and Rug Institute, it is recommended that low-use areas be vacuumed two to three times a week, while heavy traffic areas should be vacuumed daily ("CRI," 2009). Deep cleaning most likely would occur on a monthly or annual basis. Table 40 shows the emissions resulting from vacuuming five days a week for a year. These values are still considerably smaller than a single application of deep cleaning; suggesting vacuuming is a relatively low-impact form of carpet maintenance. Even if deep cleaning occurs once a year, it is still substantially more detrimental to the environment than vacuuming.

Table 40. Annual Emissions for Vacuuming 5 days a week for one year

Greenhouse Gases [g-pollutant/ kg-PCC]			Criteria Pollutants [g-pollutant/ kg-PCC]				Additional Pollutants [g-pollutant/ kg-PCC]				
CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
0.11	0	0	7.14E-04	1.34E-04	0	0	0.00	1.16E-09	0	0	0

The larger emissions associated with deep cleaning are due to the production of cleaning solution. The energy consumption of the actual cleaning process is negligible compared with the production energy of producing cleaning solution.

4.12.3. Maintenance and Carpet Lifespan

Despite these production emissions, the net environmental impact may be better if deep cleaning can increase the life of the carpet and avoid more frequent recycling. Compared to producing or recycling carpet, cleaning requires very little resources. The average life span for carpet tile is ten years (Oliva & Quinn, 2003).

Determining the advantage or disadvantage of carpet maintenance is difficult given that no relationship has been calculated between the frequency of cleaning and the lifespan of the carpet. Further complicating calculations is the fact that many carpets are replaced for aesthetic, rather than functional reasons (CARE, 2007). The next section will attempt to shed some light on the effects of carpet maintenance by presenting a series of assumptions and conducting some basic calculations. Deep cleaning may be environmentally advantageous if it is able to extend the life of carpet to the point where the avoidance of carpet disposal or recycling saves energy over the energy needed for cleaning.

Each deep cleaning session results in the emissions shown in Table 40. These emission values are smaller than the results from recycling carpet tile, but over numerous uses the carpet cleaning impacts begin to accumulate. Environmentally, deep cleaning posses an advantage only if the cleaning processes extends the life of the carpet; delaying the need for energy intensive recycling or disposal. To examine the time a carpets lifespan would need to be increased to justify deep cleaning the following equation was used:

$$\text{Extended Years} = (\text{Recycling Emissions})/(\text{Cleaning Emissions} + \text{Recycling Emissions}/10) \quad (1)$$

The carpet life is assumed to be ten years. Dividing the recycling emissions that occur at the carpet's EOL by its lifespan results in the annual emissions contributed by the recycling process. Adding the cleaning emission from the deep cleaning gives the total annual emissions of the carpet. Dividing the total recycling process emissions by the annualized emission values results in the number of carpet years that the emissions are equivalent to. The values on the left of Table 41 indicate how many deep cleaning applications are conducted over the ten year life of the carpet. The remaining values in the table are the number of years beyond the initial ten-year lifespan the carpet must last to justify the carpet cleaning depending on which emission criteria is of concern. In other words, these values were found by equating the carpet cleaning emissions with the emissions that are avoided by reducing the frequency of carpet recycling. Complicating this comparison process is the fact that this study examines 12 different emission factors, which vary depending on production methods and energy sources. The emissions reduced in one criterion may not translate equally to another. The average values in the far right column are given to give a general idea of how many additional years carpet must last if cleaning emissions are to be negated by extended use[1]. In the case of CO_2, for example, if

[1] Values for VOCs are not included in the average value because of the larger magnitudes

over the ten year life of a carpet it was deep cleaned every two years (5 cleanings) the life of the carpet would need to be extended 6.41 years beyond the original 10-year life before being recycled to offset the emissions from cleaning. The very large figures found for VOCs is a result of the large disparity of volatile gases being released to manufacturing of chemical cleaners versus the carpet recycling process. As shown in Table 37, manufacturing enough cleaner to clean 1kg worth of carpet tile releases 0.25g of VOCs. Table 30 shows that recycling an equivalent amount of carpet tile releases only 0.005g of VOCs.

Table 41. Lifespan Extensions Needed for Varying Deep Cleaning Applications

# of Cleaning Applications Over 10-years	Required Carpet Life Extension to Justify Carpet Cleaning (depending on pollutant of concern)												Average
	CO2	**CH4**	**N2O**	**SO2**	**NOx**	**Pb**	**CO**	**VOCs**	**Hg**	**HC**	**PM**	**SOx**	
1	1.28	1.03	0.07	2.20	0.53	0.00	0.20	467.59	3.50	0.41	3.84	0	1.19
2	2.56	2.06	0.13	4.41	1.07	0.00	0.39	935.18	7.00	0.82	7.67	0	2.37
3	3.85	3.08	0.20	6.61	1.60	0.00	0.59	1402.77	10.50	1.23	11.51	0	3.56
4	5.13	4.11	0.26	8.81	2.13	0.00	0.78	1870.35	14.00	1.64	15.34	0	4.75
5	6.41	5.14	0.33	11.01	2.67	0.00	0.98	2337.94	17.50	2.05	19.18	0	5.93
6	7.69	6.17	0.40	13.22	3.20	0.00	1.18	2805.53	21.00	2.46	23.01	0	7.12
7	8.97	7.20	0.46	15.42	3.74	0.00	1.37	3273.12	24.50	2.87	26.85	0	8.31
8	10.2	8.22	0.53	17.62	4.27	0.00	1.57	3740.71	28.00	3.28	30.68	0	9.49
9	11.5	9.25	0.59	19.83	4.80	0.00	1.76	4208.30	31.50	3.69	34.52	0	10.68
10	12.8	10.28	0.66	22.03	5.34	0.00	1.96	4675.89	35.01	4.10	38.35	0	11.87

If a single carpet deep clean can extend the life of the carpet for more than a year, the emissions savings from avoiding the recycling process for an additional year are greater than the emissions that result from the cleaning process. More likely, carpet in offices is deep cleaned at least annually, and if this were the case, the carpet life would have to double for any savings to be realized. These values suggest that deep cleaning carpet to extend useable life is not a viable way to reduce emissions.

It should be noted that the emissions data for the cleaner was obtained directly from the work produced by Guidry (Guidry, 2008). However, the energy requirement data was taken directly from BEES4.0 (NIST, 2007). The energy requirements alone result in lower direct emissions, and therefore the required life span extensions needed when looking at energy alone are much shorter, as shown in Table 42. This is most likely due to the fact that the majority of emissions result in the production of individual chemicals, whereas the BEES4.0 values are based solely on final manufacturing, not including individual production energies of each chemical component. For this reason, the emission values in Table 41 are most likely the most accurate indicator of total environmental impact.

Table 42. Lifespan Extensions Needed for Varying Deep Cleaning Applications with Energy

# of Cleaning Applications Over 10-years	Required Life Extension to Offset Cleaning Emissions
1	7.1E-04
2	1.4E-03
3	2.1E-03
4	2.8E-03
5	3.6E-03
6	4.3E-03
7	5.0E-03
8	5.7E-03
9	6.4E-03
10	7.1E-03

Another way to examine this relationship is to examine how often carpet could be replaced if it is never deep cleaned. If the energy for cleaning is avoided altogether, the carpet could be removed, recycled, and replaced with greater frequency without any increase in overall emissions. This is done by calculating the total emissions from deep cleaning a carpet annually for ten years plus the recycling process and dividing this sum by the recycling process emissions. This calculation determines how many times carpet can be removed, recycled, and replaced in a ten year period if no cleaning occurs, and still maintain approximately equal emissions to carpet that is used for its full lifespan but is deep cleaned annually. The results are shown in Table 43.

Table 43. Carpet Replacement Intervals

Carpet Replacement											
Greenhouse Gases			Criteria Pollutants				Additional Pollutants				
CO2	CH4	N2O	SO2	NOx	Pb	CO	VOCs	Hg	HC	PM	SOx
2.28	2.03	1.07	3.20	1.53	1.00	1.20	469	4.50	1.41	4.84	1.00

For example, if CO_2 is a concern, a carpet can be replaced 2.28 times over 10 years, or every 4.4 years, without exceeding the emissions that would result if only a deep clean was used annually on the same carpet. The values vary depending on the pollutant criteria, but this helps illustrate the impact deep cleaning has on emissions. Deep cleaning may have limited promise as an effective way to reduce emissions by avoiding recycling processes. It should also be noted that the benefits of deep cleaning are likely to decrease over time, and reach a point of diminishing returns. This aspect of carpet maintenance is difficult to analyze with no reliable data existing on the relationship between carpet life and cleaning frequency. Careful judgment should be made by maintenance staff on the rate at which cleaning occurs.

4.13. Recycling and Maintenance Summary

The calculations done with material recycling show the environmental advantage that can be realized when recycling is utilized. Perhaps most importantly it shows which factors of the carpet’s life cycle are significant contributors to emissions, and how addressing these steps can result in savings. Raw material production creates the greatest environmental burden. Nylon recycling releases more emissions than PVC recycling, but PVC recycling occurs at greater volumes. Both recycling processes are significantly better than raw material production, and it is clear that avoiding raw material production is the best way to reduce negative impacts. Leasing should theoretically allow Interface to manage the quality of the material returning to the recycling facility so that the maximum amount of material can be recycled.

The recycling processes defined here in an attempt to recreate the processes used by Interface show that nylon recycling is a significant resource saver, and a major step towards sustainable carpets. However, it is important to remember that the nylon recycling processes assumed in this study may vary from the actual processes. Responsibility remains with Interface to determine what impact their business has on the environment.

Maintenance was included as part of Interface's Evergreen Service Agreement (Oliva & Quinn, 2003). Because carpet has no usage energy the only way maintenance could be deemed beneficial environmentally is if it significantly increased the life of the carpet. As was shown in the life cycle analysis deep carpet cleaning consumed significant energy due to the production of cleaning solution, and the necessary extended carpet life needed to offset that energy was unreasonably long. Vacuuming consumed significantly less energy but its effect on carpet life spans is minimal. Because carpet is a non-durable product with no usage energy there is no opportunity to improve efficiency during use.

Carpet maintenance is a difficult topic to analyze, but the results shown here help illustrate some interesting relationships. Vacuuming is an easy and low impact means of carpet maintenance. Deep cleaning or carpet shampooing, however, has a greater environmental impact due mostly to the production of cleaning solutions. If deep cleaning carpets can significantly increase their useful life it is possible that this would be advantageous. However, it appears from the calculations done in this study that more likely than not deep cleaning does little to reduce overall emissions and should be used sparingly and only when necessary. The advantage of the OEM being in control of maintenance is its knowledge of its products. Interface possess the best knowledge on how to clean its products and therefore can properly maintain the carpet with a minimum of deep cleans or other energy intensive cleaning processes. Regardless, the main environmental advantage comes from material recovery and recycling, whereas maintenance may be equivalent if conducted by either the building owners or Interface.

4.14. Carpet Conclusions

Is leasing green for carpet tiles? Despite the clear environmental benefits to recycling carpet shown here the Evergreen Service Agreement lease was unsuccessful and Interface was forced to abandon the leasing strategy. Although the recycling process was an integral part of the ESA the failure of the lease has not ended the recycling operations which Interface continues to invest in and expand.

ESA's failure is attributed to several factors. It was considered too complex for customers to fully understand. Numerous customers expressed interest in the lease, but turned it down after learning the details of the services (Oliva & Quinn, 2003). It was also difficult for customers to transfer funds from capital to operating expenses in order to purchase the lease (Oliva & Quinn, 2003). The greatest barrier to success for the lease was sticker shock. With the bundling of seven year lease, maintenance, and required reclamation the costs were much larger than facilities managers were used too. Although Interface believed its pricing was competitive, many facility managers were not fully aware of their operations and maintenance costs and could therefore not make an education comparison (Oliva & Quinn, 2003). Despite the inability to garner customers to agree to ESA the material recovery and recycling efforts have continued.

Leasing was argued to be important for material recovery because it allowed OEMs to control the return flow and carpet quality, ensuring that there was a consistent return of material so that a recovery operation can run at optimal efficiency. In Interface's case, however, there has been such a strong public push for carpet recycling that the LaGrange, Georgia facility receives more carpet material than can be processed at its current scale (Nelson, 2008). The flexible process that was designed to recover material from Interface's own modular carpet is also capable of processing material from broadloom carpet and even carpet products from other manufacturers (Nelson, 2008). Various carpet types can be organized at the facility to ensure consistent materials and qualities during specific runs. Different materials can be processed and bailed before being sent to various material suppliers for further recycling. The ability for Interface to remove competitor's carpet and recycle it has actually become a competitive advantage. The company found environmentally conscious customers opting to purchase carpet from Interface because of its ability to ensure the removed material could be recycled.

This is not to say that control over recovered material quality is not important. The LaGrange facility is still relatively small and receives enough material to keep it running at capacity. Interface did not predict such a large public interest in carpet recycling. If recycling operations expand nationally it may become more important to manage used carpet quality. Still, Interface does not want to deny customers the ability to recycle their old carpet, especially if it attracts new customers and provides Interface with free recyclable material, in effect generation a secondary revenue stream (Nelson, 2008). It appears that Interface may focus on conducting quality control at its collection facilities rather than at the customer's buildings. In other words, the success of recycling is not necessarily dependent on the success of leasing and can occur independently.

The properties of carpet are largely responsible for the success of recycling despite the failure of the lease. Most successful product leases occur with items that are durable and retain much of their value after their first life cycle (Fishbein et al., 2000; King, Mursic, & Bufton, 2006; Rose et al., 2002). Carpet, however, is a non-durable product and does not retain much of its value after use. Because carpet can only be recycled and not remanufactured the material is the only redeemable value of the product. The lack of a core or durable properties does allow Interface to accept any manufacturer's carpet for recycling, but the carpet product itself holds little value. The profitability of recycling is therefore directly dependent on the market price of the recovered materials. The environmental advantages gained by recycling show that this is definitely the preferred EOL process, but it also indicates that leasing may not be necessary or advantageous for products with carpet's non-durable characteristics.

4.15. Impact on the Research Questions

In regards to third problem statement of this thesis, a product with much lower usage energy than manufacturing energy and no improving technology does not appear to require leasing to ensure a return stream of material. The significant maintenance emissions compared to usage emissions of carpet also negate any advantage that could potentially be gained with improved maintenance under lease contract.

5. Household Appliances and Vehicles

5.1. Introduction

The average American household consumes approximately 10,656 kWh annually, placing a large burden on the environment ("Energy Information Administration: Official Energy Statistics from the U.S. Government," 2008). In addition, the number of appliances has risen significantly. With increased consumer purchases comes increased disposal of household electrical appliances filled with heavy metals and toxic materials. To promote the use of energy efficient products, Energy Star was introduced in 1992 by the US Environmental Protection Agency (*ENERGY STAR and Other Climate Protection Partnerships: 2007 Annual Report*, 2008; EnergySTAR). The US Department of Energy (DOE) later joined Energy Star to set energy use standards. It is predicted that the tightening standards will have offset $2.1*10^{12}$ of energy consumption in the U.S. by 2020 (Meyers, McMahon, McNeil, & Liu, 2003). In Europe, the Waste Electrical and Electronic Equipment (WEEE) directive was put into place to deal with the growing problem of electronic waste disposal. The legislation requires manufacturers to provide consumers with a means to return their used e-waste free of charge, providing incentives for the manufacturers to recycle or re-use their products leading to closed loop supply chains ("Waste Electrical and Electronic Equipment," 2008). It has been claimed that environmental impacts can significantly be reduced with product design, increased turnover, and operations enhancement (Eades & Marston, 2002).

When leasing durable goods, customers expect relatively new items. This has a tendency to reduce the average age of a product in service. As technology improves and product models grow more efficient, increasing the turnover rates give a lessee more opportunities to pull outdated equipment out of the loop and replace it with newer, more efficient models. In addition, a lessee is responsible for providing a service; its competitiveness in the field is directly related to the quality of the service that it provides. This creates an incentive for regular maintenance and insurance that a product is operating at its optimum performance. However, this overlooks the issue of increased production and remanufacturing operations, which require increased energy and resource usage. The argument made here essentially claims that rapid turn-over is advantageous from a pure energy usage standpoint, but this also means a reduction in product life times, and a shorter life-cycle. This is an obvious disadvantage when concerned with sustainability because it increases consumption of limited resources even though product efficiency is improving.

One of the primary questions posed by this thesis is how increased product turn over potentially promoted by leasing may affect the environment. The aim of this section is to determine if a transition to servicizing will result in improved product replacement, and what effects this has on energy consumption despite increased product volumes. We will explore these questions by focusing on quantifying the energy consumption of specific household products over several life-cycles under different ownership scenarios to determine the potential for energy savings. Leasing will also be studied as a regulator and promoter of reducing energy usage. Dishwashers, clothes washers, refrigerators and vehicle engines will be used as examples. These were chosen because they provide a variety of appliance examples and the results calculated here could be verified with previous literature. The total energy usage over three decades was calculated for each product and for a variety of replacement intervals. If transitioning to servicizing is found to result in significant energy savings, this may suggest both new revenue streams and a vital advancement in resource conservation necessary to combat the global climate crisis.

5.2. Background

Currently, most businesses rely on consumption of goods for profitability with emphasis placed on volume of items sold. Durable goods have been found to have decreasing life spans, a possible result of designed obsolescence aimed at increasing product turn over by manufacturers (O. Mont, 2004). If focus is shifted from products sold to services rendered, it becomes advantageous to have reliable and long-lasting equipment. This is especially true with products where research and development costs are high. With a service-focused business model, the manufacturer has more to gain from improving product performance and reducing the number of service units delivered (O. Mont, 2004). In-use factors can be minimized with maintenance while efficiency improvements and manufacturing burdens can be improved with product take back and remanufacturing.

Regular maintenance can also increase a product's functioning lifetime, reducing the frequency of disposal (O. Mont, 2004). Lessees benefit from lease contracts because they are only responsible for financing the capital costs of a product, which is often cheaper than finance options when buying (P. Desai & Purohit, 1998). The lessor is generally obliged to perform maintenance on leased items. This is advantageous because the lessor retains special knowledge of its products and is in the best position to make repairs and upgrade components (Eades & Marston, 2002). The lessee obviously benefits from having the service available to make repairs (Eades & Marston, 2002). Leasing allows manufacturers to perform regular upgrades, making equipment younger and giving the opportunity for improved technologies to be installed on existing machines (Pongpech, Murthy, & Boondiskulchock, 2006).

Many consumer products, such as white goods and vehicles, incurred the greatest environmental burden during the usage phase of its life cycle (Chalkley et al., 2003; Horie, 2004; Kim et al., 2003; Rudenauer & Gensch, 2005a, 2005b). Energy and water consumption during a product's use can easily outweigh the requirements needed to manufacture that product. Electrolux, a Swedish appliance manufacturer, estimates that 80% of a product's environmental impact occurs during use, the remaining 20% occurring during manufacturing (Allen L. White, Mark Stoughton, & Linda Feng, 1999a). Similarly, vehicles are estimated to consume 85% of its life-cycle energy during use (V. M. Smith & Keoleian, 2004). Studies have found that servicizing has the potential to significantly reduce these in-use impacts by incorporating improved maintenance, extended life span, recycling, and part reuse (White et al., 1999a). Because the majority of emissions occur during use, it is argued that even moderate improvements in efficiency have the potential for significant savings.

5.3. Life-Cycle Optimization and Product Replacement

Another benefit of leasing, in addition to providing incentive for EPR, is the possibility for life cycle optimization. Replacing older products with new, more efficient models has potential to be environmentally beneficial. However, it is important to take into account additional energy and material resources required to produce the newer products. If the manufacturing process requires significant resources, it could negate any advantage that could be gained from efficiency improvements (V. M. Smith & Keoleian, 2004). Life cycle optimization aims to find at what point a product should be replaced based on efficiency gains of newer models while considering manufacturing costs. The maintenance stipulated in lease contracts can be used to upgrade critical components to improve efficiency. Agreements can also outline regular product replacements that align with optimal life spans, reducing household energy use. Remanufacturing can be used to upgrade appliance components which can be re-leased, avoiding landfill disposal and closing the supply chain. The environmental advantage that is gained by using leases to promote optimal life spans depends largely on the energy improvements that can be realized.

