Title
Harmonizing Technological Innovation and End-of-Life Strategy in the Lighting Industry

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Publication Date
2017

Peer reviewed|Thesis/dissertation

Harmonizing Technological Innovation and End-of-Life Strategy in the Lighting Industry

by

Rachel Victoria Dzombak

A dissertation submitted in partial satisfaction
of the requirements for the degree of
Doctor of Philosophy

in

Engineering – Civil and Environmental Engineering

and the Designated Emphasis

in

Development Engineering

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Arpad Horvath, Chair
Professor Scott Moura
Professor Sara Beckman
Professor Heather Dillon

Summer 2017

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Abstract

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Doctor of Philosophy in Engineering – Civil and Environmental Engineering
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University of California, Berkeley

Professor Arpad Horvath, Chair

Today's globalized economy largely follows a linear "take-make-dispose" model, where natural resources are extracted to manufacture products that are eventually disposed of in a landfill. Growing constraints on key resources such as energy sources, water and materials coupled with the global increased demand for goods and services render this linear model unsustainable. To address these issues, companies and governments alike are attempting to develop circular processes that preserve natural resources and reduce the global waste burden.

As new technology products are designed and brought to market, consideration must be given to how products will be managed throughout the life-cycle as well as their end-of-life fate. This research uses light-emitting diode (LED) lighting products as a case study to assess how technological innovation can be harmonized with end-of-life strategies to create increasingly closed-loop systems, a key step to bringing the circular economy to fruition. The work will: 1) examine current end-of-life strategies, 2) analyze how various design choices and failure modes influence a product's options at end of life, 3) assess how economic costs and environmental impacts vary among end-of-life strategies, and 4) develop a framework to determine the optimal management and end-of-life strategy for a given lighting product. Key methods employed will include product analysis, life-cycle assessment, and cost optimization. The end goal of the research is to provide a methodology for assessing the economic and environmental implications of end-of-life strategies for a given technology product.

This dissertation is dedicated to Dave Dornfeld

and to my parents – with all of my love and appreciation.

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Glossary

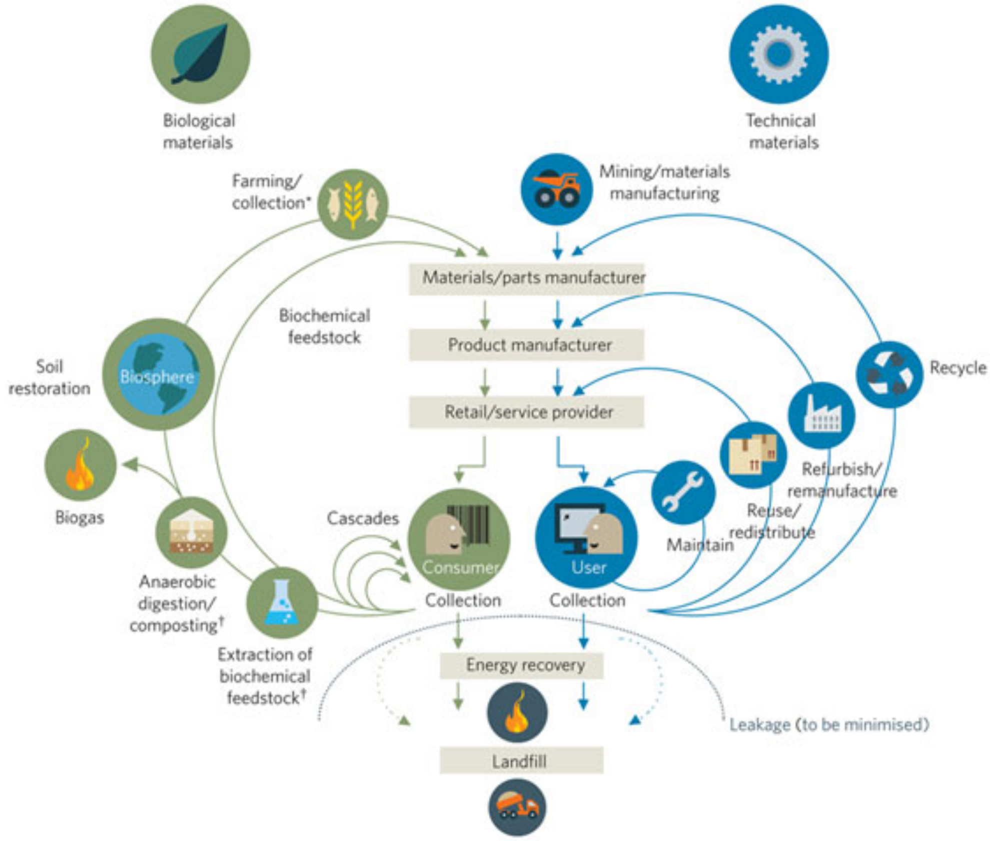
1. Circular economy: A global economic model that decouples economic growth from the consumption of finite resource [1].

2. System: A set of elements or parts that is coherently organized and interconnected in a pattern or structure that produces a characteristic set of behaviors often classified as its “function” or “purpose [2].”

3. Circular or closed-loop systems: The building blocks of a circular economy. Implemented at a local, product, or organizational level and mimic natural systems by optimizing material flows and preserving materials at their highest value at all times [1].

4. Loops: Refer to pathways shown in Figure 1. An “inner loop” is a higher material value application, such as reuse. An “outer loop” is a pathway that degrades material value such as recycling. A key principle of building circular systems is to optimize resource yields by circulating products, components and materials in use at the highest utility at all times in both technical and biological cycles [1].

5. Reverse logistics: The transport of products from their final destination, generally with a customer or user, for the purpose of capturing value, redistribution in secondary applications, or proper disposal [3].



Circular System Diagram – Illustrates the Flow of Technical and Biological Materials throughout the Value Chain [1]

6. Service-based business model: A business model that emphasizes selling performance rather than a physical product. It focuses on utilization optimization and exploits resource efficiency as well as sufficiency and prevention to gain financial advantages and higher competitiveness [4].

7. Remanufacturing: The rebuilding of a product to specifications of the original manufactured product using a combination of reused, repaired and new parts. It requires the repair or replacement of worn out or obsolete components and modules [5].

8. Repair: The process of keeping a product in good condition without changing users [5].

9. Reuse: To reintroduce a product for the same purpose and in its original form following minimal maintenance and cosmetic cleaning. Assumes a different user from original [5].

10. Parts Harvesting: Recovering components from existing products to create new or repurposed products [5]

Acknowledgements

I feel incredibly lucky to have so many people to thank for helping me through the PhD process. To my parents, Carolyn Menard and Dave Dzombak, thank you for teaching me the value of hard work, providing endless encouragement, and never letting me believe I couldn't do something. I am grateful for your love, support, and for answering the phone at 3 am when I thought I poisoned myself while disassembling a light. My older brothers, Dan and Will Dzombak, thank you for listening patiently whether I was laughing or crying, especially when I needed an extra push at the end of this process. I am also deeply appreciative of my grandparents, Agnes and William Dzombak, for establishing lifelong learning as a core family value. I pinned two of my grandpa's rules at my desk and looked at them every day: "1) Our goal in life is simply to be happy. 2) All knowledge is retrievable if we know how to read a book." Our extended family is incredible and every member cheered me on along the way.

Julia Anselmo and Gillian Love – thank you for your friendship and for always asking questions to understand how I was spending my time. I love and appreciate you both so much. Khanjan Mehta has arguably influenced my career more than anyone else – thanks for inspiring my path and telling me to go to graduate school. I am fortunate to have you as a mentor, collaborator, and friend. Steve Suffian, you serendipitously finding your way to Berkeley was a huge benefit for my life. I am so glad we could continue working together and supporting each other. Thanks for always patiently answering my coding questions and plotting next moves with me. It's only a matter of time before we start our company or department.

I have met many fantastic people since moving to California in 2013 and my life would not be the same without them. I cannot thank Molly and Mike Taptich enough for all they have done for me – cooking dinner, consulting on my research, numerous trips around California, and the most incredible spot to watch the sunset from the Berkeley hills for 3 years. A similar thanks to Aubrie and Jeb Williams – for rides home with constant cackles, providing me with a creative outlet, and many joint orders of Thai food. To Nathan Nalevanko, for shaping my graduate school years and creating a home with me filled with love, laughter, spontaneity, and adventure. Our time together made a huge imprint on my heart and my life.

Olga Kavvada, I could not have picked a better person to go through this process with. Thank you for being there with me every step of the way. Tala Daya is the most incredible officemate and friend. You put up with me -- my antics, rants, attitude, messy desk, family stories, freakouts, excitement -- and I loved sitting next to you. Our conversations on everything from food, to Middle East culture, US politics, and so much else, are among my favorite memories from the past 4 years.

To all of the other amazing students, Julia Kramer, Will Tarpeh, Maddie Foster, Max Micali, Chelsea Preble, Katya Cherukumilli, James Barazesh, and everyone else: you have all enriched my thinking and life immeasurably.

My dissertation work was funded by an NSF Graduate Research Fellowship, the Civil and Environmental Engineering and Mechanical Engineering Departments at UC Berkeley, as well as gift funding from Core Centric Solutions. I'd like to specifically thank Dr. Makarand Chipalkatti, Chris Cloutier, Nikos Papaioannou, and the rest of the Core Centric for their kindness and support of my work!

I most importantly want to thank my thesis committee and the faculty I have worked with over the past 4 years. Arpad Horvath recruited me to ECIC and supported me through personal and professional challenges. You gave me the freedom to follow my own path but always made sure I was supported and on track. I am deeply grateful for your guidance. Heather Dillon, I am so glad we were on the same panel back in 2015. Exactly one year from our first phone call, our first paper was published! Thanks for catalyzing my research and being such a seamless collaborator. Scott Moura, thank you for providing valuable feedback during my qualifying exam as well as pushing me to ensure the impact of my work in my dissertation!

Finally, I want to express gratitude for the time spent with Dave Dornfeld, who passed away during my 3rd year. Dave convinced me to stay after my master's when I was considering leaving the program. He was an amazing advisor for many reasons, but particularly because he not only tolerated my multi-disciplinary thinking, he encouraged it whole-heartedly. I cannot thank him enough. He also introduced to me to Sara Beckman, who completely transformed my PhD experience. Sara, thank you for reading every word of my dissertation and more broadly for providing me with so many opportunities. You inspire me every day to strive towards big dreams and I am thrilled to have found a like-minded co-conspirator to work with. The PhD was only the beginning!

1 Introduction

1.1 Motivation: Environmental Impacts of Rapid Technology Change

Climate change and a growing global population are placing considerable constraints on material, water, and energy resources [6] [7] [8]. Such resources are critical to the creation and distribution of products used by customers around the world every day [9]. Though original equipment manufacturers (OEMs) dedicate much time, attention, and financial resources to the design, procurement, manufacturing, and marketing of products, insufficient focus is given to the way in which design influences material and resource sustainability [10] [11] [12] [13]. Once products are sold to consumers, OEMs may be in contact with the product through repair or maintenance, but the trajectory the product takes with respect to physical obsolescence (disrepair) or functional obsolescence (need shift) depends solely on the consumer. More attention is needed on end-of-life strategies for products because disposal of products represents a waste of both critical resources and the energy embodied in a product.

A key opportunity to harmonize technological innovation and end-of-life strategy exists in the creation of closed-loop systems. Closed-loop systems help to preserve resource efficiency by extending the usable life of a given product. Since raw material extraction can be highly energy and water intensive, reusing those resources creates efficiency that is critical for long-term sustainability. While some industries, such as automotive and paper, are accustomed to high rates of recycling and reuse, many industries have neither the infrastructure nor the motivation to recover materials [14]. Analyzing the environmental and economic dimensions of end-of-life strategies for particular products will be critical to such activities' expansion.

As new technologies emerge, it is often unclear to the user when they should upgrade to the latest and greatest and when they should continue to use what they have. Once the decision to replace technology has been made, what should they do with the older version? The goal of this research is to determine the potential environmental impacts of various waste management strategies and determine the optimal technology management strategy for a given product. The data utilized in this research will all contribute towards answering the posed research questions for the lighting industry. This will help decision-makers throughout the system such as raw materials producers, manufacturers, distributors and retailers, customers (e.g., municipalities), consumers, users, and waste managers (recyclers and remanufacturers): to plan and implement environmentally optimal end-of-life strategies as early as possible, which is critical in industries such as light emitting diode (LED) lighting given the rapid technological change and resultant proliferation of products.

1.2 Lighting Industry Case Study

This research uses light emitting diode (LED) lighting products as a case study to assess how technological innovation can be harmonized with end-of-life strategy to create increasingly sustainable systems. As the energy efficiency of lighting technologies improves, production and end of life more strongly influence the environmental footprint. Currently, the majority of published research has focused on use-phase performance of lighting, however, the national transition to usage of solid-state lighting (SSL) products needs to be accompanied by the development of a system for take-back of future products that reach end of life [15].

Multiple lighting product categories are examined in this dissertation research: LED street lights and LED lighting consumer products. Each represents a unique set of product characteristics as well as a specific decision-making context. The following section outlines why the products were chosen and how they contribute to the goal of this dissertation, which is to further understand how design decisions affect the feasibility of creating closed-loop product systems.

While LED lighting product designs vary by application, the basic components are shown in Table 1. The composition of components for an A-19 product is shown in Figure 1. A LED die or chip is comprised of a p-n junction semiconductor device or chip. Multiple LEDs connected via wire bonds are referred to as an *LED Package*. Assembling multiple LED packages along with optical, thermal, mechanical, and electrical elements creates an *LED Lamp*, or light bulb to a consumer. A light fixture is referred to as an *LED Luminaire*. Luminaires are complete lighting units comprised of LED packages, a driver, branched circuitry and hardware intended to guard and align light-emitting components [16].

Table 1: LED Product Terminology and Definitions, Adapted from [15], [17]

Component Level	
Die or Chip	p-n junction semiconductor device
Package	Assembly of one or more LED dies with electrical elements, wire bonds, and an optional optical element
Array	Assembly of one or more LED packages on a printed circuit board
Module	LED package or array connected to a power source
Subassemblies and Systems	
Driver	Power source and LED control circuitry forming a device that operates an LED package, array, or lamp
Light Engine	Assembly of LED package or arrays directly connected to the branch circuit
Lamp	Assembly of LED package or array, driver, with optical, thermal, mechanical and electrical components
Luminaire	Complete lighting unit with hardware elements protecting light-emitting components

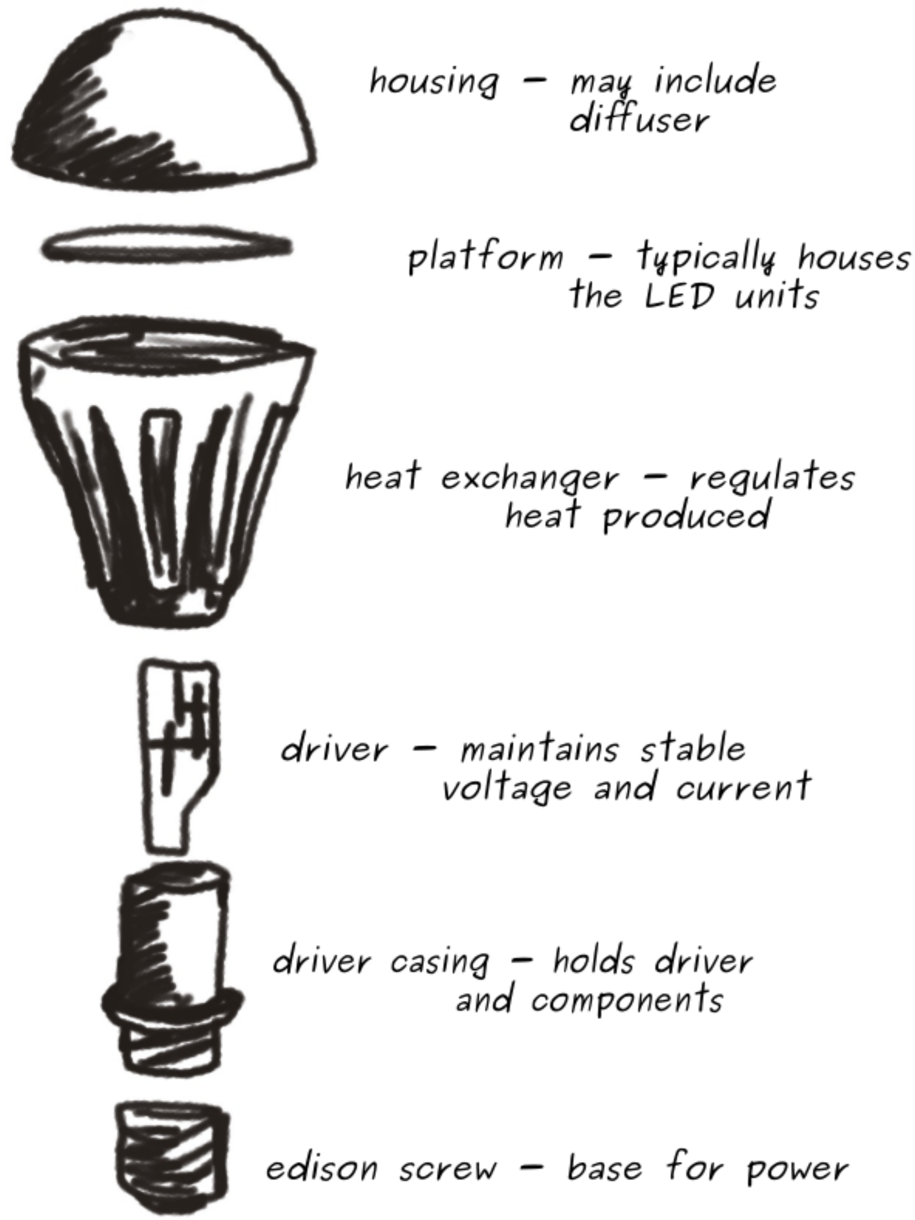


Figure 1: Overview of LED A-19 Product Components

1.3 Research Overview and Questions

Through this research, the costs and benefits of end-of-life (EOL) management strategies for LED lighting are examined and used to guide product design and technology management decisions. The purpose of the research is to investigate the environmentally and economically optimal end-of-life strategy for a given technology and to determine what is practically needed in order bring the optimal solution to fruition.

This work further provides a model to assess the environmental and cost implications of technology disposal pathways.

End-of-life decisions are examined in both business and consumer contexts. For the former, LED street lighting products will be used as a case study technology as they are rapidly growing in prevalence and are purchased in large scale. More on LED street lighting can be found in Section 2.4.2. For the consumer context, residential lighting products (A19s) are used as a case study. More on the consumer context case study can be found in Section 2.4.1. The purpose of exploring both is to understand the extent to which context drives end-of-life decisions and how product designs can be adapted to aid the decision-maker.

The key questions that were examined through this research include:

1. What currently happens when products fail or are retired? What guides decisions to replace or retire products? What factors, such as cost, damage, infrastructure, etc., dictate the end-of-life fate of a given product? How are such factors different for lighting versus other products? How do failure mechanisms influence end-of-life strategy?

2. When should a technology product be replaced? What is the connection between product replacement and the viability of different end-of-life strategies? Is the optimal cost solution also the optimal environmental solution? If not, what is driving the differences?

3. What are the costs and environmental impacts generated throughout the reverse logistics and EOL processes for lighting?

4. How can the economic and environmental implications of end-of-life decisions be communicated? What design characteristics can be altered to encourage optimal end-of-life strategies? What should be communicated to consumers and businesses when making technology decisions?

2 Background

2.1 Drivers for Change in Environmental Management of Lighting

2.1.1 Rapid Global Proliferation of LEDs

In the United States, approximately 18% of total electricity consumption is from lighting [18]; lighting constitutes 21% of commercial electricity usage, corresponding to 350 TWh annually [19]. As the global call for reduced carbon emissions grows louder, energy efficient technologies are seen as a prime mechanism to lower environmental impacts, as documented through a robust literature [20] [21] [22] [23]. As a result, the market for solid-state lighting (SSL) systems has seen a 40-fold increase in installed lamps since 2001 [19]. LEDs in particular have seen substantial growth as the U.S. implements policies pushing for high efficiency lighting [24]. Projected growth within the LED lighting market can be seen in Figure 2 [25].