5.4. Impacts of Increased Product Replacement

There is a consensus among existing LCO studies that shortening product life spans could reduce energy consumption over time. Unfortunately, users of these goods rarely upgrade the products at the optimum intervals, preferring to keep the less efficient model in service until repairs become too costly or parts failure forces replacement (Horie, 2004). This is in part because the capital cost for replacing the product by purchasing a new unit is too high. Leasing could lower the upfront financial burden on the consumer, allowing more frequent product replacements. In this section we investigate and quantify the benefits of such a strategy in terms of energy savings for a large time span.

5.5. Determining Lease Terms

Operating leases are most common for products leased to businesses, not to private consumers. However, in this paper we assume the terms of an operating lease also apply to consumers. Operating leases ensure the ownership of the product remains with the producer and the producer gets the tax benefit from the depreciation of the product. Since the consumer cannot take advantage of the tax deduction from the product's depreciation but the producer can, it is reasonable to assume that operating leasing will become more common for consumer transactions in the future.

Leasing may lead to increased product replacement because lease terms are shorter than a product’s expected useful life. The length of a lease varies depending on the agreements between lessee and lessor. Industry practice tends to align lease terms with the value of the items being leased. Expensive, big ticket items, such as airplanes, tend to have long lease periods of 10 to 15 years. Small ticket items of less value, such as appliances, often have lease terms of three to seven years (Coyle, 2000). The maximum length of the term is limited by US tax regulations, stipulating that a maximum lease term be no more than 75% of a product’s expected lifetime (Fishbein et al., 2000).

The following section examines the energy savings that can be realized with leasing versus the optimal life-cycle. Although lease terms are flexible and can be adjusted to any length under the limit set by tax regulations, the base leasing scenario will be set at 75% of each product's expected life.

5.6. Calculating Optimum Life Spans

The focus of this study is the extent that leasing may reduce long term energy consumption as a result of increased product replacement. The reduction of energy and number of times a product is replaced over a given timeframe will also be compared to a calculated optimum. Dishwashers, clothes washers, refrigerators and vehicle engines will be used as examples. These were chosen because they provide a variety of appliance examples and results calculated here could be verified with previous literature. The total energy usage over three decades was calculated for each product and for a variety of replacement intervals. Table 44 outlines these scenarios.

Table 44. Replacement Scenarios

Scenario	Product Life Span
Product purchase	Full Life Span
Basic Lease	75% of full life span
Optimal	Calculated optimal replacement intervals for minimizing energy consumption

Because most appliances are currently owned for their entire usable life, this will form the base case with which the other scenarios will be compared. The estimated usable life for each product is given in Table 45. The life spans for the various appliances are based on values from the Association of Home Appliance Manufacturers (AHAM) and vehicle life data is from Kim et al (AHAM, ; Kim et al., 2003).

Table 45. Product Useful Life spans (AHAM, ; Kim et al., 2003; Kim et al., 2004)

Product	Average Useful Life
Dishwasher	13
Clothes Washer	14
Refrigerator	14
Vehicle	20

To calculate the optimum life span of products, the calculation method developed by Chalkley et al. is followed. This method determines the optimum life by "comparing the environmental impacts associated with continued use of an existing product and that associated with replacement by a new product" (Chalkley et al., 2003). Annual energy consumption values are used to evaluate a product's environmental impact. The historical data of annual energy consumption forms the trend line that is used to determine how much energy a product consumes and when it should be replaced. This optimum life span can be found by calculating the energy differences between two model years and comparing this to manufacturing energies. The optimum life span will be the difference in model years that results in the least total energy consumption.

Although numerous factors can burden the environment, attempting to calculate these values would require detailed and complex Life-Cycle Analysis (LCA) studies. Energy usage provides an adequate approximation of negative impacts, especially when the use phase contributes the majority of emissions (Chalkley et al., 2003).

Appliance energy usage trend information was used from a report from the Canadian Department of Natural Resources (*Energy Consumption of Major Household Appliances Shipped in Canada: Trends for 1990-2005*, 2007). Data collected between 1990 and 2005 was used, and the trends can be seen in Figure 26.

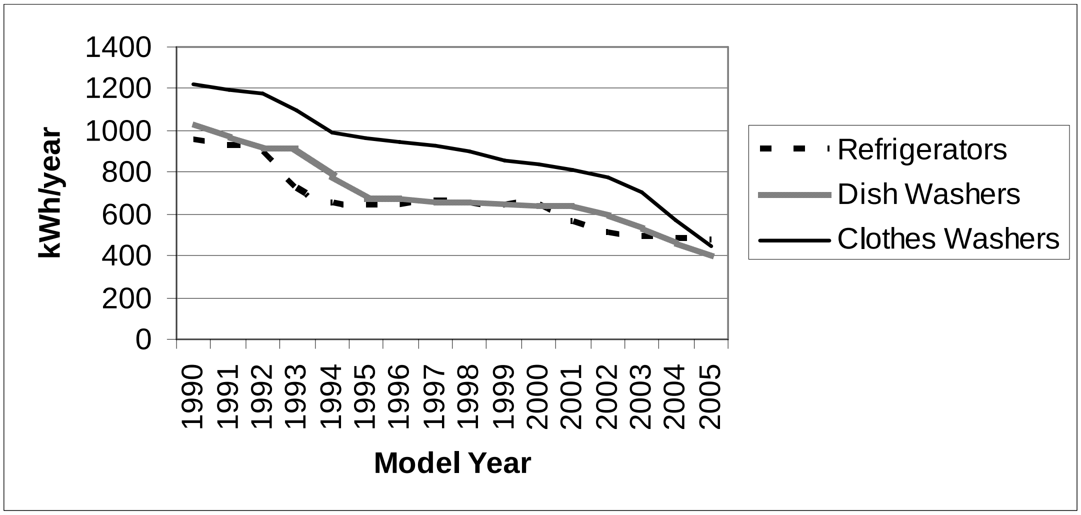

Figure 26. Appliance Energy Trends (*Energy Consumption of Major Household Appliances Shipped in Canada: Trends for 1990-2005*, 2007).

Vehicle fuel efficiency data was obtained from EPA documentation (*Light-Duty Automotive Technology and Fuel Economy Trends: 1995 through 2007*, 2007). The energy usage was calculated from vehicle miles per gallon and the energy density of gasoline. Because no significant improvements have been made in vehicle fuel efficiency in the last 20 years, data had to be collected back to 1975, shown in Figure 27. It should be noted that this study focuses on traditional combustion engines, and does not take into consideration new developments such as hybrid vehicles. Hybrids still account for a small fraction of the total vehicles on the road, accounting for only 2.5% of the total market share in March of 2009, and are therefore not considered a major factor in general automotive efficiency trends ("US Hybrid Sales in March 2009 Down 44% Year-on-Year; Monthly New Vehicle Market Share of 2.5%," 2009).

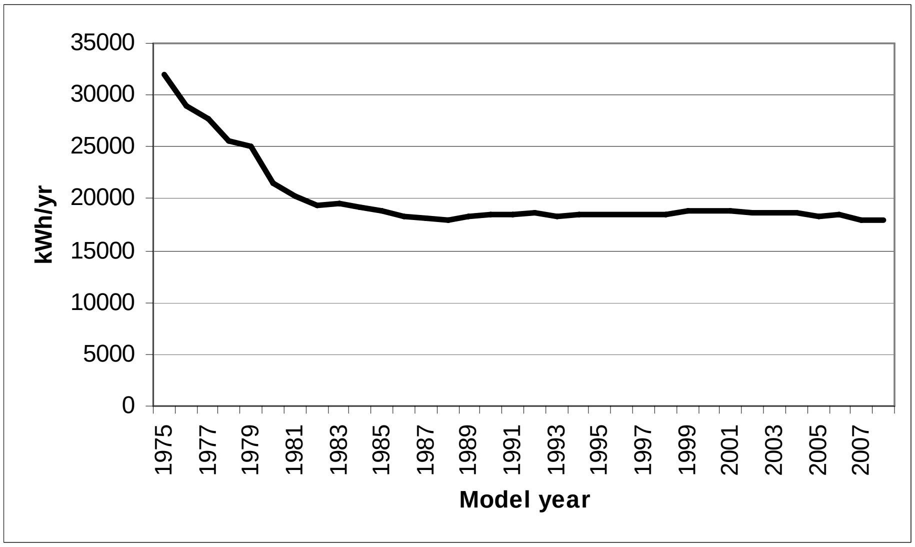

Figure 27. Vehicle Engine Efficiency Trends

Table 46 shows the curves that were fitted to this data, with *t* being the model year. The correlation coefficient R2 is given to indicate the amount of variability that can be accounted for with the given equations. Product designs tend to experience diminishing returns as technology is engineered to its maximum potential (Kim et al., 2006). With the exception of vehicles, an exponential curve was therefore used to approximate trends. Only vehicle efficiency could not be approximated with an exponential curve because of the flattening seen in the last two decades. A power curve was found to more closely follow this trend line.

Table 46. Trend Curve Formulas

Product	Trend Curve	R^2
Dishwasher	Energy (kWh) = -1012.5e^(-0.046t)	0.91
Clothes Washer	Energy (kWh) = -1367.9005e(-0.0526t)	0.87
Refrigerator	Energy (kWh) = -941.95e^(-0.045t)	0.89
Vehicle Engine	Energy (kWh) = -107426*0.157t^(-0.157-1)	0.82

Unfortunately, the efficiency trends of appliances may not always be easily approximated by an equation, and even the curves fitted here cannot account for sudden advances or decreases of efficiency. Regardless, these approximations are adequate for the purposes of this study. The need and frequency for product upgrades is dependent on the slope of the fitted curve with steeper slopes indicating more rapid improvements and therefore more rapid replacements and vice versa. The net effect is always the same with savings being realized and energy savings driving the replacement of older products albeit at varying intervals.

A detailed derivation of optimized life-cycles can be found in Chalkley et al (Chalkley et al., 2003). An abbreviated explanation of the process is explained here. It is assumed that consumers replace their appliances every *n* years. The average age of an appliance is therefore *n/2,* and this average represents the whole population. A start year, *T,* is chosen as the start year the ideal life span will be calculated. At a specific time *T*, the value of *n* that will cause the least consumption of energy is calculated.

The annual energy consumption of the average machine and the latest machine is compared. The difference between these values is how much more energy is consumed by using the existing model rather than a new one.

For calculating the optimal life span, the trend lines are assumed to be locally straight. The variable *t* will be used to indicate the number of years since the beginning of the trend graph. The basic energy equation is represented as:

$$E(t) = Ae^{-Bt} \qquad (2)$$

For the exponential function used with appliances, and

$$E(t) = At^{-B} \qquad (3)$$

for the power function used for vehicle engines. *A* and *B* are the constants from the energy consumption trend graphs. By assuming local straight lines the graphs can be described by $E = mt + c$ (from the standard form $y = mx + b$), where *m* is the gradient of the line at a point, calculated by differentiating equations (2) and (4) as shown.

$$m = \frac{dE}{dt} \tag{4}$$

The excess energy is the difference between the amount of energy that would be consumed by continuing to use an existing machine versus replacement with a new model, found by subtracting the *E(t)* value at one point in time from another. When simplified the resulting equation is given as:

$$\Delta E(t) = E(t)_2 - E(t)_1 = \left[m\left(T - \frac{n}{2} \right) + c \right] - (mT + c) = -\frac{mn}{2} \tag{5}$$

Where *n* is the optimum life span. This now accounts for the energy difference between two different product models. Manufacturing new products also requires energy which adds to the environmental impacts over a product’s life. The manufacturing energy per year is expressed as *b/n*, where *b* is the energy usage to produce a product. The total energy required is the combination of usage energy and manufacturing energy, defined by Chalkley et al. as the variable energy *V*.

$$V = \frac{b}{n} + \frac{mn}{2} \tag{6}$$

The optimum life span will be the time in which both usage and manufacturing energy will be smallest. The minimum value of *V* is found by differentiating equation (5). Because *dV/dn* is equal to zero, the differentiation can be equated to zero and then rearranged to solve for *n*.

$$n = \sqrt{\frac{2b}{-m}} \tag{7}$$

Equation (7) requires a value for the slope at a specific time. Ideally, the annual consumption of the average-aged machine at a given time would be used. The slope value for these average-aged machines occurs at (*T-n/2)*, but at this point *n* is unknown. Therefore, an initial calculation step is performed at time *T* to obtain a value for *n*. The process is then repeated with a new start year at (*T – n/2)* and repeated until a consistent answer is reached, resulting in the best estimate of the optimum lifespan. This concept is illustrated in Figure 28.

An iterative process is used with this calculation. The optimal life span for every model year is calculated to determine how long a product should be used at any given time. A product is used for however long the optimal life span was calculated to be at its purchase. When the item is replaced, the new unit is used for the optimal duration determined for the replacement model year and so forth. For the sake of completeness and reproducibility, a detailed example using the clothes washer scenario is given in Appendix A.

The life-cycle optimization calculations are conducted for two major cases. The first case assumes that at the end of a life span the old appliance is discarded and replaced with a newly manufactured model. The *b* value in equation (7) is the amount of energy required to produce a new good from raw materials. This additional energy is added every time the product is replaced. The second case examined assumes that an appliance is remanufactured at the end of its life, not discarded and replaced. The *b* value is adjusted accordingly to account for remanufacturing energies which are added every time a unit is replaced.

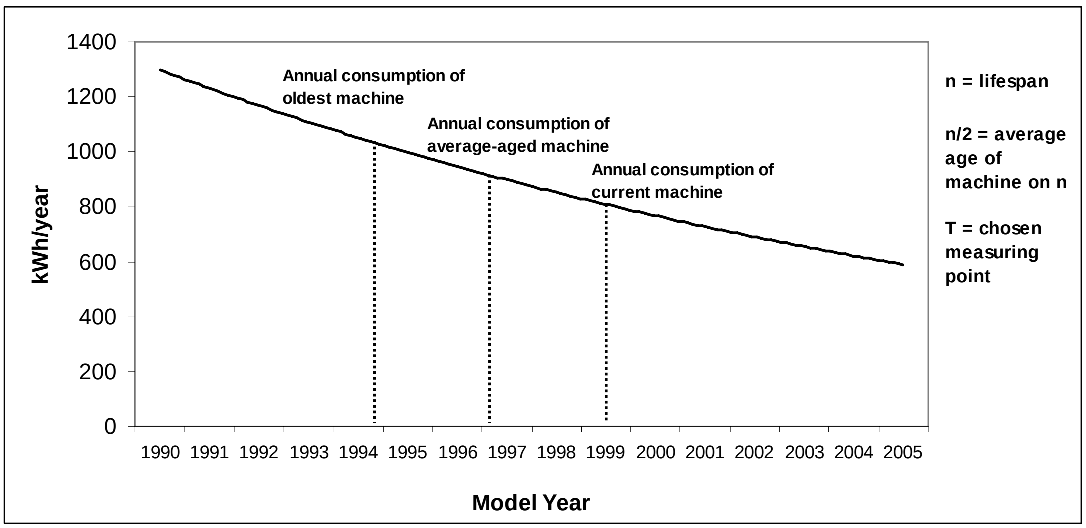

Figure 28. Energy Consumption Trend Showing Significant Points (Chalkley et al., 2003)

5.7. Assumptions

The following assumptions were made.

- Because customers already own these appliances for nearly their full life span (AHAM), it is assumed that they would not require updated styling as their appliances are upgraded over time.

- Only energy consumption is examined in this study. No consideration is made for global warming potential, greenhouse gases, waste water, and other emissions. Although this is not considered adequate for a full environmental assessment, it is sufficient when attempting to gain a better understanding of possible trends. Vehicle data is concerned only with energy (calculated from mpg). This does not consider improved emission standards. Overall environmental impacts may improve but are not considered here. Hazardous chemicals such as toxic refrigerant fluids are also not accounted for.
- Transportation is not included in the calculations for energy consumption. Transportation impacts are insignificant compared to the manufacturing or usage phase of products (Chalkley et al., 2003; Govetto, 2007; V. M. Smith & Keoleian, 2004).
- Damage to products during transportation is not considered a major factor in this study. Minor damage can easily be repaired as part of the remanufacturing processes. In addition, because the OEM is assumed to be responsible for transportation services, design of reusable packaging aimed at improving product mobility could potentially reduce transportation related damage.

5.8. Results

Sections 5.8.1 and 5.8.2 are concerned only with optimizing life-cycles when new products are produced to replace old products with no remanufacturing. Section 5.8.3

recalculates the optimal life cycles with products being remanufactured at the end of every life-cycle, rather than being replaced with new products.

5.8.1. Optimal Life Cycles

For the following cases when a product is replaced, the old model is assumed to be discarded. If a product is recycled, the required processes have added energy costs to perform the process. For simplification no end-of-life process energy is included, which is analogous with the items being discarded in a landfill.

A summary of the calculated results are shown in Table 47 and compared with the replacement intervals for full life spans and leasing. The year value indicates how long a product should be used before being replaced starting in 1990 for appliances and 1975 for vehicle engines. Although appliance trend data is only available until 2005, it is assumed the trends continue onward until 2020 to provide a long enough timeframe for relationships to emerge.

Table 47. Replacement Intervals

Product	Scenario	Replacement Intervals
Dishwasher	Full Life Span	13, 13, 13
	Lease (75% of full life span)	10,10,10
	Optimal Life Spans	4, 4, 5, 6, 6, 7
Clothes Washers	Full Life Span	14, 14, 14
	Lease (75% of full life span)	10,10,10
	Optimal Life Spans	4, 5, 6, 6, 7, 9
Refrigerators	Full Life Span	14, 14, 14
	Lease (75% of full life span)	10, 10, 10
	Optimal Life Spans	7, 8, 10, 12
Vehicle Engine	Full Life Span	20, 20
	Lease (75% of full life span)	15, 15, 15
	Optimal Life Spans	1,1,2,3,4,5,6,7,8

The optimum life span of the products varied over time as efficiency gains increased or decreased. For the best savings to be realized, the product must be replaced at varying intervals.

5.8.2. Long Term Energy Savings with New Product Replacement

The energy consumption for dishwashers over the thirty year period is shown in Figure 29. Utilizing the product for its full 13 year life span demonstrated the highest energy consumption, with a hypothetical 10 year lease (75% of 13 years) being slightly improved. Even the calculated optimal replacement strategy was only slightly better. The 30 year savings earned with the optimal replacement strategy given in Table 48 is approximately 2,600 kWh less than the 13 year life spans, a 13% savings.

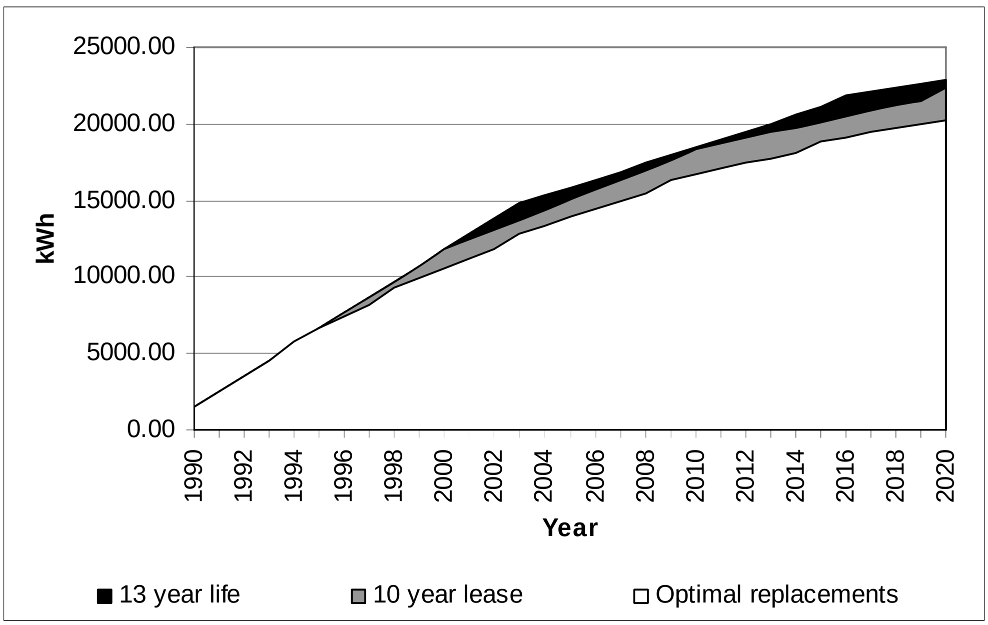

Figure 29. Dishwasher Lifetime Energy Consumption

Clothes washer results were similar, shown in Figure 30. The base case of a clothes washer only being replaced after its full life consumes 28,218 kWh over 30 years. The leasing case has a small improvement of 27,809 kWh. Optimizing the life span further reduced this to 25,695 kWh and six replacements over the same period, a 9% savings when compared to the full life scenario.