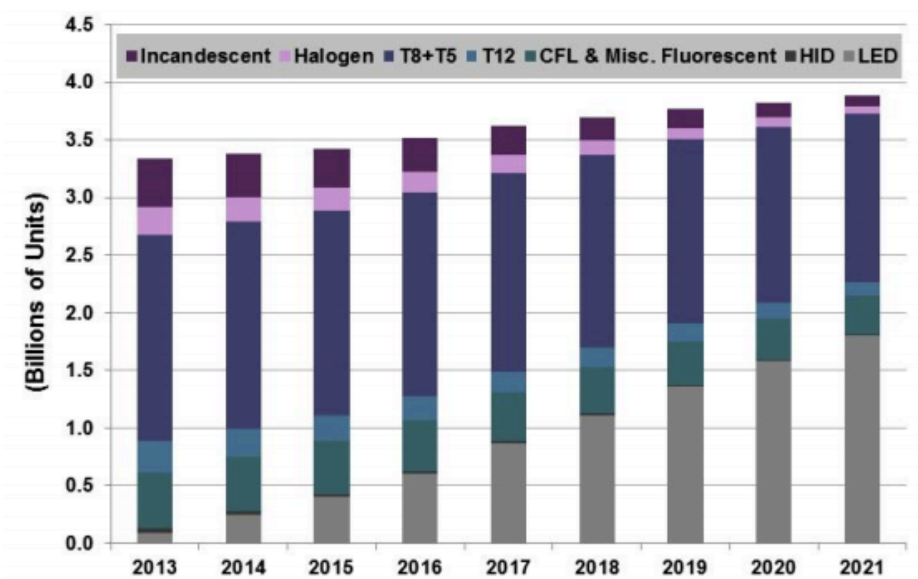


Figure 2: Global Shipment Forecast - Commercial Lamps and Luminaires [25]

As Figure 2 shows, the expected number of lighting products shipped each year is between 3-4 billion. The proportion of LED products is increasing each year as consumers recognize the potential cost and energy savings that are possible and older technologies are replaced [26]. Though the size of individual products may be small, the total volume of lighting products in the global market is large [27]. The sheer size of the lighting product market signifies it as an important sustainability opportunity. Changes in the design of lighting products that facilitate material recovery or increased product sustainability could lead to a significant decrease in industry material and energy usage [15] [28].

2.1.2 Increasing Product Complexity

The rise of new technologies and products has led to a fundamental shift within the lighting industry. The cost per lumen for LEDs has decreased by a factor of ten every decade since their invention in the 1960s [29], democratizing the availability of LEDs and expanding their potential to be incorporated into product systems [30]. In addition to the development of the core diode technology, significant changes have been seen in LED lighting efficiency, color balance, power supply and controls [23]. LED products are increasingly more complex than conventional technologies such as incandescent or complex fluorescent lights, leading many in the industry to report that while they had sold light bulbs in the past, now they sell semi-conductors. LED lighting integrates multiple components to produce light including drive electronics, LEDs, housing, and heat dissipation elements all of which must work in unison to deliver the intended value. While such components are necessary for the lighting system to function, they also serve to increase the material complexity of LED products.

The composition of LED lighting products is poised to grow more complex in the coming years. After nearly a decade of designing for energy efficiency, companies are now examining what additional value propositions are possible to incorporate into the product design. As Katona et al. report in their review of the LED lighting industry, “In this new era of lighting design, the biggest challenge being faced is no longer ‘can it be made?’, but rather ‘should it be made?’” [31]. Light delivery has moved from an isolated fixture to entire connected systems, with higher functionality and control than previously thought possible [31]. Implementation of lighting control systems and the broader ‘Internet of Things’ remains in the early stages but allows for integration of new services with lighting products including internet connectivity, security monitoring, and weather tracking among other applications [32] [33]. In Figure 3, a simple schematic of a connected lighting system is shown. Connected lighting systems require additional hardware and software elements, however also have the potential to reduce maintenance costs over time and provide additional value by serving as a platform for the additional possible features described.

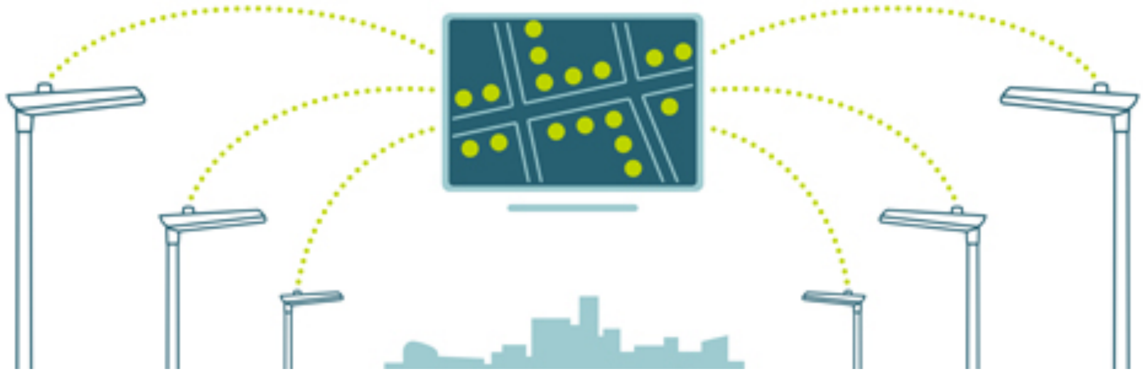


Figure 3: Philips CityWorks Connected Street Lighting System [34]

Proactive attention on LED end-of-life strategy can contribute to the diversion of a burgeoning waste stream. The inclusion of electronics in LED lamps has led to new lighting applications within agriculture, healthcare, and buildings, but also has the potential to create environmental complications at end-of-life [35]. LEDs have been shown to contain potentially harmful metals including nickel, lead, and arsenic [36]. As "smart" lighting systems are increasingly installed, the number of electronic elements integrated will grow accordingly [32]. In an effort to protect energy resources and achieve sustainability, manufacturers must remain cognizant of the environmental implications associated with design choices.

2.1.3 Premature Replacement

Development of LEDs has progressed rapidly during the last decade. Research and government initiatives have spurred improvements in lumen efficiency, lighting quality, and product life span [16]. While each contribution has significantly enhanced LED use-phase performance, none have directly addressed end-of-life management from economic or environmental standpoints. The rapid technological improvements in LED efficiency mean many lights will be replaced prior to failure in order to maximize energy savings. Replacement will also occur in the case of failure or expected failure. Anecdotal evidence suggests that in large-scale lighting applications, such as street lighting, once 20% of lamps fail, the servicer tends to replace all lamps assuming the rest will begin to fail shortly. As the energy to manufacture LED products is significantly higher than for other lighting products, decisions around what to do with the retired lighting become critical [37][38].

2.2 Defining the Need for Resource Preservation

2.2.1 Rapid Product Turnover

In 2013, the United States generated over 250 million tons of waste, a figure that has steadily grown throughout the past decade [39]. One of the most visible areas of growth is in electronic waste, or e-waste [40]. E-waste refers to products with an electronic component that are no longer used or wanted by the consumer. When a user discards the product for reuse, resale, recycling, or disposal, it becomes e-waste. Cell phones and computers are commonly discussed forms of e-waste due to their relatively short product lifespan [41]. For example, computers are discarded approximately every three years, thus creating a significant waste challenge [42]. In 2011, the U.S. Environmental Protection Agency (EPA) conducted a study to track electronic product sales over time [42]. The results are shown in Figure 4.

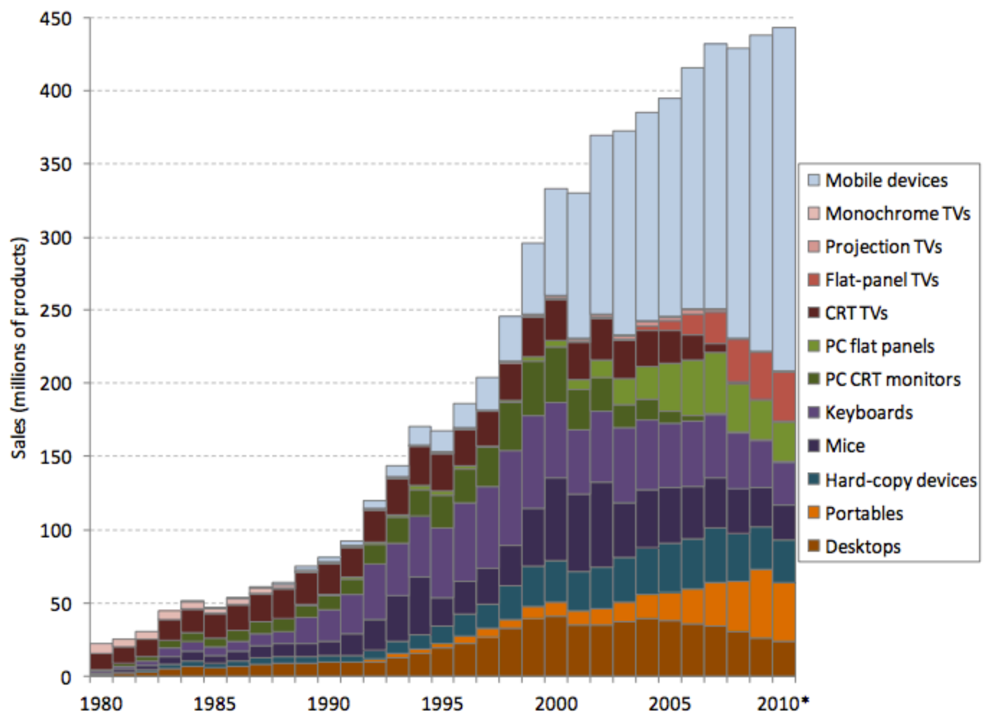


Figure 4: Sales of electronic products by model year [42]

The rapid rise in prevalence of electronic technologies left little time for waste management systems to determine the best means of dealing with these new and complex products. Such is the case for many products throughout history as shown in Figure 5. Technological advancements, increased consumer demand, and product turnover often collectively led to the shortening of the product lifespan (Figure 6) and consequently the creation of expanded and diversified waste streams.

Innovation fuels this product turnover in two ways. Incremental innovation means enhancing an existing product to better suit user needs. For example, this could mean designing a new version of a washing machine to use slightly less water. Alternatively, radical innovation presents an entirely new way of achieving an end goal or using a product [43]. Incremental innovation contributes significantly to the rich diversity of products available to complete the same task. Subtle product differences make components more or less suitable for a given end-of-life strategy. Both types of innovation contribute to the creation of pulses of technology moving through waste systems.

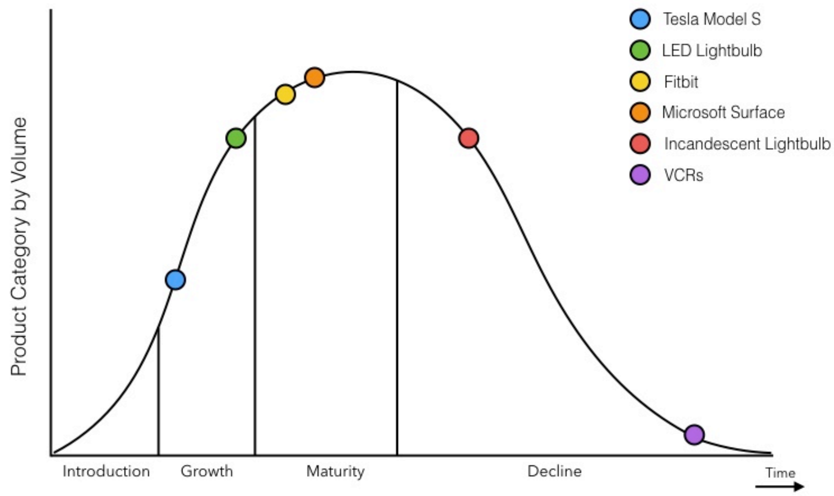


Figure 5: Products Along Product Adoption Curve, Adapted from [44]

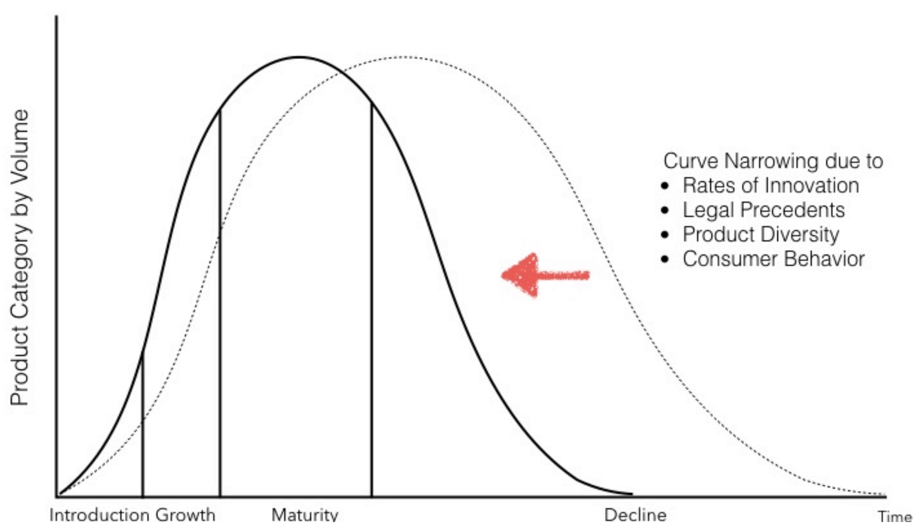


Figure 6: Factors Leading to Shortening of Product Lifespan, Adapted from [44]

A pulse, in physics, is defined as a “single, abrupt emission of particles or radiation” [45]. In this context, a technology pulse can be defined as the emergence and subsequent obsolescence of a technological product over a defined period of time. History is full of examples of technological pulses. Floppy disks, cassette tapes, and the rotary phone all experienced major surges of popularity and use before new technologies rendered them useless. As different technologies pulse through markets, waste systems must react to different volumes of products and embedded materials.

Typically, waste management systems are unprepared for such emerging waste streams. Processing continues according to the status quo as opposed to adopting practices to account for new materials and product components. One goal of this research is to determine the potential environmental impacts of various waste management strategies and determine the optimal strategy for a given product. This will help decision-makers, such as municipalities, manufacturers, and waste collectors, to implement environmentally optimal technology management strategies.

2.2.2 Moving to a Circular Economy

The current global economy follows a linear model of “take-make-dispose” [1] The typical path of raw material extraction, followed by processing, manufacturing, and distribution, leads to product use and disposal—often to landfills—by consumers. Driven by continuous throughput and consumption of finite resources, the linear economic model is unsustainable considering growing resource constraints and the negative human health and environmental impacts associated with this model [46][47]. In contrast, the circular economy is a proposed economic system in which production, consumption, and markets minimize the use of fossil fuels, raw materials, water, land, and other resources. The circular economy aims to eliminate waste, increase the efficiency of resource use, and reduce energy consumption through recovery and reuse of materials [48]. The end goal of the circular economy is to create a global system that is regenerative by design, modeled after biologically regenerative systems, that use “waste as food” for the creation of new products [1].

Circular, or closed-loop systems eliminate waste from product cycles by redirecting materials to new applications at the end of a use phase [49]. Companies integrating circularity into their operations shift industrial paradigms by designing products, such as appliances, machinery, and vehicles, for multiple cycles of remanufacturing or reuse [1], or examining how products at end-of-use, such as carpet tiles can be converted into materials and used as feedstocks for alternative commodities. When a product reaches end of life, several options exist, as shown in Figure 7. Value in the form of capital costs and labor is maintained most effectively within the smallest loop.

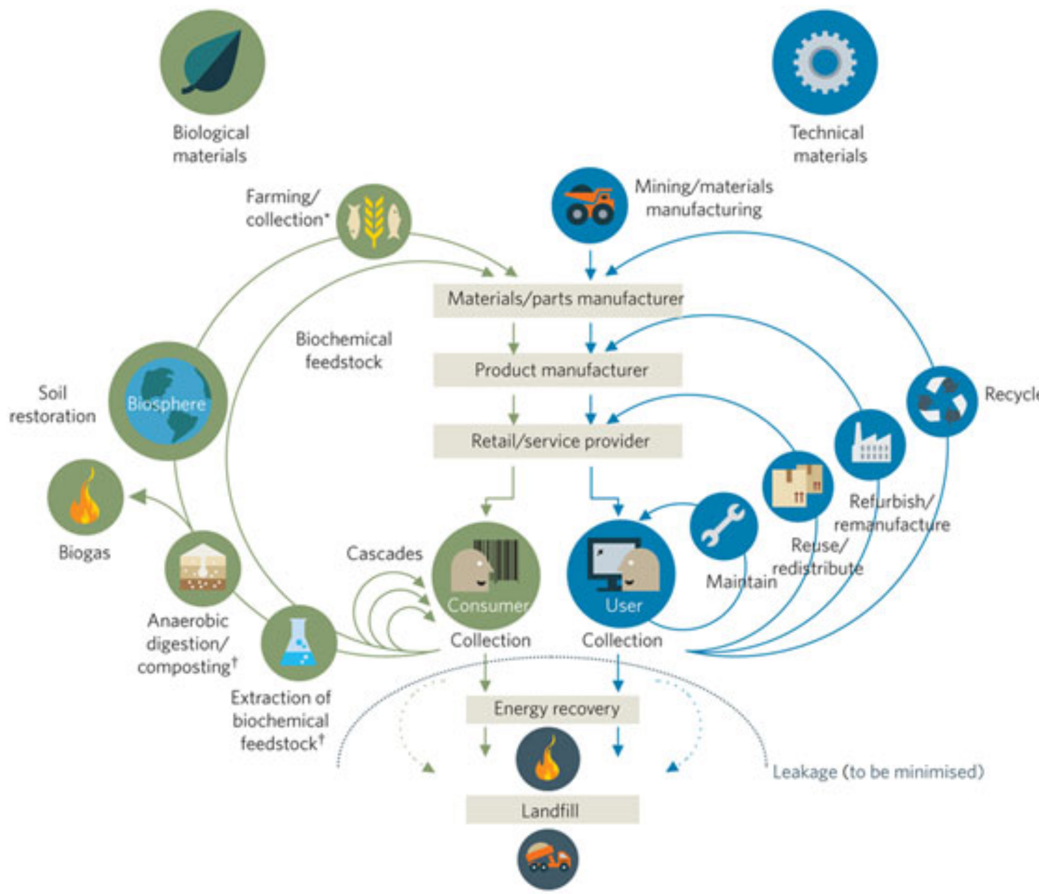


Figure 7: Circular System Diagram: Illustrates the Flow of Technical and Biological Materials throughout the Value Chain [1]

The circular economy is growing in popularity as a result of efforts within the European Union (EU) and China to adopt circularity as a sustainable development strategy [50]–[53]. However, movement from theoretical concepts of the circular economy to actual implementation has been slow [54], [55]. Furthermore, the available case studies of companies, industries, or regions that have enacted circular practices are often limited in scope [56], [57]. In order to bring the circular economy to fruition it is critical to determine and understand the incentives that exist for governments, companies and consumers as well as the decisions each stakeholder makes throughout the product life cycle.

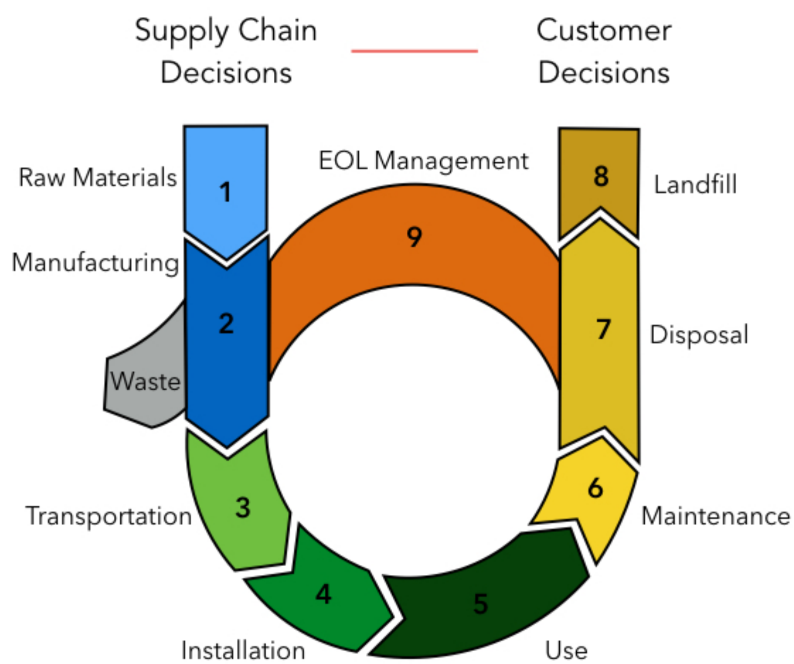


Figure 8: Decisions Along the Product Life Cycle

The creation of closed-loop systems is dependent on the symbiosis between supply chain (company) decisions and consumer decisions. On the supply chain side, companies currently are in charge of decisions regarding raw material extraction, manufacturing, and transportation. Customers are the primary decision makers in product use, maintenance, disposal and if a product is landfilled. One strategy for closing the product system loop is end-of-life management, as shown in Figure 8. End-of-life management is what connects products in the hands of consumers back to the original manufacturers, thus closing the product system loop. End-of life management can lead to material recovery, preserve embodied energy, and decrease the overall environmental footprint of a product. By examining both decisions throughout the entire product life-cycle, insights about how product design informs customer decisions and vice versa can be drawn.