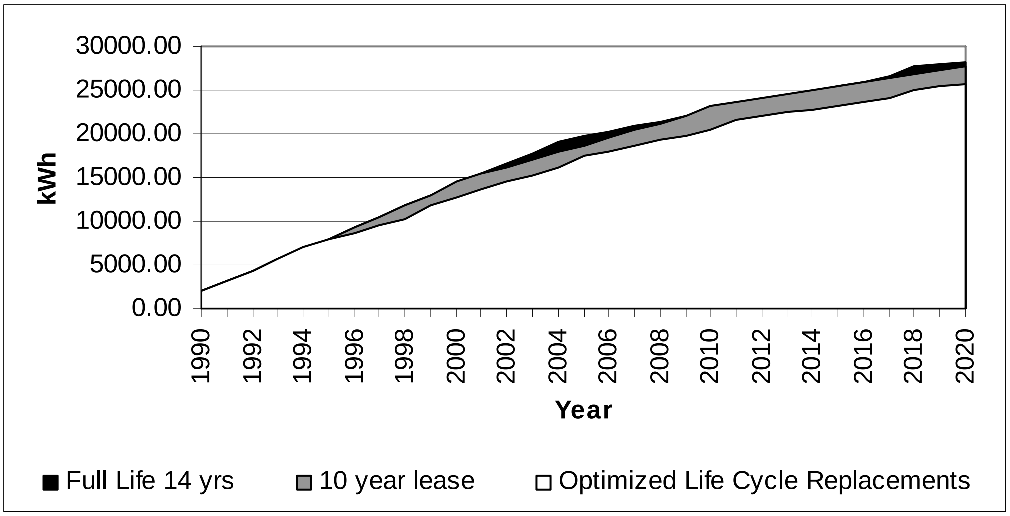

Figure 30. Clothes Washer Lifetime Energy Trends

Refrigerators were the only appliance in this study that was assumed to undergo significant performance degradation over time. Studies have found that even with regular maintenance refrigerators experience degrading efficiency over time (Horie, 2004; Kim et al., 2006). To account for this decreasing efficiency an equation was used and applied to the energy requirements. This equation was derived by an analysis by Johnson and also used by Kim et al. (Johnson, 2000):

$$\Delta E = r\left(\frac{20-a}{20}\right)^{c} \tag{8}$$

ΔE is the annual increase in energy, a the age, and r and c are constant values calculated by Johnson to account for losses (r=0.045 and c=2.5 where used in this study) (Johnson, 2000). The decreasing efficiency over time coupled with the rapidly improving efficiency of new models causes the dramatic saw-tooth shaped graph shown in Figure 31. Each dip occurs when an old model is replaced with a new unit. The new model is initially more efficient, but begins to degrade causing a steeper slope than seen with other appliances. The total energy consumption for all three scenarios were unexpected with leasing and optimized replacement both having slightly higher values than the base case. Leasing consumed 405 kWh more, and the optimized rate consumed 142 kWh more than full-life ownership. Figure 31 shows the optimized replacement rate consuming less energy than the other cases for most of the time period. Occasionally, this value climbs higher due to reducing efficiency until replaced. The mathematical method used is not trying to reduce consumption within the specific 30 year timeframe, but works continuously as time progresses. As a result, the total energy consumption may exceed other scenarios before the calculations determine the product should be replaced at a specific time. Despite this, the optimized replacement intervals result in lower power consumption for the majority of the product life.

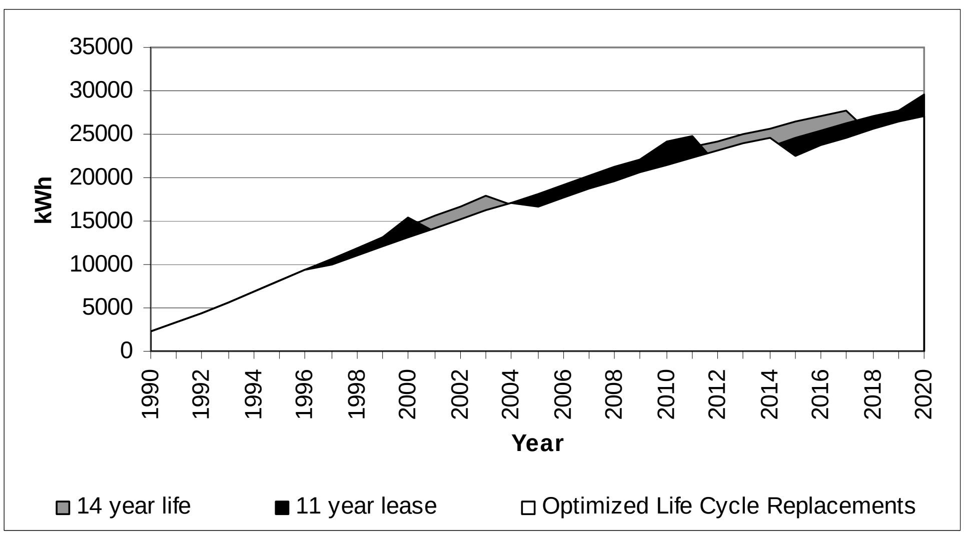

Figure 31. Refrigerators Lifetime Energy Trends

Engines exhibited a slightly different pattern. Automobile engine replacements were far less common than the appliances. This is largely due to the lack of efficiency improvements made to vehicles in the last 20 years. In fact, data collected from the EPA showed a slight decrease in efficiency, most likely due to the proliferation of large SUVs in the vehicle market. Despite this, a marginal improvement is still obtained through optimized life spans. Leasing saved 67,909 kWh over the period examined, an 8% improvement. The optimal replacement intervals reduced this an additional 109,090 kWh, or a 20% improvement overall.

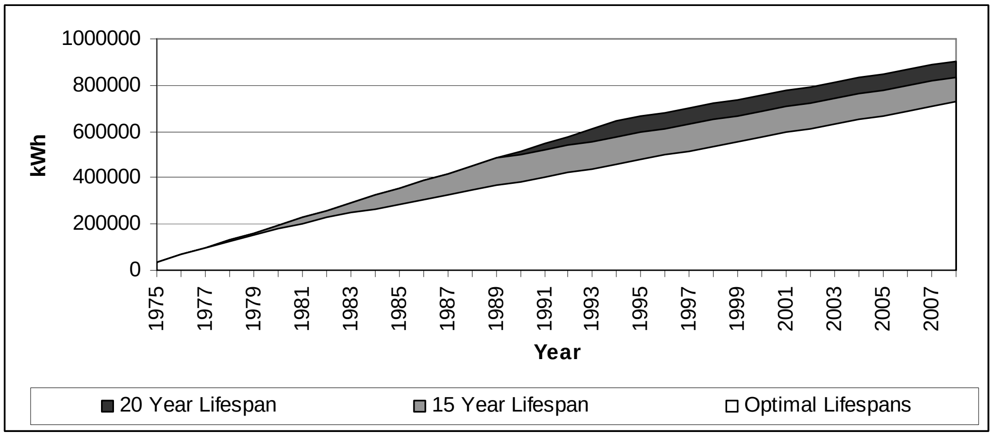

Figure 32. Vehicle Lifetime Energy Consumption

5.8.3. Long Term Energy Savings with Remanufacturing

The preceding results show only a marginal improvement when the basic lease case is implemented. Replacing products when they reach 75% of their expected life slightly increases product turnover, but still remains less desirable than the optimal intervals calculated. There are further opportunities for leasing to reduce energy consumption when remanufacturing is included.

As discussed earlier, research has found leasing to be beneficial environmentally not for its affect on product turn over, but on its promotion of extended producer responsibility (EPR). The management of a product at the end of its life can be a significant factor in its overall environmental impact. EPR encourages firms to recycle or better yet, remanufacture old products, which requires significantly fewer resources than producing products from virgin materials. This section recalculates the optimal life-cycles with remanufacturing being used instead of products being disposed of and replaced with new models. Several additional conditions and assumptions are also made.

- At the initial purchase in the year 1990, the product is manufactured from raw materials, and the full manufacturing energy is included at this point.
- All following replacements result in the product being remanufactured. Remanufacturing the same product can occur as many times as necessary for the remaining time frame.
- When a product is remanufactured, its efficiency is made equivalent to the current model year.
- Transportation is again not included in the calculations for energy consumption. Energy consumption and emissions are minimal compared the manufacturing or usage phase of products (Chalkley et al., 2003; Govetto, 2007; V. M. Smith & Keoleian, 2004).

It should also be noted that this is a best case scenario. In reality there may be other factors that limit the efficiency improvements that can be made through remanufacturing. It is possible that in order for efficiency gains to be made all major components need to be replaced, further increasing the remanufacturing energy requirements. Or it may be that upgrading a few vital components does not achieve the same level of efficiency as a brand new product. If large jumps in technological innovations are made, it might not be possible to remanufacture the products to like new condition, and a phase of brand new manufacturing would need to take place. Despite these issues, the calculations performed here are aimed at finding relationships and trends more than determining exact energy values.

No remanufacturing energy requirements were found for dishwashers, so this product is not included in this comparison. Table 48 compares the energy requirements for manufacturing and remanufacturing. Remanufacturing values for washers and refrigerators were calculated by Hilden et al., and vehicle engine values were calculated by Kim et al (Hilden, Kumpulainen, Mattas, & Nikkanen, 2003; V. M. Smith & Keoleian, 2004). Manufacturing values include raw material processing as well as product assembly.

Table 48. Energy Requirements for Manufacturing and Remanufacturing

Product	Manufacturing (kWh)	Remanufacturing (kWh)	Source
Clothes Washer	750	24	(Hilden et al., 2003)
Refrigerator	1182	20	(Hilden et al., 2003)
Vehicle	11600	3740	(V. M. Smith & Keoleian, 2004)

The same calculation method developed by Chalkley et al. is used. When a product is first purchased (in 1990 for appliances and 1975 for engines), the energy required to manufacture that product from raw materials is included. Every time the unit is replaced in following years, a remanufacturing energy value is added to account for this process. With smaller energy requirements at each replacement period, less time is required before the energy savings of newer models offsets the energy needed to remanufacture a product. The result is shorter optimal life spans and more frequent upgrading, indicated in Table 49.

Table 49. Optimized Life Spans with Remanufacturing

Product	Replacement Intervals with Remanufacturing in Years (starting in 1990)	Total kWh
Clothes Washers	1,1,1,1,1,1,1,1,1,1,1,1,1,1,2,2,2,2,2,2,2,2	21,230
Refrigerators	1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,2,2,2,2,2	16,059
Vehicle	1,1,1,1,2,2,2,2,3,3,3,4,4,4,5	712,596

For both clothes washers and refrigerators, the optimization found that the remanufacturing energies were small enough to promote a yearly remanufacturing schedule to benefit from efficiency improvements for much of the 30 year period. Vehicles experienced rapidly improving efficiency beginning in 1975, resulting with short optimal life spans early on. However, as the efficiency gains diminish significantly for the remaining time frame, the recommended life spans grow.

Remanufacturing clothes washers regularly can save up to 6,988 kWh of energy over the 30 year timeframe. Using remanufacturing reduces energy use 17% over the previous optimum scenario when products were disposed at the end of each term.

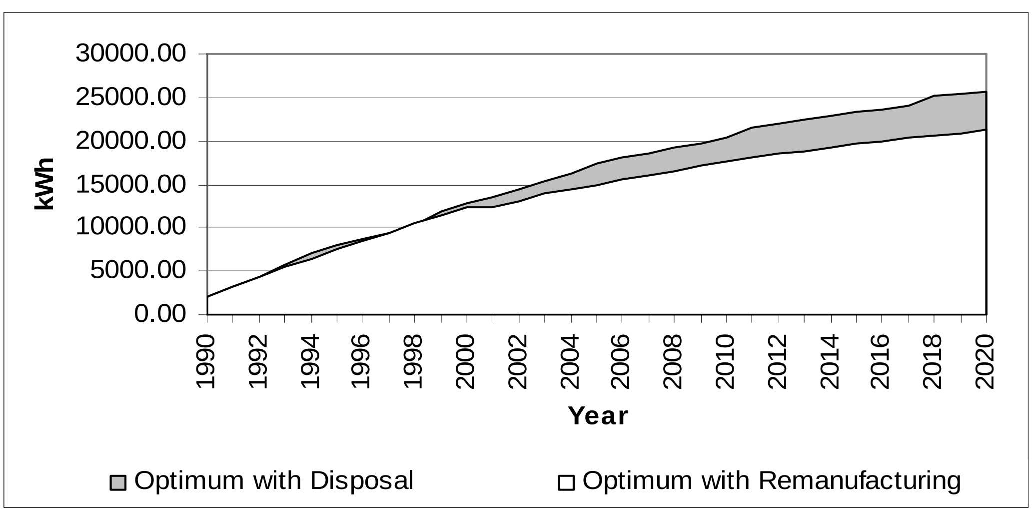

Figure 33. Clothes Washer Comparison with Remanufacturing

The optimized life spans with remanufacturing resulted in bigger energy savings when applied to refrigerators, as shown in Figure 34. Even with very short life cycles, remanufacturing of refrigerators reduces energy consumption over the 30 years by 38%.

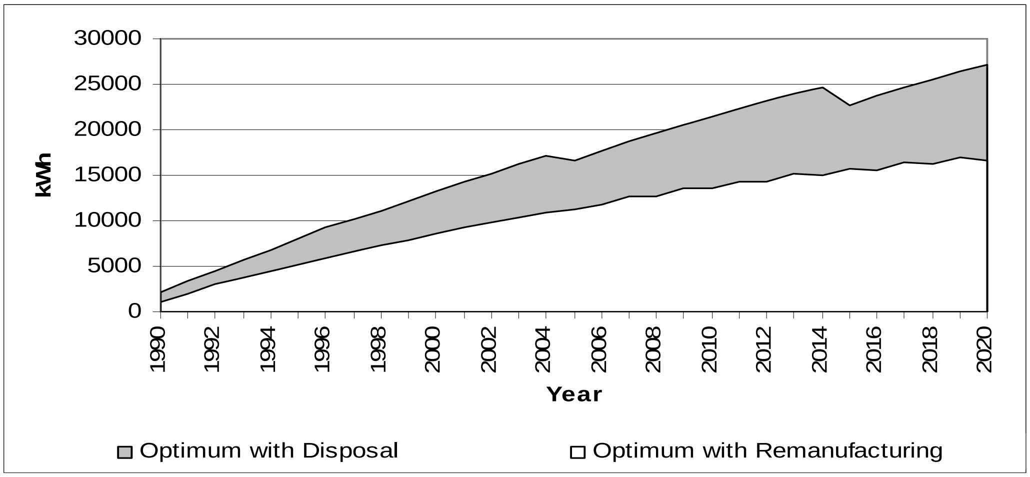

Figure 34. Refrigerator Comparison with Remanufacturing

Vehicle engines showed the greatest total savings with 191,594 kWh of energy saved when remanufacturing was combined with optimized life spans. Over the 30 years that this vehicle operates, it consumes 727,191 kWh. This is a 20% savings over operating the engine for its full life-span. The impact was made when remanufacturing occurred early in 1976 and 1979, which reduced the rate at which energy was consumed early in the engine’s life during a period when engine efficiency was significantly improving. This reduced its energy consumption for the remaining years despite decreasing efficiency improvements within the last two decades. The improvement seen when remanufacturing is implemented is notably less dramatic compared to household appliances. The comparison is shown in Figure 35, which shows only a 2% improvement when remanufacturing instead of disposal is utilized. The savings with remanufacturing are limited in this case because fewer remanufacturing cycles are conducted, and the resulting energy savings from technical improvements are minimal during much of the engine's life. This is due to the limited progress made in efficiency in the later half of the time period.

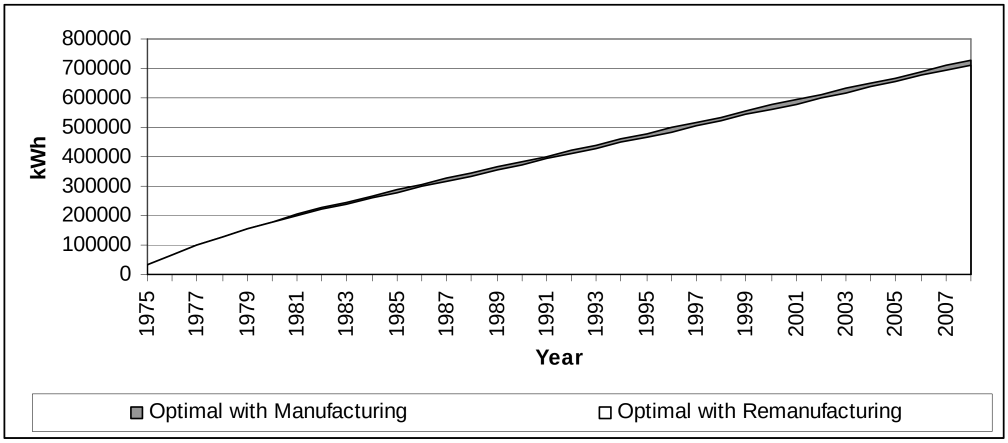

Figure 35. Vehicle Engine Comparison with Remanufacturing

The data used for vehicle fuel mileage is an aggregate view of vehicles in the US. The proliferation of SUVs has therefore offset many of the efficiency gains made. If a more category specific study was done that focuses on the specific vehicle class or engine displacement then the efficiency trend curve would most likely have a greater downward slope and therefore could benefit from LCO more. This would result in possible larger savings than found here.

Table 50 reiterates the savings that could be achieved with each of the scenarios discussed. The savings for refrigerators when using the basic leasing scheme or optimization with disposal are negative, as a result of the timing discussed earlier in Section 4.2.

Of the examples used in this study, vehicle engines that are remanufactured while rapid improvements were being made saved significant energy largely due to the long timeframe examined here. However, the savings are small compared to the total life-time emissions of the engine, which in the best case still consumed 712,596 kWh. Refrigerators were most improved when manufacturing was implemented, with a 38% reduction in energy consumption. These significant savings are due to the rapid efficiency improvements made in refrigeration technology. This demonstrates the importance and potential of efficiency improvements in common appliances. Remanufacturing improved the savings that can be realized when combined with optimized life cycles, but even without remanufacturing, optimized life spans can be seen to reduce energy usage.

Table 50. Energy Savings Comparison

		Energy Savings (1990-2020) [kWh] (%)		
Product	**Full Life [kWh]**	**Lease (75% of full life)**	**Optimized**	**Optimized with Remanufacturing**
Dishwasher	22,827	481 (2%)	2607 (11%)	-
Clothes Washer	28,218	408 (1,4%)	2,523 (9%)	6,988 (25%)
Refrigerator	27,003	-405	-142	10,308 (38%)
Vehicle Engine	904,191	67,909 (7.5%)	176,999 (20%)	191,594 (21%)

Leasing as it was applied in this study had a very small impact on energy savings, but perhaps not enough to justify signing a lease contract. It is clear that basing lease terms only on a percentage of the estimated useful life of products is not a reliable way to reduce emissions.

Additional scenarios could be examined, such as using the 75% lease terms and combining this with remanufacturing. However, this is not necessary because using optimal life cycles in combination with remanufacturing is a best case scenario. Both strategies have been shown to reduce energy usage individually in previous studies and in the calculations shown here. It can be safely assumed that combining the two methods will result in the maximum savings possible.

5.9. Maintenance

Unlike carpet, appliances and vehicles are durable goods with high usage energy and product performance during this time has significant environmental impacts. With improper maintenance a product’s performance can degrade resulting in poorer fuel efficiency. Refrigerators and vehicles in particular have been shown to suffer from performance degradation during use (Horie, 2004; Kim et al., 2006; Norman, Huff, & West, 2009; V. M. Smith & Keoleian, 2004). Research has shown that following the manufacturer’s maintenance schedule the lowest emissions over time and mileage is attained (*Degredation Effect on Motor Vehicle Exhaust Emission*, 1976).

The issue is that maintenance, because it does not involve upgrading components, can only bring a product’s efficiency back to its original state. In addition, each maintenance operation requires resources and energy. Replacement of parts such as spark plugs, cooling coils, gaskets, air filters, and oil all require energy, adding to the net impact. This can be visualized in Figure 38.

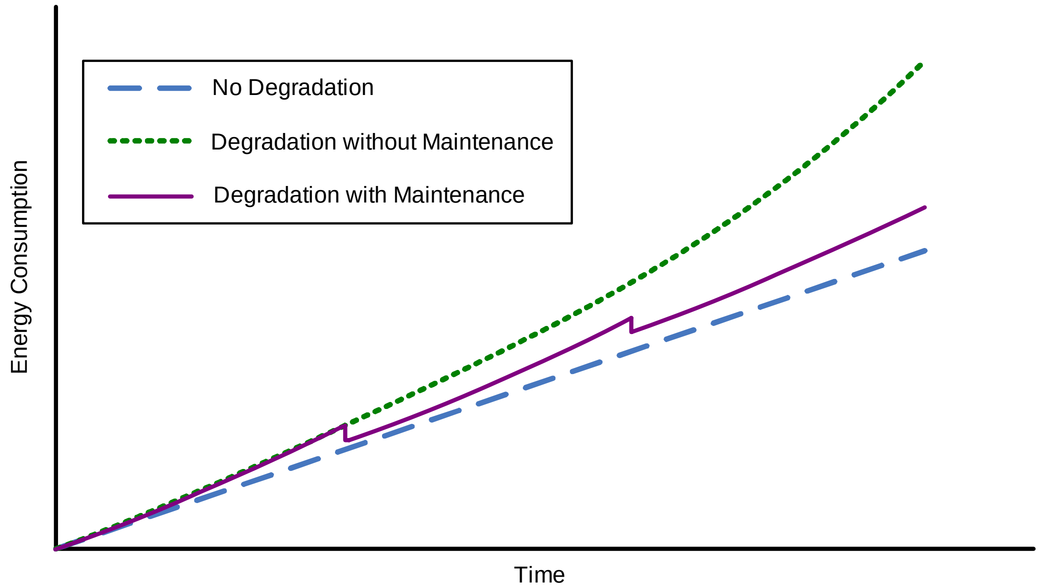

Figure 36. Performance Degradation and Maintenance

The dashed blue line shows an ideal situation where efficiency remains the same during the entire usage phase. Without any maintenance a product's performance can degrade significantly hampering fuel efficiency as shown with the dotted green line. Regular maintenance can help offset this degradation, but the usage phase energy consumption can never return to the ideal scenario because each maintenance operation requires resources and energy.

It is important to perform studies on the impacts of maintenance for deciding how best to implement a maintenance policy. Refrigerators experience performance degradation as gaskets become less effective and coils collect dust over time. However, a study conducted by Meier et al. found that maintenance and replacement of these parts made no apparent efficiency improvements (Meier & Megowan, 1993). These results are confirmed by Kim et al. which found that the mechanism of performance deterioration for refrigerators is still unknown (Kim et al., 2006).

Vehicle performance has been shown to be linked to proper maintenance. Fuel efficiency can degrade as much as 3.4% after 7000km on vehicles such as buses (Ang & Deng, 1990). Considering the number of miles that may be traveled this is significant. Maintenance is relatively low impact compared to the overall usage energy and should therefore be practiced with regularity (Kim et al., 2003). However, it is clear that maintenance cannot be used to improve efficiency beyond the original design.

The impact of regular maintenance versus no maintenance on a vehicle is calculated here as an illustration. Assume a vehicle averages 24.1 miles per gallon and travels 12,000 miles a year. This is equivalent to consuming 17,911 kWh annually. Three scenarios are compared here. The first is an ideal situation where no performance degradation occurs and the vehicle achieves its maximum fuel efficiency every year for its 20 year life span. The second assumes a 5% degradation in fuel economy each year due to wear and tear. In this situation no maintenance is performed during the vehicles life time and therefore the vehicle's annually energy consumption continually grows. In the final case a thorough maintenance operation is performed such as replacing spark plugs, air filters, and oil every five years. It is assumed that this operation returns the engine to its initial efficiency level. The energy requirement for this process is assumed to be 553 kWh. This value is taken from Smith and Keoleian's lower estimate for engine remanufacturing (V. M. Smith & Keoleian, 2004). Although the value is taken from a remanufacturing estimate it is the minimum amount of remanufacturing work that can be performed on an engine and is therefore a reasonable approximate to basic maintenance work and adequate for the example given here.

Figure 39 shows the resulting scenarios. The first case where no degradation occurs is a straight line. When degradation occurs with no maintenance, the vehicle's total accumulated energy consumption increases significantly. If maintenance is performed at regular five year intervals this significantly reduces the vehicle's energy usage as shown. However, this maintenance scenario never returns to the ideal case where efficiency remains constant. This is because every maintenance operation requires energy in the form of spare parts or fluids. This adds to the net energy usage of the vehicle. Even though the engine is assumed to return to its highest efficiency level after maintenance, the impact of maintenance prevents this scenario from ever returning to the ideal case.

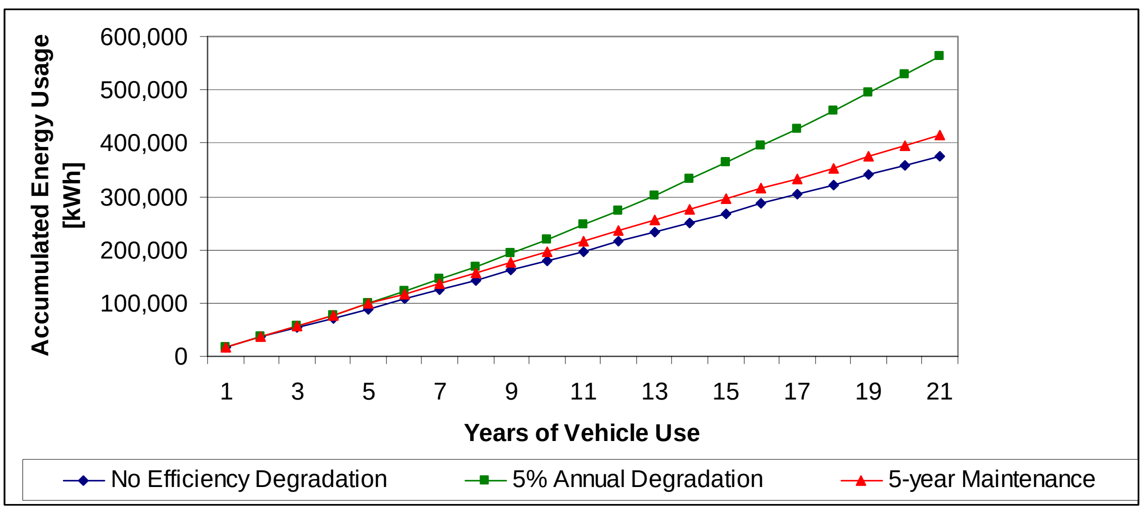

Figure 37. Comparison of Vehicle Maintenance Impact

5.10. Conclusions

OLC has potential to reduce long term energy consumption of common consumer products. When remanufacturing was used to upgrade components and improve efficiencies, much greater savings were realized. The amount of savings that can be made also depends heavily on the rate of efficiency improvements being achieved in the industry. This shows strong potential for OLC when remanufacturing, rather than disposal, is used. Government legislation has already made it prudent for companies to begin considering recovery strategies, and product efficiencies will continue to improve.

The regular maintenance required in a standard lease agreement can be used to make basic improvements on appliances and ensure they are running at maximum efficiency. Leases also provide manufacturers with information on the use and condition of its products, allowing them to make the best decision when to replace items (Chalkley et al., 2003). Given the resources available to manufacturing companies, replacement units could be delivered and installed into households with the older models returned to remanufacturing facilities.

For manufacturers there are opportunities to increase their profit margin with leasing. Studies have found that companies who specialize in functional sales are rated higher by investors than companies focused on products, increasing their stock value. This may be connected with findings that suggest higher profit margins are made on services than on products (O. Mont, 2004). Energy is not the only component put into manufactured goods. Resources and labor are significant costs during production. Remanufacturing was found to retain approximately 85% of the energy used in its original manufacturing (O. Mont, 2004). Significant savings can be made by re-leasing products to customers rather than dumping the items into landfills. For consumers, purchase of services replaces the need for capital investments. This reduces the upfront costs to consumers. Appliances and vehicles are also taxable property for the lessor, providing further financial incentives to OEMS to lease their products (White et al., 1999a).

Despite the various combinations and strategies that can be used to minimize energy consumption this studies clearly reveals the impact of the usage phase. Even in the best case, the savings remain a fraction of the total energy usage over many years. This shows that the biggest improvements can be made not by how often a product is replaced and how, but how often it is used. It may be necessary to fundamentally rethink the usage pattern of many products to obtain the savings needed to reduce their global impact. Compounding these limitations is the lack of monetary savings. Although significant kilowatt hours may be saved, when translated to dollars the savings are less impressive. In the state of Georgia, for example, the average residential cost of a kilowatt hour is 10.89 cents (EIA, 2009). Refrigerators saw significant energy savings, with a reduction of 10,308 kWh with optimal life cycles and remanufacturing. However, this translates to only a $1,112 savings over a 30-year time frame, not nearly the volume you would need to gain consumer acceptance.

5.11. Impact on the Research Questions

In regards to problem statements 1 and 2, LCO has showed that increased product turnover and shortened life spans can actually be beneficial for the environment. However, this is only true for products categories that exhibit technology improvements with each new model and have their greatest environmental impact during the use phase.

How is leasing related to this? In chapter 2, many papers argued that remanufacturing is a result of the EPR that can result when leasing is adopted by manufacturers. Because of the capital costs, consumers will replace expensive goods as little as possible, using products for as long as it continues to function. It can also safely be assumed that consumers would not voluntarily follow the optimal replacement terms especially when this should occur frequently as seen with refrigerators or clothes washers. Leasing transfers this responsibility to the manufacturer. The flexibility offered in leasing can be used to control product flow of varying replacement intervals necessary to make remanufacturing optimal.

6. Computers

6.1. Introduction

Computers are similar to household appliances in that they both have high usage energy costs. However, unlike appliances or vehicles, computers have a short life span, which makes for some interesting contrasts to white goods. For this reason, computers are chosen as the third case study of this thesis to draw some similarities and contrast with the product characteristics already discussed. Numerous LCAs on computers and their associated monitors have been produced, and several studies on the environmental impacts of replacement practices have also been studied.

As mentioned in the literature review Thurston and de la Torre found that longer lease periods are associated with improvements in cost and environmental impact (Thurston & de la Torre, 2007). This point contradicts what was often found when optimizing life cycles of household appliances. In those cases, shortening the average life span to take advantage of improving technology was usually found to be beneficial. There are several reasons the environmental impact of computers is found to be lower when their life cycle is extended.

1. Computers have an extremely short user-preferred life span.

   The average life cycle of a computer is found to be between two and four years (Choi et al., 2006; Neto & Bloemhof, 2009). The actual functioning lifetime of a computer is much greater, but given the rapid technical improvements continually being made, consumers choose to replace their computers frequently, well before their functional life time is reached. In addition, the average life cycle of a computer has been found to be decreasing steadily through the decades (Babbitt, Kahhat, & Babbitt, 2009). This shortened life span also reduces a unit's use energy, decreasing usage impacts compared to manufacturing processes.

2. Computers do not necessarily exhibit a trending improvement in efficiency

   Over the years there have been improvements motivated by government action such as Energy Star (Roberson et al., 2002). Power management software has also become more common in recent years. Power management is used to automatically reduce the energy consumption of computers by allowing the computers to 'sleep' while it is not in use. Setting can be adjusted to turn off monitors or hard drives after a computer has been idle for a certain amount of time (Roberson et al., 2002). Unfortunately, no trending data on the availability or use of power management is available, nor is there any way to ensure its proper use in the office or home (Kuehr & Williams, 2003). Additionally, even as computer components become more efficient they also become more powerful, negating any energy savings in favor of power. Overall, despite progress in reducing power consumption, computers energy trends are difficult to track given so many variables (Sanchez, 2008).

6.2. Computer Impacts

Unlike household appliances or vehicles there does not appear to be a trending improvement in overall computer energy efficiency. This is likely due to several reasons.

Computer processor chips have become more efficient, but they simultaneously become more powerful as consumer demand drives up performance. This is true with all components of a computer (video cards, hard drives, etc.), and any improvements made in efficiency are likely offset by increased performance demand. Determining a trend in computers is difficult because of the large variety of computers available to consumers. Various levels of computer performance are available to cover both low-end and high-end demand. At any point in time there are computers with very small power demands and very large.

An extensive literature search was done to obtain the energy requirements for the various stages of a computer's life cycle: manufacturing, use, and end-of-life. Table 51 is a compilation of these values found for studies done that included both a computer and CRT monitor in the calculations. The inclusion of the monitor is not ideal, but more data existed with this scenario than with the computer unit alone, and therefore all calculations assume that the computer and monitor and included together. Much of the data used here has been collected by Neto et al (Neto & Bloemhof, 2009). The originating sources have been cited in Table 51, but not all the documents could be found by this author. This makes it difficult to ensure consistency among the sources for factors such as usage time and computer wattage. Work conducted by Williams was available and these sources consistently use 3 hours a day for 365 days a year as the usage amount and combined computer and monitor usage wattage between 114 and 128 watts (E.D. Williams, 2004; Eric D. Williams & Sasaki, 2003). All the sources produce values within the same magnitude and with fairly consistent results, so it can be assumed other sources use at least somewhat similar usage and power values.

Table 51. Energy Requirements for Computer Processes

Source	Manufacturing [kWh]	Use [kWh/yr]	Recycling [kWh]	Upgrade [kWh]
(Eric D. Williams & Sasaki, 2003)	1556	126	1478	486
	2500	127	1178	
(Aanstoos, Torres, & Nichols, 1998)	2130		1600	
(Kuehr & Williams, 2003)	1400	233		
(*EU Ecolabels for personal computers. Full Draft Report.*)	1009			
(E.D. Williams, 2004)	2033			
(E. Williams, 2006)	1778	176		
(Gotthardt et al., 2005)		242		
(E. Williams, Ayres, & Heller, 2002)		208		
Average	1772	185	1419	486

What is clear from this table is that there is little agreement on the exact values. This is most likely due to the huge variety of computers available and the changing technology and features available to consumers. Regardless, these values are sufficient to put forth several ideas and concepts in this section.

6.3. Computer Life Cycle System Boundaries

Manufacturing energies in this case would ideally include raw material acquisition and processing. Much of the LCA literature lacks explicit mention of these processes and appears to include this energy in the general manufacturing value. Where available literature was used that clearly states the various processes included in the manufacturing value, Aanastoos et al. being the best to document this (Aanstoos et al., 1998). The manufacturing values shown here are reasonably consistent and it is therefore assumed that all manufacturing values include raw material acquisition and processing. For further clarification the system boundaries are defined here:

Manufacturing: Manufacturing energy values for computers includes the collection or processing of raw materials, sometimes labeled pre-manufacturing. This is the energy required to process the material from raw materials followed by refining, forming, heat treating, or other process step, resulting in a finished material ready for use in manufacturing. The production-line energy is then added to this.

Recycling: Recycling includes the energy required to break down a computer into its constituent materials and process them back into a manufacturable form, where the standard manufacturing process takes place again. Given the complexity and variety of materials present in a computer or monitor this is often a highly complicated and energy intensive process requiring solvents and other chemicals. For this reason, the savings seen from recycling computers is significantly smaller than many other recycling procedures. The primary advantage is that raw material processing is bypassed.

Upgrading: When a computer is upgraded only select components are replaced with newer technology to improve overall performance. In this case, the new component is manufactured and installed and the old component is merely disposed without any recycling taking place.

Use: The usage of a computer can vary widely depending on the user. Literature sources account for this by using average usage times split between active use which consumes more power than idle or sleep-mode which consumes significantly less power.

6.4. Computer Scenario Analysis

A simple two-period model is first addressed. Figure 36 shows what can be assumed in the case of a computer's life cycle energy consumption. This is equivalent to the energy accumulation graphs in Chapter 5 with consumer appliances with one exception. Here it is assumed that energy efficiency remains the same over time, new computer models consume the same amount of energy as the models they replaced. The slope therefore remains constant, indicated as m_i in Figure 36. Each replacement requires manufacturing energy to build a new computer, resulting in the vertical jumps in energy usage at the start or end of each period. Assume a computer is purchased and used for some time until it is replaced at time t_1. A new computer is built resulting in a jump in energy consumption which occurs again when replaced once more at time t_2. Assuming the new computer's efficiency does not improve, the resulting energy consumption would rise at the same rate, following the solid line in Figure 38. Obviously, there is no environmental advantage to replacing the computer if the efficiency does not improve. The energy consumption remains the same, but there is additional build energy that is significantly increasing the environmental impacts with each new purchase over numerous cycles.

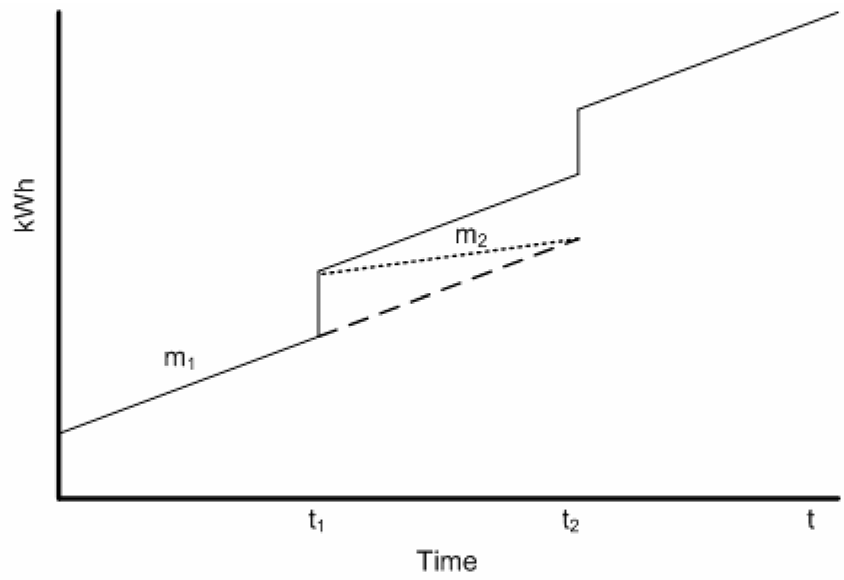

Figure 38. Accumulating Energy Consumption Pattern

The argument was made in Chapter 5 that leasing had an advantage of selling products because it promoted optimal product replacement to take advantage of improving efficiencies. If one assumes no efficiency gains, it can clearly be seen there is no environmental motivation for replacing equipment. What efficiency gains would be necessary to make purchasing a new computer a worthwhile environmental choice, and could these be realistically obtained by manufacturers? The slope m_2 in Figure 38 indicates the improved efficiency necessary to offset the manufacturing energy of a new computer for a single life cycle compared to continued use of the older model without replacement. A smaller slope would indicate greater efficiency and net energy savings over the life cycle compared to using the older model, and a greater slope would indicate an overall greater consumption of energy over the life cycle. To calculate this break-even efficiency slope the following simple two-period model is presented.