2.3 Demand from a Growing Global Middle Class Population

The implementation of a circular economy is particularly needed due to the impending growth of the global middle class. It is expected that 3 billion new consumers will enter the middle class by 2030 [58]. This economic shift will be accompanied by unprecedented demand for goods and services as well as significant amounts of raw material and energy to satisfy the increased consumer demand [59], [60]. Efforts focused on optimizing the efficiency of the current linear consumption model will be insufficient given the limits that exist on natural resources and the growing impacts of climate change [61], [62]. Furthermore, as shown in Figure 9, the economic growth and change in consumerism will primarily occur in rapidly developing countries including China, India, and Brazil [58]. The question then becomes, how do we deliver on 'sustainable development' as described by the Brundtland Commission, that is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [63].

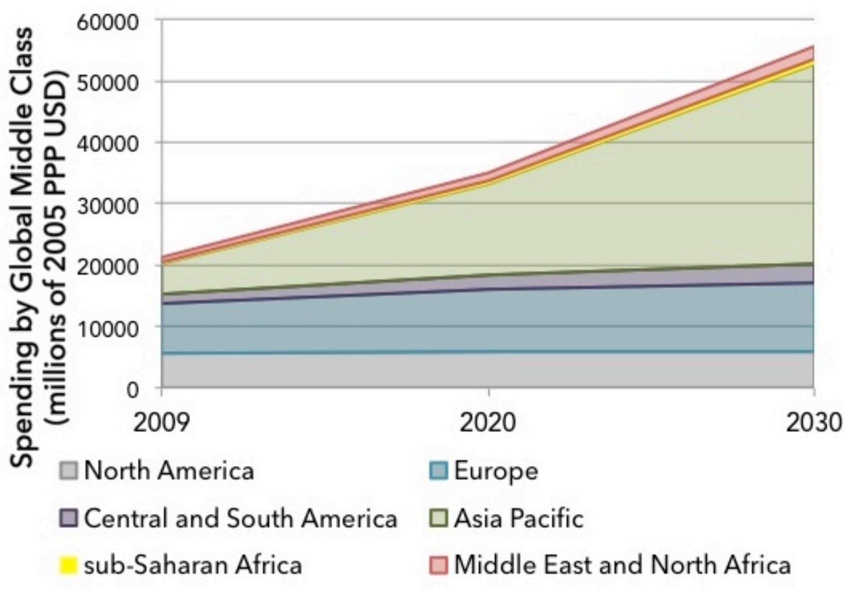


Figure 9: Growth of Global Middle Class Consumption – Data from [58]

Sustainable development requires new methods of consumption, new mechanisms for delivery value, and new economic systems in which to operate [64]. While there are technologies and ideologies that may be leveraged in order to achieve the desired outcome, sustainable product design and end-of-life management represent two high potential opportunities.

2.4 Current Lighting Management Practices for Product Categories

In order to understand the best way to redesign or optimize end-of-life management systems for LED light products, it is first necessary to determine current end-of-life practices. Several product categories are examined within this dissertation research: residential LED lights (A-19s) used in the U.S., LED street lights used in the U.S., and finally solar lanterns intended for use in low-income settings. The purpose of examining all three product categories is to understand how different use contexts influence technology end-of-life management.

2.4.1 Residential Lights

Improper disposal of LEDs is problematic due to the levels of metals contained within the products; landfilling represents a loss of scarce resources. In the consumer space, management of EOL for A19s represents a particular challenge area, because the lights are relatively low-value products and the EOL choice is made by consumers that are unaware of what should be done once the product breaks or is retired. The flow of information for consumer LEDs throughout the product life-cycle is shown in Figure 10.

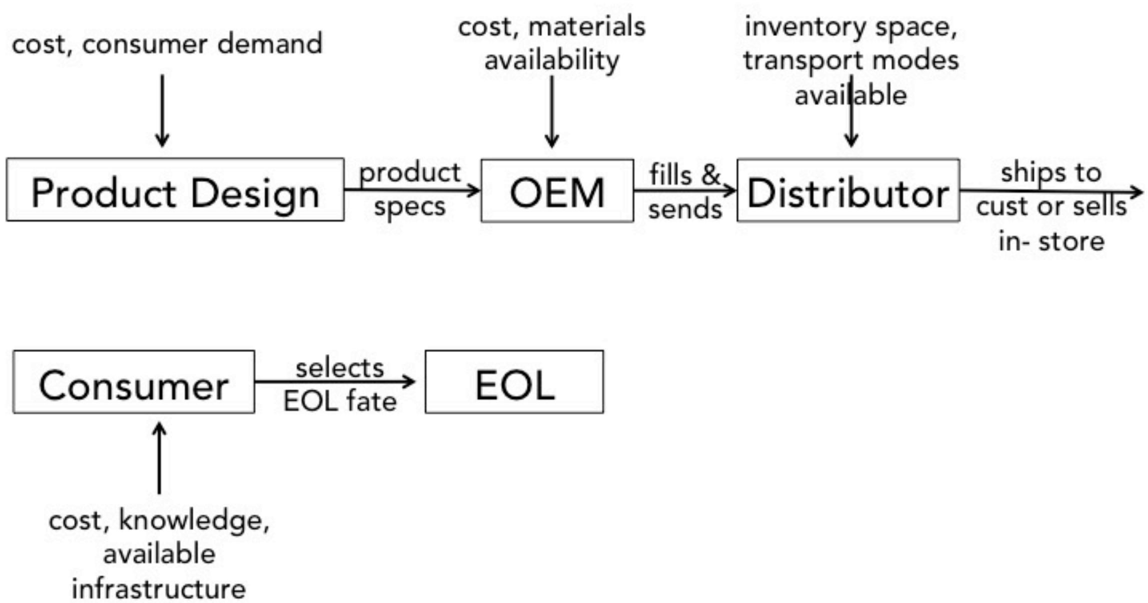


Figure 10: Information Process Flow and Influencing Factors for Residential LEDs

Here, the product's ultimate EOL fate lies entirely in the hands of the consumer. Consumers often are unaware of what is the optimal EOL decision. As LEDs begin to take a larger share of the lighting market and their product design evolves, it is important to understand the concerns around their EOL and determine how they could be best designed for their anticipated EOL fate.

2.4.2 Street Lights in U.S.

The management of street lights varies significantly according to states' and cities' policies, and thus the information chain for a specific context is shown in Figure 11.

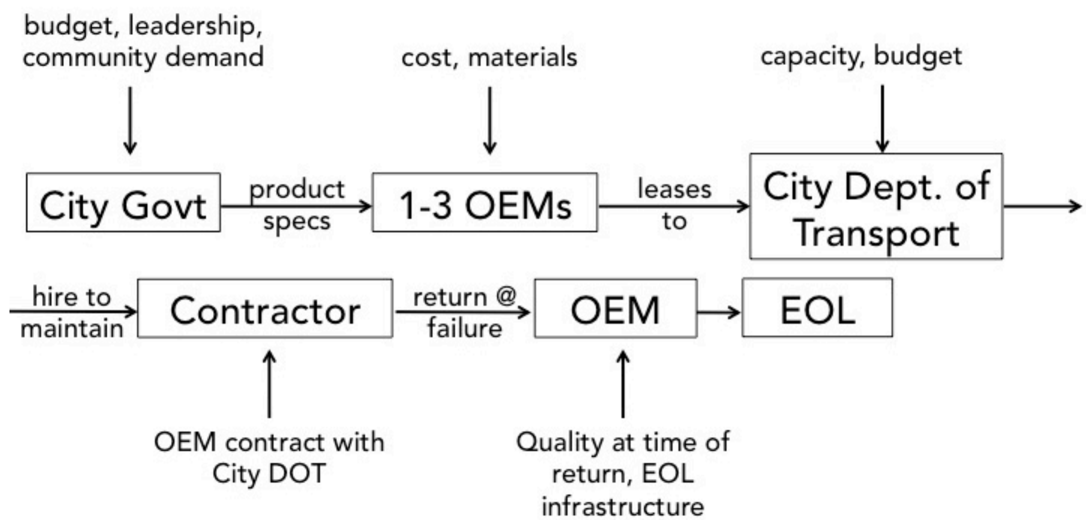


Figure 11: Information Process Flow and Influencing Factors for LED Street Lights

As shown in Figure 11 the decision chain for street lights is more complex than that for residential lights. The ownership of street lights varies throughout the country, but typically they are owned either by a public agency (such as the department of transportation) or the agency leases the lights from their utility company. What makes street lights a useful case study is that the products are evolving as rapidly as residential LEDs, but street lights are a much higher value product (on the order of 100-200 USD) and are bought in bulk. Municipalities will replace large portions of lighting fleets at once (when budgets allow), despite the fact that their existing portfolio represents products installed at different time periods. Decisions to replace lights are governed by time of installation as well as location. Lights in a particularly high-traffic area may be replaced first in order to get community buy-in, or lights in a particular neighborhood may all be replaced at once, regardless of individual install date.

2.5 Research Challenges

The investigation of optimal product end-of-life strategies under conditions of rapid technological change is complex for the following reasons:

- While the design for disassembly, modularity, and remanufacturing literature is robust, available design guidelines are generic, leading OEMs, particularly within the lighting industry, to continue business-as-usual practices without change. The process of translating generic design principles to specific products is unclear to designers and manufacturers and mechanisms of translation are limited. A framework for conducting product-specific design assessments is needed, as are examples of how to generate industry-specific deign guidelines.

- Many growing consumer markets exist in contexts without waste management infrastructure. Designers working to create products for new markets are often unfamiliar with challenges of design, manufacturing, and end-of-life for technologies used in developing countries. A taxonomy of considerations is required for designers to determine the product design strategy that ensures sustainability as well as appropriateness for the specific context and stakeholder needs.
- Factors influencing end-of-life management decisions are numerous and differ based on the decision-context and particular stakeholder interests. Successful implementation of technology management strategies that minimize environmental impacts requires understanding of all factors presently driving decisions. Empirical characterization of factors influencing end-of-life decision-making for lighting technologies is needed.
- Life-cycle assessment is frequently used to determine cost and environmental impacts. In the case of energy-consuming technologies, end-of-life impacts are assumed to be small relative to the use phase if products are kept for their entire expected life and therefore not analyzed in-depth. The end-of-life phase plays a significant role particularly for products that are replaced prior to failure. A framework for assessing cost and environmental impacts for all potential product end-of-life strategies is needed.
- Determining optimal product replacement strategies in a way that incorporates the complexities of the decision-making process as well as the product characteristics remains a challenge. It is therefore necessary to construct a model which integrates these features to examine product replacement. The construction of a comprehensive model will aid significantly aid future decision-makers and policy-makers.

2.6 Dissertation Contributions

This dissertation aims to examine and analyze factors influencing product design and end-of-life management within the lighting industry as well as build a framework for system analysis within this problem context. The ultimate goal of the work is to promote more informed decisions and actions related to resource preservation and climate change mitigation by influencing product design, use, and end-of-life management. The main contributions from this work include:

- *Product assessment and generation of design guidelines (Chapter 3):* A novel method of product assessment was developed and then applied to a diverse set of lighting products. The current suitability of available products for end-of-life processing is characterized and trends for the broader industry are identified.
- *Considerations for product design within developing country contexts (Chapter 4):* A taxonomy of design, manufacturing, and end-of-life considerations is constructed for products intended for use in developing countries. The taxonomy

provides designers with insights into consequences of design decisions as well as strategies for navigating trade-offs in the design and manufacturing phases.

- *Empirical characterization of technology management problem within the street lighting context (Chapter 5):* Interviews conducted with decision stakeholders yield insights into contextual challenges that frequently constrain implementation of the "optimal" product management strategy. The interviews further provide an understanding of the system influencing decision-making and lead to a future research agenda for the academic community.
- *Integrated technical, economic, and environmental assessment for end-of-life strategies (Chapter 6):* Prior LCA work in the context of lighting technology assumed the end-of-life phase to comprise recycling and landfilling only and did not incorporate assessment of product design. The work presented here characterizes environmental and economic impacts associated with different end-of-life strategies to provide a quantitative assessment of the potential for realizing closed-loop product systems within the lighting industry.
- *Development of a Markov Decision Process model to determine optimal management (Chapter 7):* An MDP model was applied to the problem of street lighting management and incorporated factors including projected energy efficiency gains and expected product degradation and failure. The results highlighted the need for manufacturers to consider "light as a service" business models as a mechanism for resolving the trade-off between economically- and environmentally-optimal decisions.

2.7 Dissertation Organization

The analyses presented in this dissertation include multiple applications of lighting throughout. A given sector was utilized as a focal area depending on the relevance, utility, and feasibility of each type of analysis. Chapter 3 focuses on analyzing the role that design plays in influencing the end-of-life trajectory of a technology. Here, three product classes are included. Residential A-19 lighting products are the primary focus, due to their low cost and high level of accessibility. Chapter 4 analyzes technology innovation and end-of-life strategy for products intended for use in developing countries. The chapter starts with an examination of the factors that must be considered when manufacturing appropriate technology products and then examines in-depth end-of-life implications for one technology, solar-powered lanterns. In Chapters 5, 6, and 7 the focus of the dissertation shifts to street lights. Chapter 5 includes analysis of the decision processes of supply chain stakeholders. Chapter 6 examines the cost and emissions associated with various product end-of-life trajectories. Chapter 7 integrates the life-cycle and cost data into an optimization model that seeks to examine when street lighting products should be upgraded and how time of upgrade influences the feasibility of various EOL trajectories. Finally, Chapter 8 provides a summary of the work completed and outlines areas of future research.

3 Assessment of End-of-Life Design in Solid State Lighting

Adapted with permission from: Assessment of End-of-Life Design in Solid-State Lighting. (2017). Dzombak, R., Padon, J., Salsbury, J., and Dillon, H. *Environmental Research Letters,* In Press.

3.1 Role of Design in Determining End-of-Life Fate

Consumers in the U.S. market and across the globe are beginning to widely adopt light emitting diode (LED) lighting products while the technology continues to undergo significant changes. While LED products are evolving to consume less energy, they are also more complex than traditional lighting products with a higher number of parts and a larger number of electronic components. Enthusiasm around the efficiency and long expected life span of LED lighting products is valid, but research to optimize product characteristics and design is needed. This study seeks to address that gap by characterizing LED lighting products' suitability for end of life (EOL) recycling and disposal. The authors disassembled and assessed 17 different lighting products to understand how designs differ between brands and manufacture year. Products were evaluated based on six parameters to quantify the design. The analysis indicates that while the efficiency of LED products has improved dramatically in the recent past, product designers and manufacturers could incorporate design strategies to improve environmental performance of lighting products at end-of-life.

3.2 Introduction: A-19 Lighting

The DOE suggests that by 2025 LEDs will produce at least half of the electric light in the United States and even more globally. Such significant market growth necessitates consideration of the materials and resources as well as how they are joined together, because the overall design significantly influences the fate of products at end-of-use or end-of-life. Despite the evolution of designs within the lighting industry, significant potential exists to better design for material recovery at end-of-life. It is critical to assess lighting products holistically and make design improvements now before uptake by consumers expands further.

Although energy efficiency gains make LEDs a clear improvement from incandescents, LED lighting products are more complex and contain more parts than predecessor technologies (see `Figure 12`). Unlike incandescents which produce light directly from the electrical current by heating a filament, compact fluorescent (CFL) and LED lighting products require a ballast (or driver for LEDs) to control the power delivered to the light source. In the case of LEDs, the driver is an electrical device, comprised of metal and wire elements. The result is a radically different lighting technology when compared to incandescent and CFL products. Product complexity for LEDs is only set to increase as designers and manufacturers leverage the potential for lighting to provide additional value including security features and data transmission among others [65]. Design and development within the typical 60 watt replacement market (A-19) has large product variation both between product years and manufacturers. The A-19 market's wide spectrum of design suggests that the industry is still in a growth stage, and thus it is an important time to analyze design trends and the impact of design decisions on environmental sustainability.

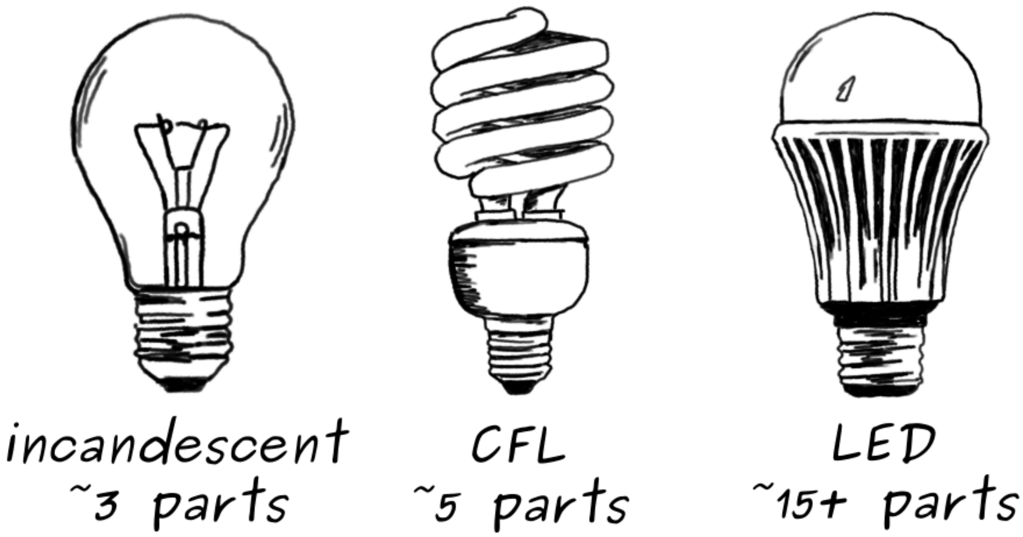


Figure 12: Number of Parts for A-19 Lighting Products

Currently, lighting products are primarily either disposed of in landfills or recycled. Conservative estimates suggest that approximately 30% of commercial lighting products are recycled each year and even less in the residential sector[66]. Landfilling of LEDs is problematic due to the levels of metals contained within the products, a contribution to environmental hazards and depletion of scarce resources. Tuenge et al. found that the concentration of California-regulated elements in LED products was similar to the concentration in cell phones and other electronic products[67]. This is due to the materials used in the drivers, screw bases, and wires. Other research teams have found that LED lighting products contain metals that are classified by the European Union as ``scarce'' due to anticipated resource depletion resulting from future disposal [68]. As access to critical resources becomes increasingly constrained, it is important to examine how to build products so that the materials used are recoverable at end-of-life. This is a key step in moving toward a circular economy, in which natural resources are preserved over time, used and reused, thus reducing the global waste burden [1][69]. In order to recover products following use by a consumer, two things have to be in place: a system of recovery as well as a product that is designed for disassembly and material recovery. Here, the latter will be explored in the context of LED lighting products. Improved end-of-life strategy can lead to lower life-cycle impacts, higher levels of material recovery, reduced embodied energy, and increased adoption of energy efficient SSL. Furthermore, understanding the current challenges (like disassembly) associated with disposal of a new technology can help to influence design to increase suitability for end-of-life options.

In this study, A-19 products from multiple vendors and product years were analyzed to examine how ecodesign principles have been incorporated over time as well as the implications of product design on end-of-life fate. To do this, 17 A-19 designs from 2013-2016 were disassembled and characterized. The properties of each were examined in an attempt to understand trends of the industry (if any exist) as well as their suitability for various end-of-life fates, including landfilling, recycling and remanufacturing. Finally, a set of design guidelines was developed specifically for A-19 LED products that could be adopted by the industry.

3.3 Background: A-19 Lighting

Solid-state lighting (SSL) has emerged as a strong market force in lighting in the last 10 years [70]. The life-cycle environmental impact of SSL has been considered by prior authors, and found to be notably better than traditional incandescent and CFL products [71] [72]. The impacts are considerably less due to the higher energy efficiency of SSL products leading to lower use phase impacts [37]. However, the environmental impacts associated with SSL product manufacturing are non-trivial and can have an even larger influence on the overall product sustainability if their useful life is shorter than expected [73]. The energy intensity of the materials and manufacturing phase for SSL products enhances the potential benefit of product recovery at end-of-life. Furthermore, upon examining the implications of global SSL uptake in the coming decades, researchers have found that future clean energy sources may emit fewer greenhouse gases but will require more metals and materials [74] [75]. This in turn could increase the necessity of designing lighting sources that are well-suited for recycling and other material recovery options at end-of-life [76].

Decisions made in a product's design phase can have important implications on the environmental impacts incurred throughout the life-cycle (see Figure 13) [77]. Product design encompasses all of the steps necessary to bring a product to market, including but not limited to: planning, need identification, product specification, concept generation, selection, and testing [78]. Design influences what materials are used, how the product is manufactured, how energy efficient the product is, and what end-of-life trajectories a product can follow (e.g., is a product able to be recycled?). Several researchers have previously examined the connection between product design and sustainability for SSL products. Hendrickson et al. performed preliminary research in 2009 on early A-19 LED products to understand the end-of-life implications of SSL design [15]. They found that the early LED product mass was dominated by the LED heat sink, often made of aluminum. This was still the case in 2012 when Scholand and Dillon determined the aluminum heat sink contributed significantly to hazardous waste sent to landfills [71]. Contribution to hazardous waste was the only area in which the LED product did not outperform existing compact fluorescent (CFL) technology [71].