From the standard form $y = mx + b$ a comparison of total energy consumption is made between using a computer for two life cycles, or replacing it after the first period t_i and replacing it with a new model with a different efficiency rate until t_{i+1}. The manufacturing energy is defined as b and annual usage energy as m.

$$m_i t_{i+1} + b = m_i t_i + b + m_{i+1} t_{i+1} + b$$
$$m_i t_{i+1} - m_i t_i - b = m_{i+1} t_{i+1}$$
$$m_{i+1} = \frac{m_i (t_{i+1} - t_i) - b}{t_{i+1}}$$

In the two period model $t_i = 0$, so the equation can simplify to:

$$m_{i+1} = \frac{m_i (\Delta t) - b}{\Delta t} \quad (9)$$

Assuming the average values for manufacturing and usage from Table 51 and an average life cycle of three years the value for m_{i+1} = -406 kWh/year. This is a negative slope, indicating that for the manufacturing energy to be offset during the usage phase, the computer would actually have to generate energy, rather than consume it, as illustrated in Figure 39.

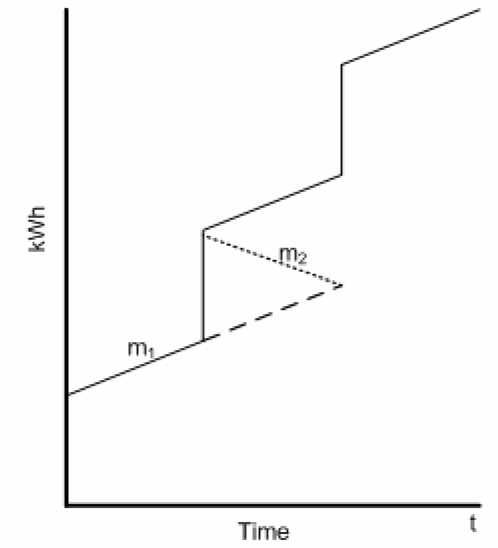

Figure 39. Accumulated Energy Trends with Large Manufacturing Energy

If recycling is considered with process energy of 1,419 kWh (includes both the computer and monitor), the usage energy would still have to be -288 kWh/year to break even with a three-year life cycle. Either usage energy would have to be reduced significantly with new technology utilizing recycled material or recycling energy requirements would need to be significantly reduced.

A leasing scenario with regular upgrades similar to what was proposed in Chapter 5 may have potential. Upgrading, with an energy requirement of only 486 kWh, can break even with a positive slope but only if the usage energy is 23 kWh/year. This is still significantly lower than the average usage value calculated in the literature and not likely a gain that would result in upgrading equipment. If the upgraded components included a power supply with greatly reduced power consumption this has the potential to be the most realizable scenario. It is complicated by the fact that computers are upgraded not for efficiency reasons, but for increased computing power. This usually involves installing a faster processor or more RAM, items that require more power and may therefore need a larger power supply rather than a more efficient one. Components can only be upgraded a limited number of times before the existing technology can no longer support new equipment or so many components have been added that the energy impact is equivalent to purchasing a new computer. Upgrading can extend computer lifespans, but at a net increase in energy consumption.

Clearly computers will not generate power, but it shows just how large of an impact the manufacturing energy has. Because consumers usually use computers for a short lifespan of two to four years the usage energy consumption is relatively small compared to manufacturing. Even a modest improvement in energy efficiency therefore cannot offset the large amount of energy it took to manufacture the product over a short life cycle. If leasing were to be used to reduce environmental impact it would need to extend the life cycle of the product, a claim supported by Thurston et al (Thurston & de la Torre, 2007). Unfortunately, this is counter to the desires of the customers, and therefore not a plausible strategy for product leasing.

The significance of manufacturing can be shown another way as well. Assuming the average usage energy it can be calculated how many years of use is needed to reach the equivalent energy requirements of manufacturing using the following equation:

$$b = m_i t \tag{10}$$

Where: b is the manufacturing energy
m_i is the slope
t is the length of time of use

With manufacturing requiring 1772 kWh and a usage energy of 185 kWh/year it would take 9.6 years for the usage requirements to match the manufacturing requirements. This is significantly longer than is preferred by consumers, even if computers are reused on secondary markets. With recycling in place of remanufacturing it would still take approximately 7.7 years of use to match the recycling energy required. Upgrading would require the least amount of years with approximately 2.6 years, fairly close to a computers actual life span. Unfortunately, as described earlier, upgrading has a number of drawbacks such as limited times computers can be upgraded and lack of efficiency improvements.

6.5. Computer Maintenance

Computer maintenance can be an effective means of prolonging the life of a computer (Steers, 2004). Clogged vents can overheat components and deteriorate delicate and moisture can damage circuit boards. Maintenance operations for computers are simple and low impact, primarily consisting of dusting and cleaning air circulation fans and ensuring no loose dust or particles are present in computer components (Steers, 2004). The biggest issue with computer maintenance is that prolonging the life a computer is of little interest to users. As mentioned earlier, the short life of the computers is facilitated by users demand for new technology, not by failure or product performance. For this reason maintenance is somewhat irrelevant for computers in the context of this study. There is potential energy savings with improved airflow and reduced fan speeds, but these gains would be limited considering the primary source of computer emissions are during manufacturing and disposal.

6.6. Conclusion

Computers pose a significant problem for the environment. Due to their complexity manufacturing energies are large. The short life spans of computers add to the impact, and although components may become more efficient they also become more powerful, negating any technological improvements. At the current state the scenario analyses performed here show that with such short life cycles there is little chance of technological improvements making a difference. To offset manufacturing energies computer energy consumption would have to non-existent, or even generate power. Only extending the life of a computer can be reasonably seen as a way to reduce impacts, but this goes against consumer demands. The incredible complexity of computers also makes material recover difficult. With so many materials used to build computers, recycling is an energy intensive process, and does not exhibit the significant savings seen with other products such as carpet. Because computers are not seen as durable there is little incentive to remanufacture. Computers may benefit the most for a strategy focusing on designing for remanufacture.

6.7. Impact on the Research Questions

Problem statement 3 was concerned with product characteristics, and computer exhibit characteristics that create many problems for leasing and for the environment. Computer life cycle energy requirements are dominated by manufacturing rather than use, a result of short life spans. Because life spans of computers are already much shorter than would be ideal there is no advantage to increased product turnover. A lack of technological improvements as far as efficiency is concerned is a primary factor in this as well. There is no advantage, environmentally, to replacing computers. Therefore, there is no need for lease agreement to moderate product life cycles. At best, a lease could extend computer life spans or redirect used computers to secondary markets, but consumer demand will not likely allow such a business model.

7. Best Practices / Decision Support Tool

Over the course of the case studies examined here the goal has been to develop a better understanding on the relationship between leasing and environmental impacts. Three questions were posed at the beginning of this thesis:

1. Does the shortened life span stipulated by US tax regulations for leasing negatively impact the environment?
2. Can closed material loops offset the impacts of greater product production volume and increased product turn over?
3. What relationships exist between product characteristics and successful leasing for the environment?

Life Cycle Optimization was used to gain a better understanding of increased product turnover and related characteristics. LCA on carpet tile recovery and recycling added to the base of knowledge regarding how different aspects of a product affect the success of leasing. Scenario analysis on appliances, vehicles, computers and various maintenance strategies were used to focus on different factors and how they relate to the interactions between product replacement, technology advancement, and lease agreements. The results of these case studies are summarized below:

7.1. Case Study Summaries

Carpet: The collection of post consumer carpet tiles for recycling resulted in a closed loop material cycle with significant environmental benefits. The avoidance of producing raw materials saw a dramatic savings in energy. The case study also showed that leasing was not necessary to provide a consistent return stream and that the material loop could be closed without written agreements outlining end-of-life responsibilities for consumers and manufacturers. Carpet consumes no energy during use, with all life cycle energy usage occurring during its manufacturing or end-of-life phases. Because it is a non-durable good, it cannot be remanufactured, only recycled.

Vehicles and Appliances: Life cycle optimization showed that trending efficiency improvements played a significant role in the environmental impact of a product over numerous life cycles. Shortening life spans to replace old technology in favor of improved efficiency could actually be environmentally advantageous. Energy savings were minimal with disposal, but closing the material loop with remanufacturing resulted in significant energy savings. These products have extremely large impacts during the usage phase compared to manufacturing energy requirements. The amount of energy required to operate these products also improved with new technology. These products are also durable goods that can be remanufactured.

Computers: Unlike appliances or vehicles computer exhibited the vast majority of their energy usage during manufacturing rather than use due to their short life cycle. The large amount of energy required to manufacture a computer made even theoretical improvements in efficiency negligible over the short life cycle of computers. Given the complexity of the components recycling is possible but energy savings are significantly less than was seen in carpets. Remanufacturing occurs as upgrading with limited savings and applications. No consistent trend in efficiency improvements is evident. A summary of these product characteristics can be seen in Table 52.

Table 52. Summary of product characteristics

	Durability	Usage Energy	Manufacturing Energy	Close Loop
Carpet Tile	Non-durable	Zero	High	Recycle
Vehicles	Durable	High	Low	Remanufacture
Appliances	Durable	High	Low	Remanufacture
Computers	Non-durable	Low	High	Recycle

7.2. Implications of these Studies

The case studies have shown that leasing is not necessarily ‘green’. Except under very certain conditions, there appears only limited conditions under which leasing is environmentally advantageous.

Interface’s attempts at leasing failed, but that did not prevent the closing of the material loop. It was found in this case that leasing was not necessary to ensure a return flow of materials because public interest in recycling was a sufficient factor. Additional government restrictions on landfilling of materials are likely to further encourage closed loops of similar products regardless of the presence of leasing.

Leasing of computers has been touted in various literature as environmentally beneficial, but the finding here show that because recycling is only marginally better than raw manufacturing and computer life cycles are so short, there is little improvement with leasing. With products that have a relatively small usage energy compared to manufacturing there is no environmental benefit to replacing the product as each replacement incurs a significant drain on resources. If the best alternative to disposal is only marginally better, in this case recycling, there is little benefit to replacing the product. Leasing therefore would not reduce the life cycle energy consumption. Even if the material loop were closed the only environmental advantage can be had by extending the product life cycle and reducing the volume of products manufactured. Leasing theoretically could be used to extend the useful life of products with regular maintenance and long lease terms, but these are not conditions that appeal to users who prefer to replace their computers every two to four years (Choi et al., 2006; Eric D. Williams & Sasaki, 2003). Leasing would not be a viable business option in this case.

The only case studies that showed environmental promise with leasing involved household appliances and vehicles, products that are durable and have high usage impacts relative to manufacturing. Life cycle optimization alone saw only marginal energy savings, but use of remanufacturing resulted in substantial savings. The role of leasing in this case served two major roles; ensuring OEMs were responsible for upgrading and remanufacturing products to take advantage of new technology and moderating product life cycles.

It is important to note that energy savings are not possible with only remanufacturing. Recycling has the same potential if the difference between manufacturing and recycling is great enough. The important factor is not the type of process, but that the energy requirements of that process are significantly lower than the alternative. In this section, the term remanufacturing is used for simplicity, but can be exchanged with recycling.

Leasing as a sole business strategy does not lead to improved environmental performance. Only when combined with remanufacturing does are any significant savings realized. Indeed, much of the literature reviewed emphasizes that the savings are found not by the act of leasing, but by the potential shift to closed material loops and recycling or remanufacturing in conjunction with leasing with OEMS. It is important to highlight this relationship. Leasing alone does very little to reduce environmental impacts. Only if it drives companies to adopt a recycling or remanufacturing process can it be considered environmentally beneficial, and even then the results are not necessarily clear cut. The ‘greening power’ of leasing may be overestimated by much of the existing literature.

7.3. Decision Model

The results from the case studies can be condensed down to some very basic rules. The major characteristics among the products are the relationship between usage energy and manufacturing or remanufacturing energy, and the presence of improving technology.

The Interface carpet tile case showed that a product with no or very low life cycle usage energy compared to manufacturing and no efficiency improvements across life cycles does not benefit from leasing. The only other factor leasing can influence is the length of each life cycle. Recycling, although significantly better than raw material manufacturing, requires energy that would not be consumed if the carpet was left installed for longer periods. To improve this further with leasing, the lease agreements would need to extend the life cycle and reduce the volume or the number of recycling operations needed. However, as was shown in the carpet case study, proper maintenance is not an environmentally viable option when the usage phase accounts for a small portion of the total environmental impact. The length to which a product's life cycle can be extended is also limited by the requirements set by lease laws.

What about a product category with improving efficiencies with each new model but keeping with low usage impact? Because the usage energy in this case is small efficiency improvements would also be relatively small compared to the remanufacturing energy it would always be beneficial to extend the life of the product to avoid manufacturing. Without improving technology, extending product life spans is the only way to reduce environmental impacts.

In a case with products that have a significantly larger use impact compared to manufacturing and trending efficiency improvements some environmental savings may be realized with leasing. As in the case study with appliances and vehicles, if leasing can successfully be used to manage life cycles to take advantage of new technology then minor savings can be made. Without these efficiency improvements the motivation for increased product replacement is eliminated and leasing is no longer attractive.

Leasing should theoretically drive increased remanufacturing or recycling. If that is the case then there are savings to be found with leasing paired with improved EOL processes. These relationships are summarized in Table 53.

Table 53. Conditions affecting successful leasing for the environment

	Improving Product Efficiency	No Efficiency Improvements
Use << Manufacturing	No advantage with leasing	Leasing must extend life cycle for environmental improvement
Use >> Manufacturing	Marginal improvement with leasing	No advantage with leasing
Use << Remanufacturing	No advantage with leasing	Leasing must extend life cycle for environmental improvement
Use >> Remanufacturing	Significant improvement with leasing	No advantage with leasing

If the usage energy became comparable to the manufacturing, remanufacturing, or recycling processes then a case-by-case study would be needed to determine if a specific product could benefit from such processes. This applies to products that could potentially be recycled or remanufactured.

8. Conclusions

A lease is defined as "a contract between a lessor and lessee for the hire of a specific asset selected from a manufacturer of such assets by the lessee. The lessor retains ownership of the asset. The lessee has possession and use of the asset on payment of specified rentals over a period" (Clark, 1978). Although numerous types of leasing exist, this paper is concerned only with operating leases, where payments are made in exchange for use of a service or product. Historically, leasing was primarily believed to be proliferated primarily for financial reasons (Eades & Marston, 2002). More recently, a growing number of researchers have argued that leasing has environmental benefits as well (Fishbein et al., 2000; White et al., 1999a). These benefits lie primarily in the lease agreements ability to promote extended producer responsibility (EPR) which includes product take-back strategies and increasing product efficiency and reliability.

When an item is sold in a traditional sales transaction, ownership of the product transfers from the manufacturer to the consumer. Once the transaction has been made the consumer is responsible for all maintenance and disposal. With the concept of servicizing, the manufacturer maintains ownership, making it responsible for the product's final destination. Consumers merely pay for the benefit of the services offered. Lease agreements have the potential to improve product performance and manufacturability as well as facilitate better end-of-life management.

Although numerous articles have made the claim that leasing is 'green' the work shown here reveals the difficulty in determining the true impacts. Numerous variables exist that can affect environmental impacts, successful leasing, and end-of-life processes.

1. Does the shortened life span stipulated by US tax regulations for leasing negatively impact the environment?

Section 5.8 showed that with life cycle optimization negative environmental impacts can actually be lessened with increased product turn over and shortened life spans. This is dependent on the presence of improving technology that continually increases product efficiency. Without this characteristic there is no environmental advantage to product replacement as is evident from section 6.4. The optimal shortened life spans found were shorter than consumer patterns, and therefore a motivating factor is needed to replace products at the optimal intervals. For this leasing can be used to ease the replacement process and reduce capital costs to consumers. Closing the material loop and remanufacturing was found to be the key to reducing environmental impacts as this significantly reduced. Without remanufacturing the energy savings are limited and leasing would not be recommended if end-of-life processes with significant energy savings were not used. It is important to keep in mind the long length of the period used in this study. On a much shorter time scale the process of optimization would yield much smaller savings, making it difficult to promote to consumers and manufacturers without strong financial incentives as well.

2. Can closed material loops offset the impacts of greater production volume and increased product turn over?

This question is closely related to the previous question regarding shorter life spans. Closed loops material streams that utilize some sort of material recover (recycling or remanufacturing) were shown to more than offset the increased product volumes.

3. What relationships exist between product characteristics and successful leasing for the environment?

Perhaps most revealing through the calculations done is that savings are more difficult to achieve than previous literature would suggest. Under only limited conditions would leasing appear appealing both as a business and environmental decision.

Table **53** outlined what conditions are necessary for leasing to be potentially ‘green’. One primary factor not often cited in literature as an important characteristic is the need for improving technology. In cases where products exhibit high usage energy closing the material loop and reusing materials is offers little advantage due to the shortening of life spans. Only when this is combined with continually improving technology that increases product energy efficiency with each new model does this become advantageous as evident in section 5.8. Products that consume less energy during use than manufacturing should be kept in use for as long as possible, as evident from Chapters 4 and 6.

8.1. Maintenance

Operating leases usually include more than just an agreement on how to recover products after use. Most leases include a service contract that stipulates maintenance as well (Fishbein et al., 2000; Gray & Charter, 2008; Oliva & Quinn, 2003). This relieves the lessor of the responsibility of maintenance and moves the tasks into the hands of a business that has special expertise of the product and therefore better suited for maintenance. Servicizing promotes improved maintenance which may lead to better product performance to reduced environmental impacts (White et al., 1999a). As with many aspects of leasing for the environment, the true impact that maintenance has over the life cycle of products is not clear cut and depends on numerous factors.

Maintenance can have a positive environmental impact in two major ways; by significantly increasing a products useful life and thereby reducing volume and end-of-life processes or by improving ensuring a product runs at optimal performance and avoids degradation which can increase energy consumption. Section 5.9 discusses the opportunities with maintenance agreements as part of leases. However, it is important to remember that maintenance cannot improve the environmental benefits beyond the product's original efficiency level and will therefore always add to a product's overall energy usage, as was shown by Section 4.12 and Section 6.5.

8.2. Summary

In many respects the results found here agree with previous works discussed in Chapter 2. Agrawal et al. determined that leasing has a lower environmental impact for products with high enough impact in the usage phase (Agrawal et al., 2009). Thurston et al. agree with the findings here that the longer the lease periods for computers the greater the improvement on environmental impact (Thurston & de la Torre, 2007). Much of the literature comes to the conclusion that when leasing leads to closed material loops it can reduce environmental impacts when remanufacturing or recycling is utilized. However, the work here also reveals some interesting connections not common among the literature.

The most prominent of these is the connection possible with leasing and increasing efficiency over product model years revealed in Chapter 5. With the LCO operations performed it was shown that leasing will increase product volume. According to some literature this increase in volume has detrimental environmental impacts (Agrawal et al., 2009). The life cycle optimization literature and the calculations performed on household appliances found this is not necessarily the case. Two conditions are necessary for this to be true. A majority of the product's life cycle energy consumption must come from the usage phase and there must be efficiency improvements being made on each consecutive product model. The results from section 5.8.2 show when these two conditions are present, environmental benefits can be obtained with increased product turnover. However, these benefits are limited. When an end-of-life process is utilized, such as remanufacturing or recycling, that consumes significantly less energy than traditional manufacturing, significant energy savings result. These results can be found in Section 5.8. Consumer patterns have shown that optimal life cycles are not followed but under a lease agreement regular upgrades can be part of the services included. Without these specific conditions the value of leasing for the environment was not found to be as appealing as the literature may suggest. Indeed recycling and remanufacturing are significant energy savers, but leasing may not necessarily fit into a viable business situation as evident by the carpet lease case in Chapter 4 or computer leases in Chapter 6.

Except for the carpet LCA this thesis focused primarily on energy usage as the environmental metric. Energy was chosen because it makes comparison between various products easy and greatly simplifies calculations. However, it leaves out numerous environmental factors that are important to consider for a full impact assessment. Computers contain various heavy metals hazardous to the environment and the recycling processes often require toxic chemicals. Many end-of-life processes and manufacturing processes consume large amounts of water, an increasingly vital resource in today's world. Energy usage impacts can vary depending on the source of power generation. Clearly, there are many other factors not considered in this study, but due to the variety and complexity of these factors including them is an extremely challenging task. The work here focusing on energy usage is the first step in a process that can be expanded on with further studies. Energy remains a useful predictor of environmental impacts and remains a vital factor in all industrial processes that must be conserved.

Depending on which other environmental factors are examined it is possible the conclusions reached here may be different. For example, refrigerators were found to benefit from increased product turnover with remanufacturing. However, a thorough environmental assessment of the refrigerant used in refrigerators may significantly change this outcome. Each replaced product requires refrigerant to be replaced and produced, and this chemical process may have significant negative impacts. Processing a refrigerant such as HFC-134a may have large chemical and energy requirements, and increased product turnover could lead to significant detrimental affects due to the chemical processing. Issues such as this must be kept in mind while interpreting the results found here.

From an environmental standpoint the advantages of leasing as a means to reduce environmental impacts are limited. The findings here suggest that only when the combination of a high-usage phase impact and improving efficiency are met does there stand to be any gains from leasing. If leasing of such a product is used to moderate optimized life cycles significant energy savings may be obtained. Leasing alone is not a guarantee for improved environmental performance. Leasing for this purpose is more of a means to an end, and is the motivator for business to adopt close material loops that utilize remanufacturing or recycling. Without these recovery processes there is little to support leasing as an environmental decision.

Section 5.10 pointed out the lack of monetary incentives. Despite fairly large energy savings when life cycle optimization is used with remanufacturing, these savings resulted over large time periods of 30 years or more. Because residential power is fairly cheap, the monetary value of these savings is small, and spread over such a large time the payback period is nearly incomprehensible to the average homeowner.

Is leasing green? This study found that only when two specific product characteristics are met and a material recovery operation is utilized does leasing make environmental sense. This does not consider financial factors as energy consumption was the lone focus of this research. The energy savings that were realized may pale in comparison to other methods available to business, and Interface's experience has shown leasing is not always necessary for closing the material loop. Given the proper product characteristics energy savings can be made if leasing is used to manage product life spans. The findings made in Chapter 5 are a best case scenario, and in real life the savings would likely be less significant. Given the low cost of energy it would be difficult to find support for adopting such a leasing agreement. The next step after determining if leasing is green is to determine if those environmental gains are worth the effort of shifting entire business strategies.

8.3. Future Work

This work is intended to pose the possibility of leasing as a means to reduce energy consumption and overall environmental impact. However, significant work is still needed to further understand the possible connections and incentives. The economics of the lease situations proposed in this study were not the primary focus of this research, but remain an important aspect before business will consider it a viable option. An economic study is needed to determine if leasing can be cost effective and appealing to both lessors and lessees. The matter of consumer adoption also needs to be considered. Interface's attempts at leasing failed because of poor consumer response. Optimizing life cycles could only be successful with strong consumer support, most likely in the form of monetary incentives. Given the limited dollar savings with the energy reductions produced, finding customers willing to adopt an appliance lease may prove difficult.

More manufacturing and remanufacturing energy data is needed to expand this study to other appliances. Despite the wide range of appliances available, only remanufacturing values were found for refrigerators, clothes washers, and vehicles engines. The lack of reliable data required numerous assumptions to be made. With reliable data on a large number of products, trends among products may become apparent and help define characteristics that facilitate increased product efficiency. Replacement intervals were determined using past data trends, but for any useful applications, future predication must be made. Developing a predictive model for efficiency of future technology is also necessary.

Further remanufacturing savings may be realized with design for remanufacture practices. As numerous Xerox case studied have found, designing products with the intention to remanufacture can result in significant cost and energy savings. Further work remains to be done on how incorporating planned upgrades into appliances or vehicles may improve their life span efficiencies.

This study does not account for other factors such as new material development that would hasten the obsolescence of many products. The full impacts of such a transition need to be examined in a separate study.

There is also the pesky issue of rebound effects that so often plagues studies such as this. Sorrell explains that “energy-efficiency improvements reduce the marginal cost of energy services – the consumption of those services may be expected to increase” (Sorrell, 2008). Because increased efficiency would reduce household energy costs, there is less incentive for users to reduce their use. Much disagreement surrounds the issue of rebound effects, but it must be acknowledged as a concern when studying issues of efficiency and it points to the fact that the user can negate any technological efficiency gains (Sorrell, 2008).

Appendix A

A.1. Dishwashers Optimum Life Cycle Calculations with Disposal & Manufacturing

The average annual energy consumption for each model year between 1990 and 2005 are shown in Table 54.

Table 54. Dishwasher Model Year Consumption Rates (*Energy Consumption of Major Household Appliances Shipped in Canada: Trends for 1990-2005*, 2007)

Model Year	kWh/yr.
1990	1025.7
1991	959
1992	908
1993	913.5
1994	776.7
1995	670.9
1996	668.2
1997	649.2
1998	646.7
1999	640.1
2000	637.4
2001	633.7
2002	592
2003	523.9
2004	456.8
2005	395.7

These values are graphed so that a trend line can be approximated, as shown in **Figure 40**. This trend line is used to extrapolate to the desired time frame used in this study.

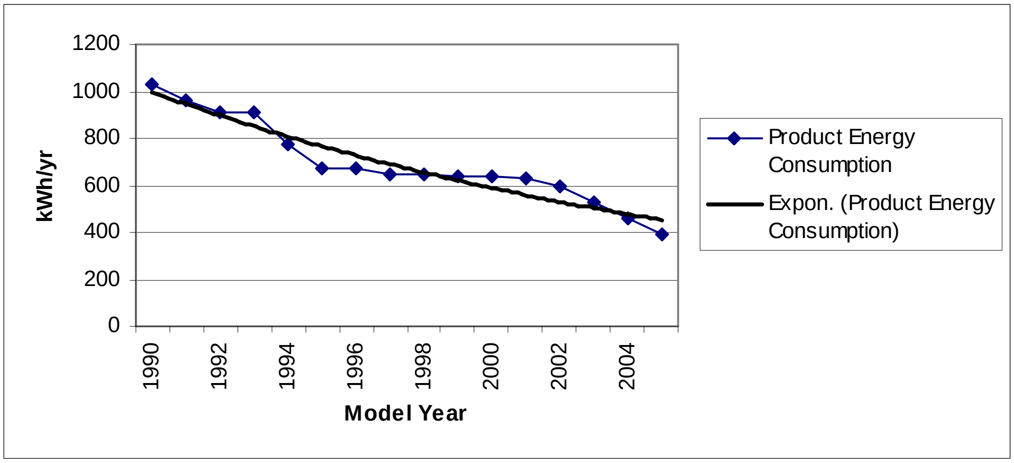

Figure 40. Dishwasher Efficiency Improvement Trend

This trend line is an exponential function defined as:

$$E(t) = Ae^{-Bt} \tag{11}$$

Equation 11 is derived from this trend line.

$$\text{Energy (kWh)} = 1012.5e\text{^}(-0.0459t) \tag{12}$$

Where:
A = 1049.9
B = 0.0525
b = 470 kWh (Manufacturing energy)
T= t = 30 years

The slop is then determined by taking the derivative of this equation.

$$m = \frac{dE}{dt} = -ABe^{-Bt} \tag{13}$$

$$m_0 = dE/dt = -0.0459*1012.5e\text{^}(-0.0459t) \tag{14}$$

Once the slope at each year has been calculated these values can be plugged into Equation (15) to find the optimal life span. The product energy b is known to be 470kWh (Sundin & Tyskeng, 2003). The first calculation is shown here:

$$n_0 = \sqrt{\frac{2b}{-m}} = \sqrt{\frac{2*470}{52.30}} = 4.24 \tag{15}$$

This initial calculation step was conducted when at time t=T, so that a value for n can be obtained. The process is now repeated with t=(T-n/2) which is the value of the average-aged machine. This will provide a more accurate replacement scenario. The process is repeated until the values between each iteration are consistent. The first calculation is shown here:

$$t_1 = \left(T - \frac{n}{2}\right) = \left(1 - \frac{4.24}{2}\right) = -1.12 \qquad (16)$$

This process is then repeated for another iteration

$$m_1 = 5 - 8.45$$
$$n_1 = 4.0$$

Repeat for each iteration until answers become more consistent. Four iterations of calculations are shown as an example in Table 55.

Table 55. Calculation Iterations for LCO of Dishwashers (4 iterations shown)

Year	t0	m0	n0	t1	m1	n1	t2	m2	n2	t3	m3	n3
1990	1	-52.301	4.239	-1.120	-58.457	4.010	-1.005	-58.106	4.022	-1.011	-58.125	4.021
1991	2	-49.626	4.352	-0.176	-55.632	4.111	-0.055	-55.280	4.124	-0.062	-55.299	4.123
1992	3	-47.088	4.468	0.766	-52.947	4.214	0.893	-52.595	4.228	0.886	-52.614	4.227
1993	4	-44.679	4.587	1.707	-50.396	4.319	1.841	-50.043	4.334	1.833	-50.063	4.333
1994	5	-42.394	4.709	2.646	-47.972	4.427	2.787	-47.618	4.443	2.778	-47.638	4.442
1995	6	-40.226	4.834	3.583	-45.668	4.537	3.732	-45.313	4.555	3.723	-45.334	4.554
1996	7	-38.168	4.963	4.519	-43.479	4.650	4.675	-43.123	4.669	4.666	-43.145	4.668
1997	8	-36.216	5.095	5.453	-41.398	4.765	5.617	-41.042	4.786	5.607	-41.064	4.784
1998	9	-34.364	5.230	6.385	-39.421	4.883	6.558	-39.064	4.905	6.547	-39.086	4.904
1999	10	-32.606	5.369	7.315	-37.542	5.004	7.498	-37.183	5.028	7.486	-37.207	5.026
2000	11	-30.939	5.512	8.244	-35.755	5.127	8.436	-35.396	5.153	8.423	-35.420	5.152
2001	12	-29.356	5.659	9.171	-34.057	5.254	9.373	-33.697	5.282	9.359	-33.722	5.280
2002	13	-27.855	5.809	10.095	-32.443	5.383	10.309	-32.082	5.413	10.294	-32.108	5.411
2003	14	-26.430	5.964	11.018	-30.909	5.515	11.243	-30.547	5.547	11.226	-30.573	5.545
2004	15	-25.078	6.122	11.939	-29.451	5.650	12.175	-29.088	5.685	12.158	-29.114	5.682
2005	16	-23.796	6.285	12.857	-28.064	5.787	13.106	-27.700	5.825	13.087	-27.727	5.822
2006	17	-22.579	6.452	13.774	-26.746	5.928	14.036	-26.381	5.969	14.015	-26.409	5.966
2007	18	-21.424	6.624	14.688	-25.493	6.072	14.964	-25.126	6.116	14.942	-25.155	6.113
2008	19	-20.328	6.800	15.600	-24.301	6.219	15.890	-23.933	6.267	15.866	-23.963	6.263
2009	20	-19.288	6.981	16.510	-23.168	6.370	16.815	-22.799	6.421	16.789	-22.830	6.417
2010	21	-18.302	7.167	17.417	-22.090	6.523	17.738	-21.720	6.579	17.711	-21.752	6.574
2011	22	-17.366	7.357	18.321	-21.065	6.680	18.660	-20.694	6.740	18.630	-20.727	6.734
2012	23	-16.478	7.553	19.224	-20.091	6.840	19.580	-19.719	6.904	19.548	-19.752	6.899
2013	24	-15.635	7.754	20.123	-19.164	7.004	20.498	-18.790	7.073	20.464	-18.825	7.066
2014	25	-14.835	7.960	21.020	-18.283	7.170	21.415	-17.908	7.245	21.377	-17.943	7.238
2015	26	-14.077	8.172	21.914	-17.444	7.341	22.330	-17.068	7.421	22.289	-17.104	7.413
2016	27	-13.357	8.389	22.805	-16.647	7.514	23.243	-16.269	7.601	23.199	-16.306	7.593
2017	28	-12.673	8.612	23.694	-15.888	7.692	24.154	-15.509	7.785	24.107	-15.547	7.776
2018	29	-12.025	8.841	24.579	-15.167	7.873	25.064	-14.786	7.973	25.013	-14.825	7.963
2019	30	-11.410	9.076	25.462	-14.480	8.057	25.971	-14.098	8.166	25.917	-14.138	8.154
2020	31	-10.827	9.318	26.341	-13.827	8.245	26.877	-13.443	8.362	26.819	-13.484	8.349

The final 'n3' column indicates the number of years the appliance should be used if purchased in that year.

A.2. Clothes Washer Life Cycle Optimization – with Disposal & Manufacturing

The optimal replacement scenario for clothes washers is calculated here with remanufacturing being the end-of-life process. Table 56 shows the raw annual consumption values.

Table 56. Clothes Washers Annual Consumption Values (Energy Consumption of Major Household Appliances Shipped in Canada: Trends for 1990-2005, 2007)

Model Year	kWh/yr.	t
1990	1218	1
1991	1197.4	2
1992	1175.5	3
1993	1094.1	4
1994	989.1	5
1995	965.9	6
1996	948.7	7
1997	930.1	8
1998	903.3	9
1999	859.9	10
2000	838.3	11
2001	810.1	12
2002	779.2	13
2003	708.4	14
2004	572.9	15
2005	443.6	16

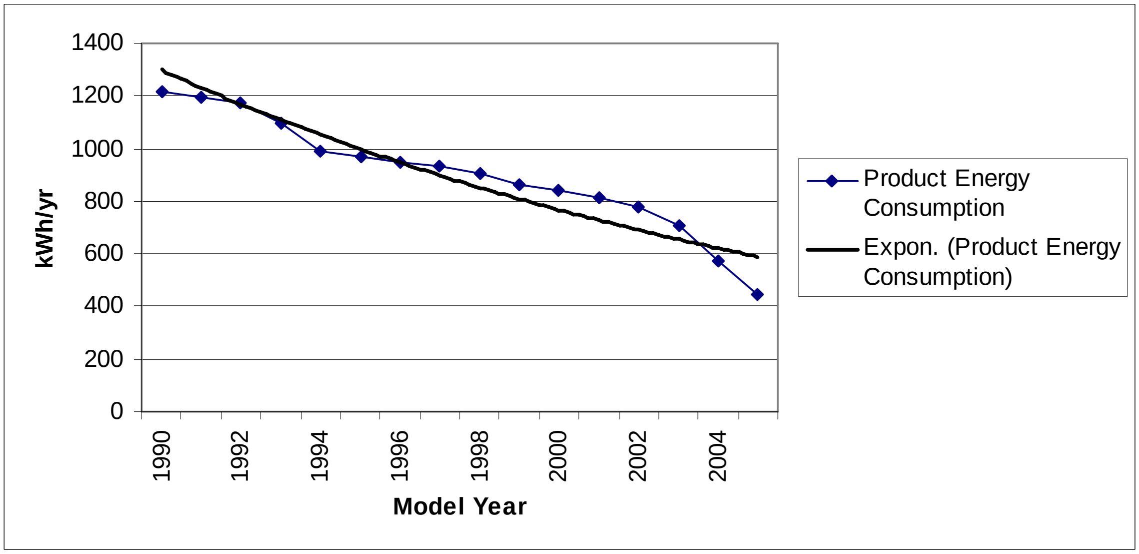

Figure 41. Clothes Washer Data and Trend

An exponential equation is used to approximate the data

$$E(t) = Ae^{-Bt} \tag{17}$$

When graphed and an exponential trend line is fitted to the data the resulting equation is given as:

$$\text{Energy (kWh)} = 1367.9\text{e}^\wedge(-0.053\text{t}) \tag{18}$$

so that A=1367.9 and B = 0.053. The slope is determined by using the equation

$$m = \frac{dE}{dt} = -ABe^{-Bt} \tag{19}$$

Once the slope at each year has been calculated these values can be plugged into equation (6) to find the optimal life span. The product energy b is known to be 750 kWh (Sundin & Tyskeng, 2003).

$$n = \sqrt{\frac{2b}{m}} \tag{20}$$

Table 57 shows the resulting m and n values calculated for clothes washers. It should be noted that these values were calculated until the year 2020. The calculations were extended to provide a long enough timeframe for trends to be understood. Equation (18) was assumed to describe the continuing trend until the year 2020.

Table 57. Calculation Iterations

Year	t0	m0	n0
1990	1	-68.265	4.688
1991	2	-64.767	4.812
1992	3	-61.448	4.941
1993	4	-58.299	5.072
1994	5	-55.312	5.208
1995	6	-52.478	5.346
1996	7	-49.789	5.489
1997	8	-47.238	5.635
1998	9	-44.817	5.785
1999	10	-42.521	5.939
2000	11	-40.342	6.098
2001	12	-38.275	6.26
2002	13	-36.314	6.427
2003	14	-34.453	6.598
2004	15	-32.688	6.774
2005	16	-31.013	6.955
2006	17	-29.423	7.14
2007	18	-27.916	7.33
2008	19	-26.485	7.526
2009	20	-25.128	7.726
2010	21	-23.841	7.932
2011	22	-22.619	8.143
2012	23	-21.46	8.36
2013	24	-20.36	8.583
2014	25	-19.317	8.812
2015	26	-18.327	9.047
2016	27	-17.388	9.288
2017	28	-16.497	9.535
2018	29	-15.652	9.79
2019	30	-14.85	10.05
2020	31	-14.089	10.318

This initial calculation step was conducted when at time t=T, so that a value for n can be obtained. The process is now repeated with t=(T-n/2) which is the value of the average-aged machine. This will provide a more accurate replacement scenario. The process is repeated until the values between each iteration are consistent. In this case the calculations for four iterations is shown in Table 58.