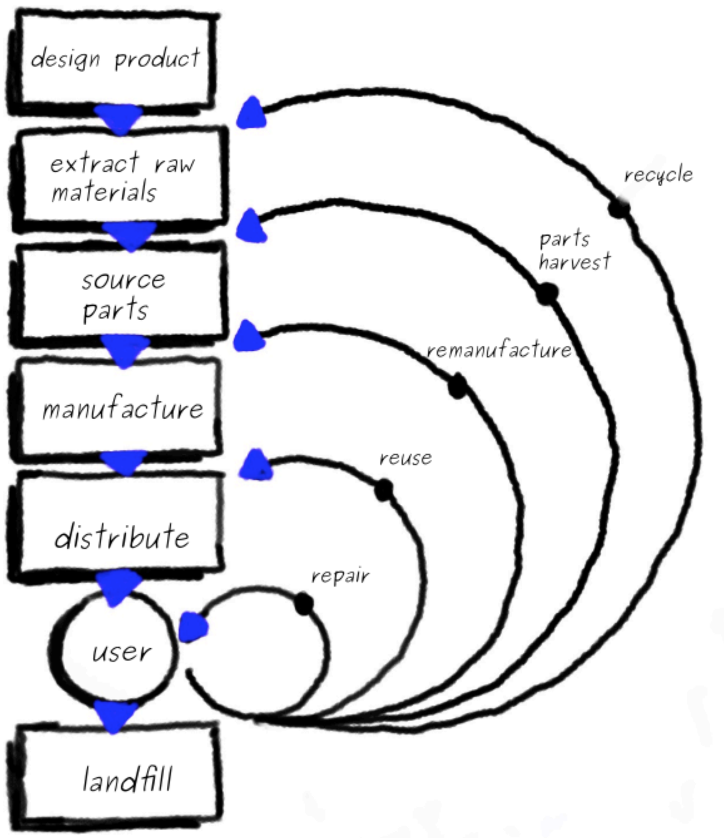


Figure 13: Product Life-Cycle Phases and End-of-Life Paths, Adapted from [1], [79]

Also in 2012, Olivetti et al. examined product design as a contributor to the overall environmental impact associated with LED lighting products. Olivetti found that despite higher energy efficiency, LED products had more component parts than the CFL or incandescent equivalents [80]. Olivetti further determined that the lamp base which includes the aluminum heat sink, insulating base and Edison screw, had the largest influence on the carbon footprint when considering both manufacturing and end-of-life, followed by the ballast (printed wiring board) and LED module [80]. In recent years LED manufacturers have worked to increase the efficacy of the LED light modules and have reduced the mass of aluminum needed in most A-19 products.

In a review summarizing the current state of SSL as well as trends for the future, Katona et al. look at the evolution of lighting products over time from multiple perspectives [65]. The authors analyze six products from unknown vendors sold between 2011-2015. The analysis shows that over that time vendors have begun to shrink (or in one case remove) the heat sink, made possible through the use of low power LEDs [65]. Katona et al. point out that lighting designers have more ability to design better products for specific applications and integrate additional value propositions. Though appealing, this also could lead to more frequent replacement of lighting products and a greater need for end-of-life processing.

Recently, Van Schaik conducted a detailed examination of the recycling potential for metals within waste electrical and electronic equipment, including lighting products [68]. Such a study is important as the metals within LED lighting products are a major source of environmental impacts. Along with Van Schaik, Reuter showed that the recycling potential for a product depends heavily on the types of materials used, how they are combined, and the available recycling technology [81]. They further encourage the research community to conduct context-specific analyses rather than generic analysis as changes in product design and the recycling system can lead to significant differences in material recovery [68]. One point that this article will pick up on is a guideline offered by Van Schaik and Reuter that states one should, "Design clusters or sub-units in products that can be easily removed and which match with the final treatment recycling options [68]." Such a practice is critical to ensure preservation of components that would be otherwise lost or have low yield in recycling processes. In this study the methodology of Hendrickson et al. is adapted to consider how current A-19 products perform for end-of-life characteristics and compare to products from 2009 to 2016 [15]. Such an analysis will allow for an assessment of whether or not the lighting industry is on track with the goal of creating products more suitable for end-of-life processing.

3.4 Methods

To assess the suitability of current and former A-19 products for end-of-life processing, 17 products were disassembled into constituent materials. The product set consisted of A-19 LEDs purchased in 2013 to 2016. The products were purchased from a single outlet for consistent pricing information. Selection of the product models was based on popularity, design characteristics, sustainability, and diversity. Prior to disassembly, product information was gathered from product labels, online sources and lab instrumentation (see Table 2).

Table 2: Summary of the A-19 Products Analyzed – products selected represent a range of power and color temperature reported by manufacturers.

Product Label	Date Sold	Rated Wattage (W)	Rated Lumens (lm)	Efficiency (lm/W)	Rated Lifespan (hours)	Product Mass (g)
P01	2013	12.5	800	64.0	25,000	160.4
P02	2013	13.5	800	59.3	27,500	217.6
P03	2013	10	830	83.0	30,000	110.1
P04	2013	10.5	800	76.2	20,000	128.5
P05	2013	8	450	56.3	25,000	62.6
P06	2013	13	800	61.5	25,000	234.7
P07	2013	10	820	82.0	50,000	123.8
P08	2013	12	800	66.7	25,000	113.7
P09	2013	7.5	450	60.0	20,000	145.2
P10	2013	13.5	800	59.3	25,000	245.2
P11	2013	12	820	68.3	25,000	168.5
P12	2013	10	940	94.0	30,000	171.1
P13	2013	7	450	64.3	25,000	97.1
P14	2016	10.5	800	76.2	20,000	124.8
P15	2016	19	1680	88.4	25,000	229.2
P16	2016	11	800	72.7	25,000	108.3
P17	2016	10	810	81.0	50,000	110.0

The common components of most A-19 lighting products are shown in Figure 14. Information collected during the disassembly included tools required, time of disassembly, component materials, disassembly difficulty, matings between parts, etc. Tools required where categorized as simple (screwdriver and pliers) or complex (Dremel tool and drill). Each step of disassembly was recorded and photographed for later analysis.

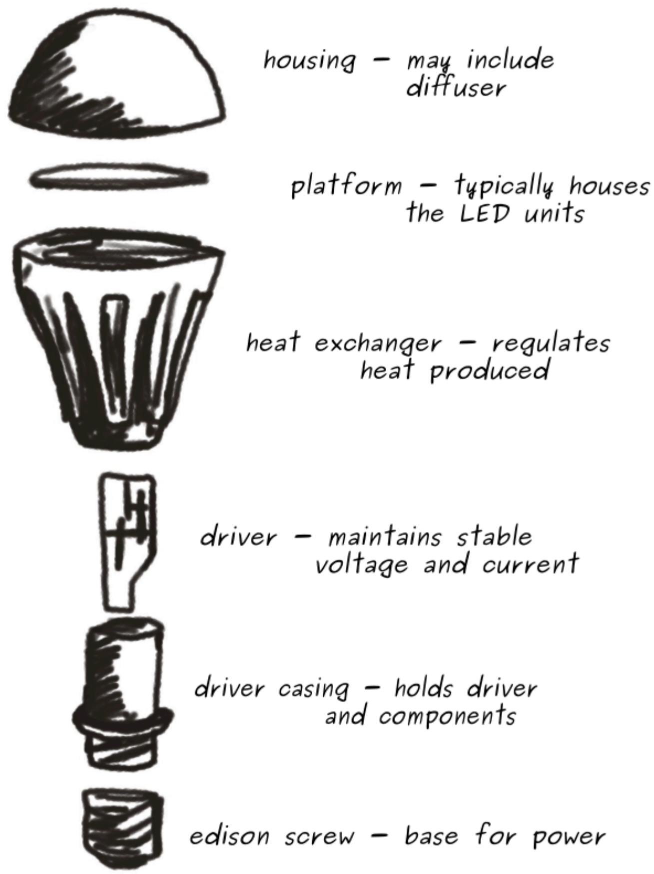


Figure 14: Overview of Typical A-19 LED Lighting Product Components

A set of qualitative and quantitative metrics was used to characterize the design of lighting products included in the study as well as the products' suitability for end-of-life processing. The metrics are detailed below. Use of both qualitative and quantitative metrics allowed for assessment of the current state of technology as well as understanding of industry trends.

- Number of Parts: Summed number of parts contained in each product.
- Time of Disassembly: Measured time of product disassembly tracked in minutes.
- Ease of Disassembly: Efficiency of product disassembly for EOL processing based on level of disassembly possible, tools needed during separation process and preservation of components post-disassembly. Likert ranking, scale in Appendix 1.
- Ease of Recycling: Design-based ease of separating materials to be recovered. Provides an assessment of the state of materials following separation (e.g., are recyclable components covered in epoxy?). Likert ranking, scale in Appendix 1.
- Modularity Level: The ability of the product's components to be separated and recombined. Likert ranking, scale in Appendix 1.
- Recovery Potential (R): Mass % of product possibly able to be recycled

- Likely Recovery (L): Calculated mass % of product likely to be recycled, including metals only
- Material Complexity (H): Quantitative measure of disassembly efficiency. Likert ranking, scale in Appendix 1.

Material Complexity (H) is defined (Eq. 3.1) as the summation of material concentrations times the natural log of concentrations where n is the number of materials and c_i is the concentration of material i. The equation is derived from information theory and provides a measure of material mixing [82].

$$H = \sum_{i=1}^{n} c_i \cdot \ln(c_i)$$ **Eq. 3.1: Material Complexity (H)**

The Recovery Potential (R) is defined (Eq. 3.2) in terms of the total mass of the product (M_t) and the mass of the product that could be recycled (M_r) including both plastics and metals.

$$R = \frac{M_r}{M_t}$$ **Eq. 3.2: Recovery Potential (R)**

The Likely Recovery (L) is defined in terms of the total mass of the product (M_t) and the mass of the product that is likely to be recycled, separable metal components given currently recycling technology and processes (M_m). In the context of LEDs, that practically means only the metal components.

$$L = \frac{M_m}{M_t}$$ **Eq. 3.3: Likely Recovery (L)**

Three different metrics are used to assess the recyclability of products in an attempt to represent the reality of the complexities associated with material recovery through recycling. The ease of recycling is important to consider since efficacy of material recovery has been shown to be dependent on the choice of materials in a product and how those materials are combined [81]. While the `Ease of Recycling' metric examines the latter, the `Material Recovery Potential' (R) and `Likely Material Recovery' (L) metrics consider the former. Whereas R takes into account the mass of both plastic and metal components, L considers only metal components. This is because plastics are often mixed and hard to isolate, reducing the ability to recover such materials. The scoring rubric for metrics L and R are based on work completed by Reuter et al. (2015), that examined product-centric recycling in the context of LED lamps [83].