Table 58. Calculation Iterations for LCO of Clothes Washers (4 iterations shown)

Year	t0	m0	n0	t1	m1	n1	t2	m2	n2	t3	m3	n3
1990	1	-68.265	4.688	-1.344	-77.221	4.407	-1.204	-76.654	4.424	-1.212	-76.687	4.423
1991	2	-64.767	4.812	-0.406	-73.506	4.517	-0.259	-72.937	4.535	-0.267	-72.971	4.534
1992	3	-61.448	4.941	0.530	-69.975	4.630	0.685	-69.405	4.649	0.676	-69.440	4.648
1993	4	-58.299	5.072	1.464	-66.619	4.745	1.627	-66.048	4.766	1.617	-66.084	4.764
1994	5	-55.312	5.208	2.396	-63.431	4.863	2.569	-62.859	4.885	2.558	-62.895	4.884
1995	6	-52.478	5.346	3.327	-60.401	4.983	3.508	-59.827	5.007	3.496	-59.864	5.006
1996	7	-49.789	5.489	4.256	-57.521	5.107	4.447	-56.946	5.132	4.434	-56.984	5.131
1997	8	-47.238	5.635	5.182	-54.784	5.233	5.384	-54.207	5.260	5.370	-54.247	5.258
1998	9	-44.817	5.785	6.107	-52.182	5.361	6.319	-51.604	5.391	6.304	-51.645	5.389
1999	10	-42.521	5.939	7.030	-49.710	5.493	7.253	-49.130	5.526	7.237	-49.172	5.523
2000	11	-40.342	6.098	7.951	-47.359	5.628	8.186	-46.778	5.663	8.169	-46.821	5.660
2001	12	-38.275	6.260	8.870	-45.125	5.765	9.117	-44.542	5.803	9.098	-44.586	5.800
2002	13	-36.314	6.427	9.786	-43.001	5.906	10.047	-42.416	5.947	10.027	-42.461	5.944
2003	14	-34.453	6.598	10.701	-40.982	6.050	10.975	-40.395	6.094	10.953	-40.442	6.090
2004	15	-32.688	6.774	11.613	-39.062	6.197	11.902	-38.473	6.244	11.878	-38.521	6.240
2005	16	-31.013	6.955	12.523	-37.237	6.347	12.827	-36.646	6.398	12.801	-36.696	6.394
2006	17	-29.423	7.140	13.430	-35.502	6.500	13.750	-34.909	6.555	13.722	-34.960	6.550
2007	18	-27.916	7.330	14.335	-33.851	6.657	14.672	-33.257	6.716	14.642	-33.309	6.711
2008	19	-26.485	7.526	15.237	-32.282	6.817	15.592	-31.686	6.880	15.560	-31.739	6.875
2009	20	-25.128	7.726	16.137	-30.790	6.980	16.510	-30.192	7.049	16.476	-30.246	7.042
2010	21	-23.841	7.932	17.034	-29.371	7.146	17.427	-28.770	7.221	17.390	-28.826	7.214
2011	22	-22.619	8.143	17.928	-28.021	7.316	18.342	-27.418	7.396	18.302	-27.476	7.389
2012	23	-21.460	8.360	18.820	-26.738	7.490	19.255	-26.133	7.576	19.212	-26.192	7.568
2013	24	-20.360	8.583	19.708	-25.517	7.667	20.166	-24.909	7.760	20.120	-24.970	7.751
2014	25	-19.317	8.812	20.594	-24.355	7.848	21.076	-23.745	7.948	21.026	-23.808	7.937
2015	26	-18.327	9.047	21.477	-23.250	8.032	21.984	-22.638	8.140	21.930	-22.703	8.128
2016	27	-17.388	9.288	22.356	-22.199	8.220	22.890	-21.585	8.336	22.832	-21.651	8.324
2017	28	-16.497	9.535	23.232	-21.199	8.412	23.794	-20.582	8.537	23.732	-20.650	8.523
2018	29	-15.652	9.790	24.105	-20.248	8.607	24.696	-19.628	8.742	24.629	-19.698	8.726
2019	30	-14.850	10.050	24.975	-19.343	8.806	25.597	-18.720	8.951	25.524	-18.792	8.934
2020	31	-14.089	10.318	25.841	-18.481	9.009	26.495	-17.856	9.165	26.417	-17.929	9.147

The values in the ‘n3’ column are the number of years a product should be used before being replaced depending on the year it was purchased. For example, a washer purchased in 1990 should be used for four years before the efficiency of newer models offset the production energy required to make a new product. Because efficiency improvements have slowed over the years, so a washer purchased in 2008 should be used for seven years before being replaced.

A.3. Clothes Washers Optimum Life Cycle Calculations with Remanufacturing

Table 59. Clothes Washers Model Year Consumption Rates

Model Year	kWh/yr.
1990	1218
1991	1197.4
1992	1175.5
1993	1094.1
1994	989.1
1995	965.9
1996	948.7
1997	930.1
1998	903.3
1999	859.9
2000	838.3
2001	810.1
2002	779.2
2003	708.4
2004	572.9
2005	443.6

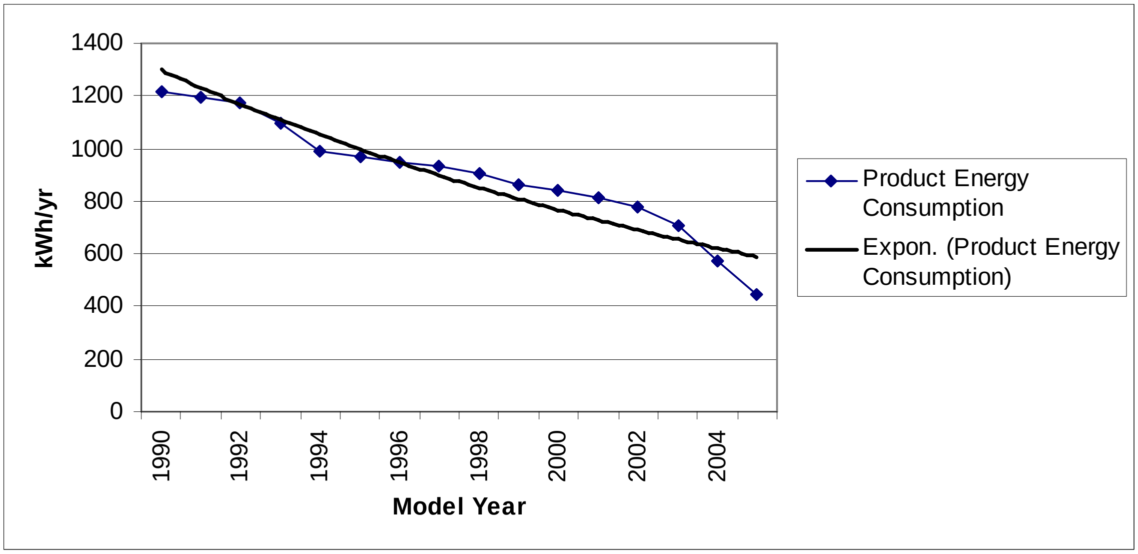

Figure 42. Clothes Washers Energy Consumption Trend

Energy (kWh) = 1367.90e-0.0526x (21)

A = 1367.9

B = 0.0526

b = 750 kWh (Manufacturing energy)

T = 30 years

m0 = dE/dt = -0.0526*1367.90e^(-0.526t) (22)

t0 = 1

$$n_0 = \sqrt{\frac{2b}{-m}} = \sqrt{\frac{2*750}{6826}} = 4.69 \quad (23)$$

$$t_1 = \left(T - \frac{n}{2}\right) = \left(1 - \frac{4.24}{2}\right) = -1.34 \quad (24)$$

$$m_1 = -77.22$$

$$n_1 = 4.41$$

Table 60. Clothes Washers LCO Calculations (4 iterations shown)

Year	t0	m0	n0	t1	m1	n1	t2	m2	n2	t3	m3	n3
1990	1	-68.265	0.839	0.581	-69.787	0.829	0.585	-69.770	0.829	0.585	-69.770	0.829
1991	2	-64.767	0.861	1.570	-66.250	0.851	1.574	-66.233	0.851	1.574	-66.233	0.851
1992	3	-61.448	0.884	2.558	-62.893	0.874	2.563	-62.876	0.874	2.563	-62.876	0.874
1993	4	-58.299	0.907	3.546	-59.707	0.897	3.552	-59.691	0.897	3.552	-59.691	0.897
1994	5	-55.312	0.932	4.534	-56.684	0.920	4.540	-56.667	0.920	4.540	-56.667	0.920
1995	6	-52.478	0.956	5.522	-53.815	0.944	5.528	-53.798	0.945	5.528	-53.798	0.945
1996	7	-49.789	0.982	6.509	-51.091	0.969	6.515	-51.074	0.969	6.515	-51.075	0.969
1997	8	-47.238	1.008	7.496	-48.507	0.995	7.503	-48.490	0.995	7.503	-48.490	0.995
1998	9	-44.817	1.035	8.483	-46.054	1.021	8.490	-46.037	1.021	8.489	-46.037	1.021
1999	10	-42.521	1.062	9.469	-43.726	1.048	9.476	-43.709	1.048	9.476	-43.709	1.048
2000	11	-40.342	1.091	10.455	-41.516	1.075	10.462	-41.499	1.075	10.462	-41.499	1.075
2001	12	-38.275	1.120	11.440	-39.419	1.103	11.448	-39.402	1.104	11.448	-39.402	1.104
2002	13	-36.314	1.150	12.425	-37.428	1.132	12.434	-37.411	1.133	12.434	-37.412	1.133
2003	14	-34.453	1.180	13.410	-35.539	1.162	13.419	-35.522	1.162	13.419	-35.522	1.162
2004	15	-32.688	1.212	14.394	-33.746	1.193	14.404	-33.729	1.193	14.404	-33.729	1.193
2005	16	-31.013	1.244	15.378	-32.044	1.224	15.388	-32.027	1.224	15.388	-32.027	1.224
2006	17	-29.423	1.277	16.361	-30.429	1.256	16.372	-30.412	1.256	16.372	-30.412	1.256
2007	18	-27.916	1.311	17.344	-28.895	1.289	17.356	-28.878	1.289	17.355	-28.879	1.289
2008	19	-26.485	1.346	18.327	-27.440	1.323	18.339	-27.423	1.323	18.338	-27.423	1.323
2009	20	-25.128	1.382	19.309	-26.058	1.357	19.321	-26.041	1.358	19.321	-26.042	1.358
2010	21	-23.841	1.419	20.291	-24.747	1.393	20.304	-24.730	1.393	20.303	-24.730	1.393
2011	22	-22.619	1.457	21.272	-23.502	1.429	21.285	-23.485	1.430	21.285	-23.486	1.430
2012	23	-21.460	1.496	22.252	-22.321	1.466	22.267	-22.304	1.467	22.266	-22.304	1.467
2013	24	-20.360	1.535	23.232	-21.199	1.505	23.248	-21.182	1.505	23.247	-21.183	1.505
2014	25	-19.317	1.576	24.212	-20.135	1.544	24.228	-20.118	1.545	24.228	-20.118	1.545
2015	26	-18.327	1.618	25.191	-19.124	1.584	25.208	-19.107	1.585	25.208	-19.107	1.585
2016	27	-17.388	1.661	26.169	-18.165	1.626	26.187	-18.148	1.626	26.187	-18.148	1.626
2017	28	-16.497	1.706	27.147	-17.254	1.668	27.166	-17.237	1.669	27.166	-17.237	1.669
2018	29	-15.652	1.751	28.124	-16.390	1.711	28.144	-16.372	1.712	28.144	-16.373	1.712
2019	30	-14.850	1.798	29.101	-15.569	1.756	29.122	-15.552	1.757	29.122	-15.552	1.757
2020	31	-14.089	1.846	30.077	-14.790	1.802	30.099	-14.773	1.803	30.099	-14.773	1.803

A.4. Refrigerators Optimum Life Cycle Calculations

Table 61. Refrigerator Annual Consumption Values

Model Year	kWh/yr
1990	956.2
1991	931.2
1992	901.7
1993	719.6
1994	650.4
1995	641.6
1996	640.4
1997	656.5
1998	653.5
1999	645.5
2000	639.5
2001	559.4
2002	506.3
2003	487.1
2004	477.7
2005	469.2

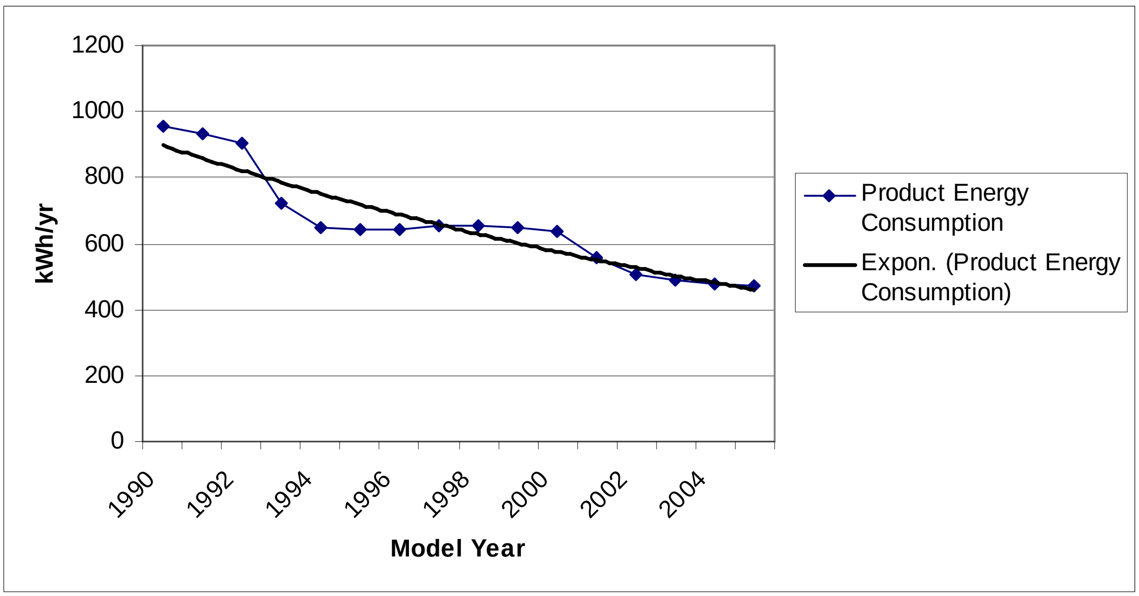

Figure 43. Refrigerator Efficiency Improvement Trend

$$\text{Energy (kWh)} = 941.95e^{(-0.0452t)} \qquad (25)$$

A = 941.95
B = 0.0452

b = 1182 kWh (Manufacturing Energy)
T = 30 years

$$m0 = dE/dt = -0.\ 0452*941.95e\text{^}(-0.0452t) \quad (26)$$

$$t0 = 1$$

$$n_0 = \sqrt{\frac{2b}{-m}} = \sqrt{\frac{2*1182}{40.69}} = 7.62 \quad .. \quad (27)$$

$$t_1 = \left(T - \frac{n}{2}\right) = \left(1 - \frac{7.62}{2}\right) = -2.81 \quad (28)$$

$$m_1 = -48.34$$

$$n_1 = 6.99$$

Repeat for each iteration until answers become equivalent to the second significant figure, as shown in Table 62.

Table 62. Refrigerator LCO Calculations (4 iterations shown)

Year	t0	m0	n0	t1	m1	n1	t2	m2	n2	t3	m3	n3
1990	1	-40.695	7.622	-2.811	-48.344	6.993	-2.496	-47.662	7.043	-2.521	-47.716	7.039
1991	2	-38.896	7.796	-1.898	-46.390	7.139	-1.569	-45.706	7.192	-1.596	-45.761	7.187
1992	3	-37.177	7.974	-0.987	-44.519	7.287	-0.644	-43.833	7.344	-0.672	-43.889	7.339
1993	4	-35.534	8.156	-0.078	-42.727	7.438	0.281	-42.039	7.499	0.251	-42.097	7.494
1994	5	-33.964	8.343	0.829	-41.011	7.592	1.204	-40.321	7.657	1.172	-40.380	7.651
1995	6	-32.463	8.534	1.733	-39.368	7.749	2.125	-38.676	7.818	2.091	-38.737	7.812
1996	7	-31.028	8.729	2.636	-37.794	7.909	3.046	-37.101	7.982	3.009	-37.162	7.976
1997	8	-29.657	8.928	3.536	-36.287	8.071	3.964	-35.591	8.150	3.925	-35.655	8.143
1998	9	-28.346	9.132	4.434	-34.844	8.237	4.882	-34.146	8.321	4.840	-34.211	8.313
1999	10	-27.094	9.341	5.330	-33.462	8.405	5.797	-32.761	8.495	5.753	-32.828	8.486
2000	11	-25.896	9.554	6.223	-32.138	8.577	6.712	-31.435	8.672	6.664	-31.503	8.663
2001	12	-24.752	9.773	7.114	-30.869	8.751	7.624	-30.165	8.853	7.574	-30.234	8.843
2002	13	-23.658	9.996	8.002	-29.654	8.929	8.536	-28.947	9.037	8.482	-29.018	9.026
2003	14	-22.612	10.225	8.888	-28.491	9.109	9.445	-27.781	9.225	9.388	-27.854	9.213
2004	15	-21.613	10.458	9.771	-27.376	9.293	10.354	-26.664	9.416	10.292	-26.738	9.403
2005	16	-20.658	10.697	10.651	-26.308	9.479	11.260	-25.593	9.611	11.195	-25.669	9.597
2006	17	-19.745	10.942	11.529	-25.284	9.669	12.165	-24.567	9.809	12.095	-24.645	9.794
2007	18	-18.872	11.192	12.404	-24.304	9.862	13.069	-23.584	10.012	12.994	-23.664	9.995
2008	19	-18.038	11.448	13.276	-23.364	10.059	13.971	-22.642	10.218	13.891	-22.724	10.200
2009	20	-17.241	11.710	14.145	-22.464	10.258	14.871	-21.740	10.428	14.786	-21.823	10.408
2010	21	-16.479	11.977	15.011	-21.602	10.461	15.769	-20.874	10.642	15.679	-20.960	10.620
2011	22	-15.751	12.251	15.874	-20.775	10.667	16.666	-20.045	10.860	16.570	-20.132	10.836
2012	23	-15.055	12.531	16.734	-19.983	10.877	17.562	-19.250	11.082	17.459	-19.339	11.056
2013	24	-14.389	12.817	17.591	-19.224	11.089	18.455	-18.488	11.308	18.346	-18.579	11.280
2014	25	-13.754	13.110	18.445	-18.497	11.305	19.347	-17.757	11.538	19.231	-17.851	11.508
2015	26	-13.146	13.410	19.295	-17.799	11.524	20.238	-17.057	11.773	20.114	-17.153	11.740
2016	27	-12.565	13.717	20.142	-17.131	11.747	21.126	-16.385	12.012	20.994	-16.483	11.976
2017	28	-12.009	14.030	20.985	-16.490	11.973	22.013	-15.741	12.255	21.873	-15.842	12.216
2018	29	-11.479	14.351	21.825	-15.876	12.203	22.899	-15.124	12.502	22.749	-15.227	12.460
2019	30	-10.971	14.679	22.661	-15.288	12.435	23.782	-14.532	12.755	23.623	-14.637	12.709
2020	31	-10.487	15.014	23.493	-14.723	12.671	24.664	-13.964	13.011	24.494	-14.071	12.961

Account for performance deterioration

Annual increase in energy use

$$\Delta E = r\left(\frac{20-a}{20}\right)^{c} \tag{29}$$

r = 0.045
c = 2.5
a = age of product

Table 63. Deterioration Values

Year Elapsed	E [%]	Accumulated Deterioration [%]
1	0.0396	0.0396
2	0.0346	0.0742
3	0.0300	0.1041
4	0.0258	0.1299
5	0.0219	0.1518
6	0.0184	0.1703
7	0.0153	0.1856
8	0.0125	0.1981
9	0.0101	0.2082
10	0.0080	0.2162
11	0.0061	0.2223
12	0.0046	0.2269
13	0.0033	0.2301
14	0.0022	0.2323
15	0.0014	0.2337
16	0.0008	0.2346
17	0.0004	0.2349
18	0.0001	0.2351
19	0.0000	0.2351
20	0.0000	0.2351

The next table is a summation of the total energy consumed over thirty years of refrigerator use and replacement, listed in the center column. The deterioration rate is applied to each life cycle of the refrigerator as calculated in Table 62 with the results given in the third column of Table 63.

Table 64. Accumulated Energy Consumption over 30 years with Manufacturing & Replacement

Year	kWh	kWh with Deterioration
0	2138.2	2222.8
1	3094.4	3323.9
2	4050.6	4472.4
3	5006.8	5657.2
4	5963.0	6868.3
5	6919.2	8097.3
6	7875.4	9337.0
7	9713.9	10098.4
8	10370.4	11139.5
9	11026.9	12175.2
10	11683.4	13201.1
11	12339.9	14213.3
12	12996.4	15209.3
13	13652.9	16186.8
14	14309.4	17144.7
15	15969.1	16601.2
16	16446.8	17666.6
17	16924.5	18687.0
18	17402.2	19662.7
19	17879.9	20594.4
20	18357.6	21483.3
21	18835.3	22331.1
22	19313.0	23139.8
23	19790.7	23911.9
24	20268.4	24650.3
25	21741.2	22601.8
26	22032.1	23666.0
27	22322.9	24647.6
28	22613.7	25551.2
29	22904.6	26381.9
30	23195.4	27144.8

A.5. Refrigerator LCO with Remanufacturing

$$\text{Energy (kWh)} = 941.95e\text{^}(-0.0452t) \quad (30)$$

A = 941.95

B = 0.0452

b = 20 kWh (Manufacturing Energy)

T = 30 years

$$m0 = dE/dt = -0.\ 0452*941.95e\text{^}(-0.0452t) \quad (31)$$

t0 = 1

$$n_0 = \sqrt{\frac{2b}{-m}} = \sqrt{\frac{2*20}{40.69}} = 0.99 \quad (32)$$

$$t_1 = \left(T - \frac{n}{2}\right) = \left(1 - \frac{7.62}{2}\right) = 0.50 \quad (33)$$

$$m_1 = -41.61$$

$$n_1 = 0.98$$

Table 65. Refrigerator LCO Calculations with Remanufacturing

Year	t0	m0	n0	t1	m1	n1	t2	m2	n2	t3	m3	n3
1990	1	-40.695	0.991	0.504	-41.617	0.980	0.510	-41.606	0.981	0.510	-41.606	0.981
1991	2	-38.896	1.014	1.493	-39.798	1.003	1.499	-39.787	1.003	1.499	-39.788	1.003
1992	3	-37.177	1.037	2.481	-38.059	1.025	2.487	-38.049	1.025	2.487	-38.049	1.025
1993	4	-35.534	1.061	3.470	-36.396	1.048	3.476	-36.386	1.048	3.476	-36.386	1.048
1994	5	-33.964	1.085	4.457	-34.807	1.072	4.464	-34.797	1.072	4.464	-34.797	1.072
1995	6	-32.463	1.110	5.445	-33.287	1.096	5.452	-33.277	1.096	5.452	-33.277	1.096
1996	7	-31.028	1.135	6.432	-31.835	1.121	6.440	-31.824	1.121	6.439	-31.824	1.121
1997	8	-29.657	1.161	7.419	-30.446	1.146	7.427	-30.435	1.146	7.427	-30.435	1.146
1998	9	-28.346	1.188	8.406	-29.118	1.172	8.414	-29.107	1.172	8.414	-29.107	1.172
1999	10	-27.094	1.215	9.392	-27.848	1.198	9.401	-27.837	1.199	9.401	-27.838	1.199
2000	11	-25.896	1.243	10.379	-26.634	1.225	10.387	-26.623	1.226	10.387	-26.624	1.226
2001	12	-24.752	1.271	11.364	-25.473	1.253	11.373	-25.463	1.253	11.373	-25.463	1.253
2002	13	-23.658	1.300	12.350	-24.363	1.281	12.359	-24.353	1.282	12.359	-24.353	1.282
2003	14	-22.612	1.330	13.335	-23.302	1.310	13.345	-23.292	1.310	13.345	-23.292	1.310
2004	15	-21.613	1.360	14.320	-22.288	1.340	14.330	-22.277	1.340	14.330	-22.278	1.340
2005	16	-20.658	1.392	15.304	-21.318	1.370	15.315	-21.307	1.370	15.315	-21.308	1.370
2006	17	-19.745	1.423	16.288	-20.390	1.401	16.300	-20.380	1.401	16.300	-20.380	1.401
2007	18	-18.872	1.456	17.272	-19.504	1.432	17.284	-19.493	1.432	17.284	-19.493	1.432
2008	19	-18.038	1.489	18.255	-18.656	1.464	18.268	-18.645	1.465	18.268	-18.645	1.465
2009	20	-17.241	1.523	19.238	-17.845	1.497	19.251	-17.834	1.498	19.251	-17.835	1.498
2010	21	-16.479	1.558	20.221	-17.070	1.531	20.235	-17.059	1.531	20.234	-17.059	1.531
2011	22	-15.751	1.594	21.203	-16.328	1.565	21.217	-16.318	1.566	21.217	-16.318	1.566
2012	23	-15.055	1.630	22.185	-15.620	1.600	22.200	-15.609	1.601	22.200	-15.609	1.601
2013	24	-14.389	1.667	23.166	-14.942	1.636	23.182	-14.931	1.637	23.182	-14.932	1.637
2014	25	-13.754	1.705	24.147	-14.294	1.673	24.164	-14.283	1.673	24.163	-14.284	1.673
2015	26	-13.146	1.744	25.128	-13.674	1.710	25.145	-13.664	1.711	25.145	-13.664	1.711
2016	27	-12.565	1.784	26.108	-13.082	1.749	26.126	-13.071	1.749	26.125	-13.071	1.749
2017	28	-12.009	1.825	27.087	-12.515	1.788	27.106	-12.505	1.789	27.106	-12.505	1.789
2018	29	-11.479	1.867	28.067	-11.973	1.828	28.086	-11.963	1.829	28.086	-11.963	1.829
2019	30	-10.971	1.909	29.045	-11.455	1.869	29.066	-11.445	1.870	29.065	-11.445	1.869
2020	31	-10.487	1.953	30.023	-10.960	1.910	30.045	-10.949	1.911	30.044	-10.949	1.911

Annual increase in energy use

$$\Delta E = r\left(\frac{20-a}{20}\right)^c \tag{34}$$

r = 0.045

c = 2.5

a = age of product

Applying the same method as previous calculations. Center column is the total accumulation of energy consumption with calculated LCO. Refrigerators are now remanufactured at replacement, lowering the overall energy requirements. The third column then accounts for deterioration values calculated previously.

Table 66. Adjusted values for efficiency deterioration

Year	kWh	kWh with Deterioration
0	979.2	1018.0
1	1933.4	2009.9
2	2858.1	2971.2
3	3600.7	3743.2
4	4274.1	4443.3
5	4938.7	5134.2
6	5602.1	5823.9
7	6281.6	6530.3
8	6958.1	7233.5
9	7626.6	7928.5
10	8289.1	8617.2
11	8871.5	9222.7
12	9400.8	9772.9
13	9910.9	10303.2
14	10411.6	10823.7
15	10903.8	11335.4
16	11363.6	11813.5
17	11800.5	12675.6
18	12222.5	12706.4
19	12621.6	13557.7
20	13009.2	13524.2
21	13373.8	14365.6
22	13729.9	14273.3
23	14062.9	15105.9
24	14390.2	14959.8
25	14694.5	15784.3
26	14995.5	15589.0
27	15273.4	16406.2
28	15550.4	16166.0
29	15804.4	16976.5
30	16059.4	16695.1

A.6. Vehicle LCO Calculations with Manufacturing

Table 67. Vehicle Efficiency Values

Year	EPA Rated MPG Average	Equivalent kWh/Year
1975	13.5	31,975
1976	14.9	28,970
1977	15.6	27,670
1978	16.9	25,542
1979	17.2	25,096
1980	20.0	21,583
1981	21.4	20,171
1982	22.2	19,444
1983	22.1	19,532
1984	22.4	19,270
1985	23.0	18,768
1986	23.7	18,213
1987	23.8	18,137
1988	24.1	17,911
1989	23.7	18,213
1990	23.3	18,526
1991	23.4	18,447
1992	23.1	18,686
1993	23.5	18,368
1994	23.3	18,526
1995	23.4	18,447
1996	23.3	18,526
1997	23.4	18,447
1998	23.4	18,447
1999	23.0	18,768
2000	22.9	18,850
2001	23.0	18,768
2002	23.1	18,686
2003	23.2	18,606
2004	23.1	18,686
2005	23.5	18,368
2006	23.3	18,526
2007	24.1	17,911
2008	24.1	17,911

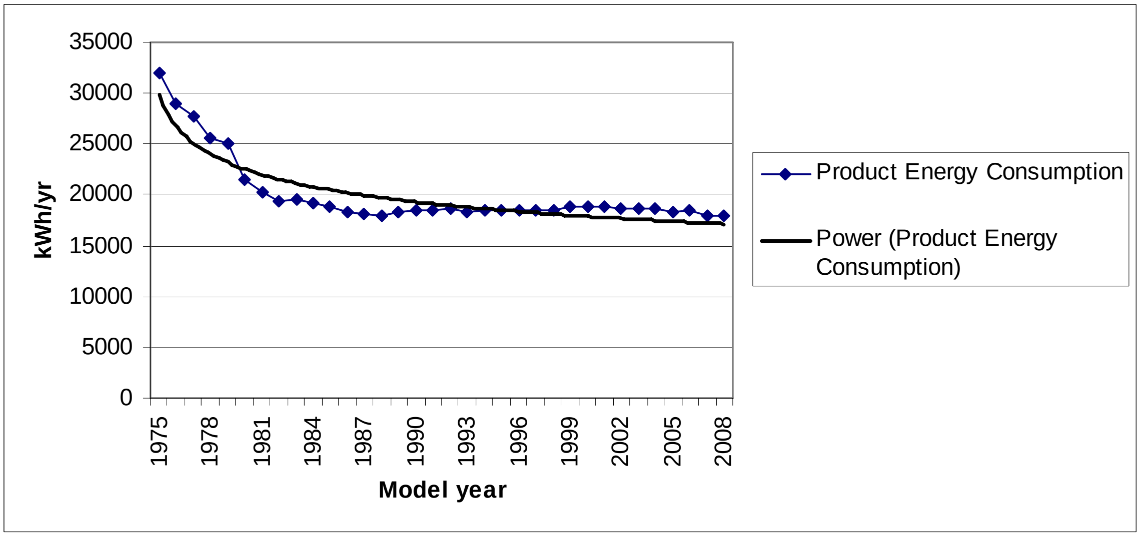

Figure 44. Vehicle Efficiency Trend

$$\text{Energy (kWh)} = 107426.6t\text{^}(-0.1574) \quad (35)$$
$$A = 107426.6$$
$$c = 0.1574$$

$$m0 = dE/dt = -107426.6*0.1574*t\text{^}(-0.1574-1) \quad (36)$$
$$t0 = 1$$

$$n_0 = \sqrt{\frac{2b}{-m}} = \sqrt{\frac{2*11600}{16908.95}} = 1.171 \quad (37)$$

$$t_1 = \left(T - \frac{n}{2}\right) = \left(1 - \frac{1.171}{2}\right) = 0.414 \quad (38)$$
$$m_1 = -46881.81$$
$$n_1 = 0.703$$

Table 68. Vehicle LCO Calculations with Disposal and Replacement(4 iterations shown).

Year	m0	n0	t1	m1	n1	t2	m2	n2	t3	m3	n3
1975	-16908.951	1.171	0.414	-46881.809	0.703	0.648	-27924.916	0.911	0.544	-34189.693	0.824
1976	-7580.617	1.749	1.125	-14749.627	1.254	1.373	-11716.728	1.407	1.296	-12520.541	1.361
1977	-4741.290	2.212	1.894	-8073.916	1.695	2.152	-6962.784	1.825	2.087	-7214.834	1.793
1978	-3398.540	2.613	2.694	-5370.867	2.078	2.961	-4813.986	2.195	2.902	-4926.393	2.170
1979	-2624.997	2.973	3.514	-3948.842	2.424	3.788	-3619.564	2.532	3.734	-3680.132	2.511
1980	-2125.614	3.304	4.348	-3085.628	2.742	4.629	-2870.010	2.843	4.578	-2906.730	2.825
1981	-1778.280	3.612	5.194	-2511.847	3.039	5.480	-2360.541	3.135	5.432	-2384.669	3.119
1982	-1523.633	3.902	6.049	-2105.728	3.319	6.340	-1994.113	3.411	6.295	-2010.921	3.397
1983	-1329.463	4.177	6.911	-1804.721	3.585	7.207	-1719.218	3.673	7.163	-1731.457	3.660
1984	-1176.838	4.440	7.780	-1573.612	3.840	8.080	-1506.152	3.925	8.038	-1515.379	3.913
1985	-1053.923	4.692	8.654	-1391.157	4.084	8.958	-1336.656	4.166	8.917	-1343.809	4.155
1986	-952.955	4.934	9.533	-1243.824	4.319	9.841	-1198.930	4.399	9.801	-1204.604	4.389
1987	-868.638	5.168	10.416	-1122.613	4.546	10.727	-1085.028	4.624	10.688	-1089.616	4.614
1988	-797.238	5.394	11.303	-1021.318	4.766	11.617	-989.416	4.842	11.579	-993.187	4.833
1989	-736.052	5.614	12.193	-935.528	4.980	12.510	-908.130	5.054	12.473	-911.272	5.046
1990	-683.075	5.828	13.086	-862.029	5.188	13.406	-838.256	5.261	13.370	-840.907	5.253
1991	-636.788	6.036	13.982	-798.425	5.390	14.305	-777.613	5.462	14.269	-779.873	5.454
1992	-596.025	6.239	14.881	-742.897	5.588	15.206	-724.532	5.659	15.171	-726.477	5.651
1993	-559.870	6.437	15.781	-694.039	5.782	16.109	-677.720	5.851	16.075	-679.408	5.844
1994	-527.600	6.631	16.684	-650.750	5.971	17.015	-636.157	6.039	16.981	-637.634	6.032
1995	-498.632	6.821	17.589	-612.155	6.156	17.922	-599.032	6.223	17.888	-600.332	6.217
1996	-472.494	7.007	18.496	-577.551	6.338	18.831	-565.689	6.404	18.798	-566.840	6.398
1997	-448.800	7.190	19.405	-546.365	6.516	19.742	-535.593	6.582	19.709	-536.619	6.575
1998	-427.228	7.369	20.315	-518.129	6.692	20.654	-508.306	6.756	20.622	-509.224	6.750
1999	-407.512	7.545	21.227	-492.455	6.864	21.568	-483.462	6.927	21.536	-484.287	6.921
2000	-389.427	7.718	22.141	-469.019	7.033	22.483	-460.756	7.096	22.452	-461.502	7.090
2001	-372.783	7.889	23.056	-447.549	7.200	23.400	-439.931	7.262	23.369	-440.607	7.256
2002	-357.418	8.057	23.972	-427.813	7.364	24.318	-420.770	7.425	24.287	-421.385	7.420
2003	-343.192	8.222	24.889	-409.616	7.526	25.237	-403.085	7.587	25.207	-403.647	7.581
2004	-329.987	8.385	25.808	-392.790	7.685	26.157	-386.718	7.745	26.127	-387.233	7.740
2005	-317.698	8.545	26.727	-377.190	7.843	27.079	-371.530	7.902	27.049	-372.003	7.897
2006	-306.236	8.704	27.648	-362.689	7.998	28.001	-357.402	8.057	27.972	-357.838	8.052
2007	-295.521	8.860	28.570	-349.180	8.151	28.924	-344.230	8.210	28.895	-344.633	8.205
2008	-285.485	9.015	29.493	-336.566	8.303	29.849	-331.923	8.360	29.820	-332.296	8.356

A.7. Vehicle LCO Calculations with Remanufacturing

Energy (kWh) = 107426.6t^(-0.1574) (39)

A = 107426.6

c = 0.1574

m0 = dE/dt = -107426.6*0.1574*t^(-0.1574-1) (40)

t0 = 1

$$n_0 = \sqrt{\frac{2b}{-m}} = \sqrt{\frac{2*3740}{16908.95}} = 0.665 \tag{41}$$

$$t_1 = \left(T - \frac{n}{2}\right) = \left(1 - \frac{0.665}{2}\right) = 0.667 \tag{42}$$

$$m_1 = -26998.37$$

$$n_1 = 0.526$$

Table 69. Vehicle LCO Calculations with Remanufacturing (4 iterations shown)

Year	m0	n0	t1	m1	n1	t2	m2	n2	t3	m3	n3
1975	-16908.951	0.665	0.667	-26998.373	0.526	0.737	-24078.654	0.557	0.721	-24678.505	0.551
1976	-7580.617	0.993	1.503	-10548.585	0.842	1.579	-9966.026	0.866	1.567	-10055.387	0.862
1977	-4741.290	1.256	2.372	-6222.471	1.096	2.452	-5988.620	1.118	2.441	-6018.729	1.115
1978	-3398.540	1.484	3.258	-4309.164	1.318	3.341	-4185.480	1.337	3.332	-4199.533	1.335
1979	-2624.997	1.688	4.156	-3251.359	1.517	4.242	-3175.497	1.535	4.233	-3183.318	1.533
1980	-2125.614	1.876	5.062	-2587.790	1.700	5.150	-2536.753	1.717	5.141	-2541.612	1.716
1981	-1778.280	2.051	5.975	-2136.103	1.871	6.064	-2099.527	1.888	6.056	-2102.783	1.886
1982	-1523.633	2.216	6.892	-1810.526	2.033	6.984	-1783.082	2.048	6.976	-1785.388	2.047
1983	-1329.463	2.372	7.814	-1565.686	2.186	7.907	-1544.364	2.201	7.900	-1546.065	2.200
1984	-1176.838	2.521	8.739	-1375.445	2.332	8.834	-1358.420	2.347	8.827	-1359.718	2.345
1985	-1053.923	2.664	9.668	-1223.742	2.472	9.764	-1209.845	2.486	9.757	-1210.861	2.485
1986	-952.955	2.802	10.599	-1100.188	2.607	10.696	-1088.637	2.621	10.689	-1089.450	2.620
1987	-868.638	2.934	11.533	-997.781	2.738	11.631	-988.033	2.751	11.624	-988.696	2.751
1988	-797.238	3.063	12.468	-911.639	2.864	12.568	-903.306	2.878	12.561	-903.854	2.877
1989	-736.052	3.188	13.406	-838.258	2.987	13.506	-831.055	3.000	13.500	-831.515	2.999
1990	-683.075	3.309	14.345	-775.062	3.107	14.447	-768.776	3.119	14.440	-769.167	3.118
1991	-636.788	3.427	15.286	-720.118	3.223	15.389	-714.586	3.235	15.382	-714.920	3.235
1992	-596.025	3.543	16.229	-671.945	3.336	16.332	-667.040	3.349	16.326	-667.329	3.348
1993	-559.870	3.655	17.172	-629.394	3.447	17.276	-625.016	3.459	17.270	-625.268	3.459
1994	-527.600	3.765	18.117	-591.559	3.556	18.222	-587.627	3.568	18.216	-587.849	3.567
1995	-498.632	3.873	19.063	-557.714	3.662	19.169	-554.165	3.674	19.163	-554.361	3.673
1996	-472.494	3.979	20.011	-527.276	3.766	20.117	-524.057	3.778	20.111	-524.231	3.777
1997	-448.800	4.082	20.959	-499.768	3.869	21.066	-496.834	3.880	21.060	-496.990	3.880
1998	-427.228	4.184	21.908	-474.795	3.969	22.015	-472.111	3.980	22.010	-472.251	3.980
1999	-407.512	4.284	22.858	-452.032	4.068	22.966	-449.568	4.079	22.961	-449.694	4.078
2000	-389.427	4.383	23.809	-431.205	4.165	23.918	-428.934	4.176	23.912	-429.048	4.175
2001	-372.783	4.479	24.760	-412.082	4.260	24.870	-409.984	4.271	24.864	-410.087	4.271
2002	-357.418	4.575	25.713	-394.469	4.355	25.823	-392.523	4.365	25.817	-392.618	4.365
2003	-343.192	4.669	26.666	-378.197	4.447	26.776	-376.389	4.458	26.771	-376.476	4.457
2004	-329.987	4.761	27.619	-363.123	4.539	27.731	-361.438	4.549	27.725	-361.518	4.549
2005	-317.698	4.852	28.574	-349.123	4.629	28.686	-347.549	4.639	28.680	-347.622	4.639
2006	-306.236	4.942	29.529	-336.088	4.718	29.641	-334.615	4.728	29.636	-334.682	4.728
2007	-295.521	5.031	30.484	-323.924	4.805	30.597	-322.543	4.816	30.592	-322.605	4.815
2008	-285.485	5.119	31.441	-312.550	4.892	31.554	-311.252	4.902	31.549	-311.310	4.902

Computer Calculations

$$m_{i+1} = \frac{m_i(\Delta t) - b}{\Delta t} \tag{43}$$

Manufacturing

$$m_{i+1} = \frac{185(3) - 1772}{3} = -405.7$$

Recycling

$$m_{i+1} = \frac{185(3) - 1419}{3} = -288$$

Upgrade

$$m_{i+1} = \frac{185(3) - 486}{3} = 23$$

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