The full rubric used to assess the products can be seen in Appendix 1. For qualitative metrics (i.e., level of modularity, ease of disassembly, and ease of recycling), a 1-5 scale was defined so that each product could be assessed as shown in Figure 15. After analyzing a set of products, the middle ground (3) was defined by three researchers and then triangulated to ensure agreement. Then the high and low ends of the scale were defined. The high end of the scale (5) is a characteristic of a product suitable for recovery at end-of-life. The low end represents a characteristic that inhibits the implementation of a closed loop system as seen in Figure 13.

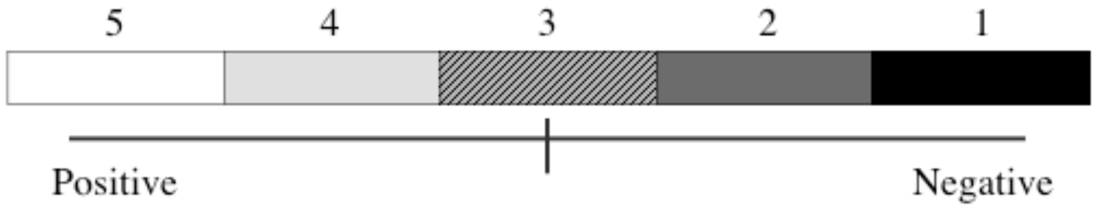


Figure 15: Scale Used to Assess Product Characteristics

For the qualitative metrics the rankings are by nature subjective and dependent on the person performing the disassembly, which was done manually to allow mass values to be collected. For this reason care was taken that the work was performed by the same person whenever possible, so the rankings are internally consistent. It was not possible to perform more than one disassembly due to time and material constraints, but each disassembly report was cross-checked by two researchers to confirm results were consistent.

3.5 Product Analysis Results and Discussion

The first step in characterizing the design of various products is understanding the material composition, as well as how such materials are joined together. Figure 16 shows the mass of components within each product analyzed as well as characteristic information about the product.

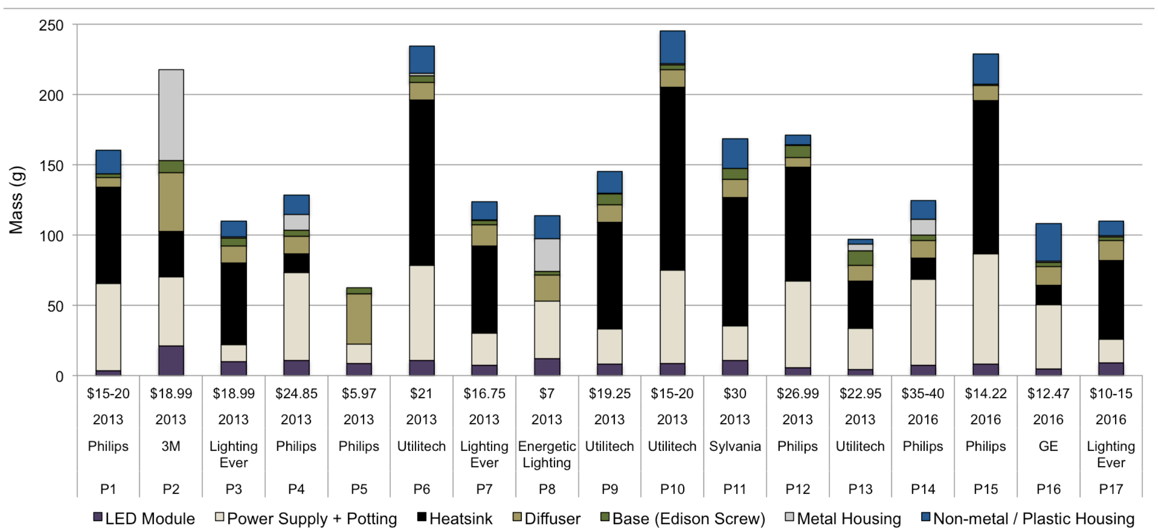


Figure 16: Overall Product Composition by Mass

A total of 17 products were analyzed that represented a wide variety of price points and designs. While the average purchase price of products has decreased since 2013, there still remains a high level of variability between products with regard to material composition, mass, and design. All products in the set made use of an aluminum heat sink except two (P05 and P08), which instead utilized plastic designs to vent heat away from the driver. Both P05 and P08 are designs from 2013; all 2016 products included an aluminum heat sink, though some (P14 and P16) had considerably reduced the heat-sink mass when compared to predecessor designs.

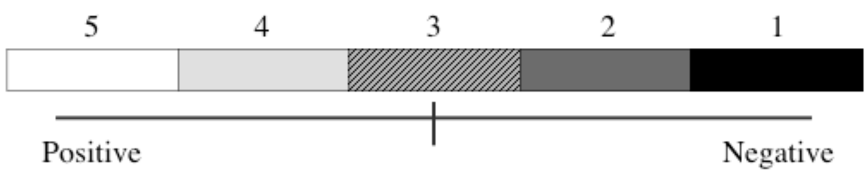
As noted in the Methods section, each product was disassembled as completely as possible. The time of disassembly, the number of processing steps, and tools required were recorded. The results of the product analysis are shown in Table 3 and Table 4.

Table 3: Raw Scores for Product Assessment

Product Label	# of Parts	Time of Disassembly (min)	Ease of Disassembly	Modularity Level	Ease of Recycling	Recovery Potential R (%)	Likely Recovery L (%)	Material Complexity H
P01	28	105	2	2	1	61	32	1.16
P02	14	45	1	1	1	69	46	1.37
P03	14	20	5	5	4	81	55	1.28
P04	15	39	2	2	1	44	22	1.32
P05	15	57	3	2	3	64	0	1.12
P06	21	26	4	4	3	67	42	1.20
P07	15	18	5	4	4	75	53	1.25
P08	21	39	4	4	3	53	35	1.38
P09	16	23	4	4	3	77	58	1.27
P10	18	58	3	2	2	70	56	1.14
P11	31	150	1	1	1	78	60	1.26
P12	32	72	2	2	2	61	51	1.19
P13	15	32	5	3	4	65	50	1.39
P14	15	30	2	2	2	45	24	1.28
P15	25	35	1	2	3	62	48	1.38
P16	18	84	1	2	2	41	16	1.49
P17	20	11	5	5	5	76	54	1.30

Table 4: Scaled Assessment of Design and End-of-Life Suitability for A-19 Products

Product Label	# of Parts	Time of Disassembly (min)	Ease of Disassembly	Modularity Level	Ease of Recycling	Recovery Potential R (%)	Likely Recovery L (%)	Material Complexity H
P01								
P02								
P03								
P04								
P05								
P06								
P07								
P08								
P09								
P10								
P11								
P12								
P13								
P14								
P15								
P16								
P17								



Once data was collected on every product, the quantitative results were converted to the same 1-5 scale as the qualitative criteria (using the rubric in the supporting materials) so that each product could be examined holistically. The authors recognize that the assessment criteria have varying degrees of relevance for different end-of-life paths. For example, ease of disassembly has greater significance in the context of remanufacturing than landfilling. However, the goal of putting on all criteria on a similar scale was so that designers and manufacturers could easily see both the strengths and weaknesses of the product.

3.6 Summary of Data Collected

There are many things to note when examining the full results of the analysis. The average number of parts is lower among products from 2013 versus 2016, though a smaller sample size for 2016 was used. This could be indicative of the emergence of more complex products rather than simplified ones. Furthermore, the products with high numbers of parts (P01, P11, P12, and P15) also ranked poorly across the other criteria. A shorter time of disassembly did not necessarily imply an easier process for disassembling. Products P13, P14, P15 all took between 30-40 min for disassembly, but the processes involved different levels of difficulty. For example, P14 proved challenging to disassemble due to the high use of thermal epoxy and adhesives as well as hard to pry fastening mechanisms. The level of modularity showed congruence with the ease of disassembly for the most part, with exceptions including P15 and P16. In these cases, the products exhibited modular design aspects such as a snapping mechanism to attach a plastic cover with the heat exchanger. However, the overall disassembly in both cases was challenged by an inability to isolate the driver. An example of this for P15 is shown in Figure 17.

Figure 17: P15 Challenging Access to Driver

The ease of recycling metric examined the ability to manually separate plastic and metal product components. Most products scored poorly within this category as the designs were often complex with product components tightly integrated or covered with adhesives. However, P17 provided an example of a highly separable, modular design that made liberating recyclable components straightforward as shown in Figure 18. In a real life application, a laborer at a recycling plant must disassemble electronic devices into constituent recyclable or non-recyclable parts. More likely than not, manufacturers do not take this as high priority when designing devices. Since LEDs are more similar to a cell phone than an incandescent bulb with regard to parts, it is reasonable to treat disassembly of LEDs similar to that of a cell phone. While most products analyzed scored in the upper range for `Material Recovery Potential', the `Likely Material Recovery' could provide a more accurate representation of the state of recycling potential amongst A-19 lighting products.

Figure 18: P17 Design with High Ease of Recycling

The ease of recycling is important to consider since efficacy of material recovery has been shown to be dependent on the choice of materials in a product and how those materials are combined [81]. While the `Ease of Recycling' metric examines the latter, the `Material Recovery Potential' and `Likely Material Recovery' metrics consider the former. While most products analyzed scored in the upper range for `Material Recovery Potential', the `Likely Material Recovery' could provide a more accurate representation of the state of recycling potential amongst A-19 lighting products. This is because the plastics are often mixed and hard to isolate, reducing the ability to recover such materials.

The final metric analyzed, `Material Complexity', shows little variation between products. Such results could indicate that despite differences in manufacturing and design approaches, the complexity inherent to the product is uniform across manufacturers and product years. This means that no significant breakthrough in the form factor of the product and the technology design has occurred yet, and there still exists opportunity for innovation.

3.7 Correlation Analysis

To further explore the data collected, the authors conducted a statistical correlation analysis of the product results. The analysis was performed using the statistical programing language R [84]. The raw data from Table 3 was used to calculate the correlation matrix. A correlation matrix indicates the relationship between the variables in the table with one another. For this work the Pearson's product moment correlation coefficient, P, was calculated based on a linear relationship. The correlation coefficient represents how closely correlated one variable is to another on a scale from 1 to -1. The results are shown in Figure 19.

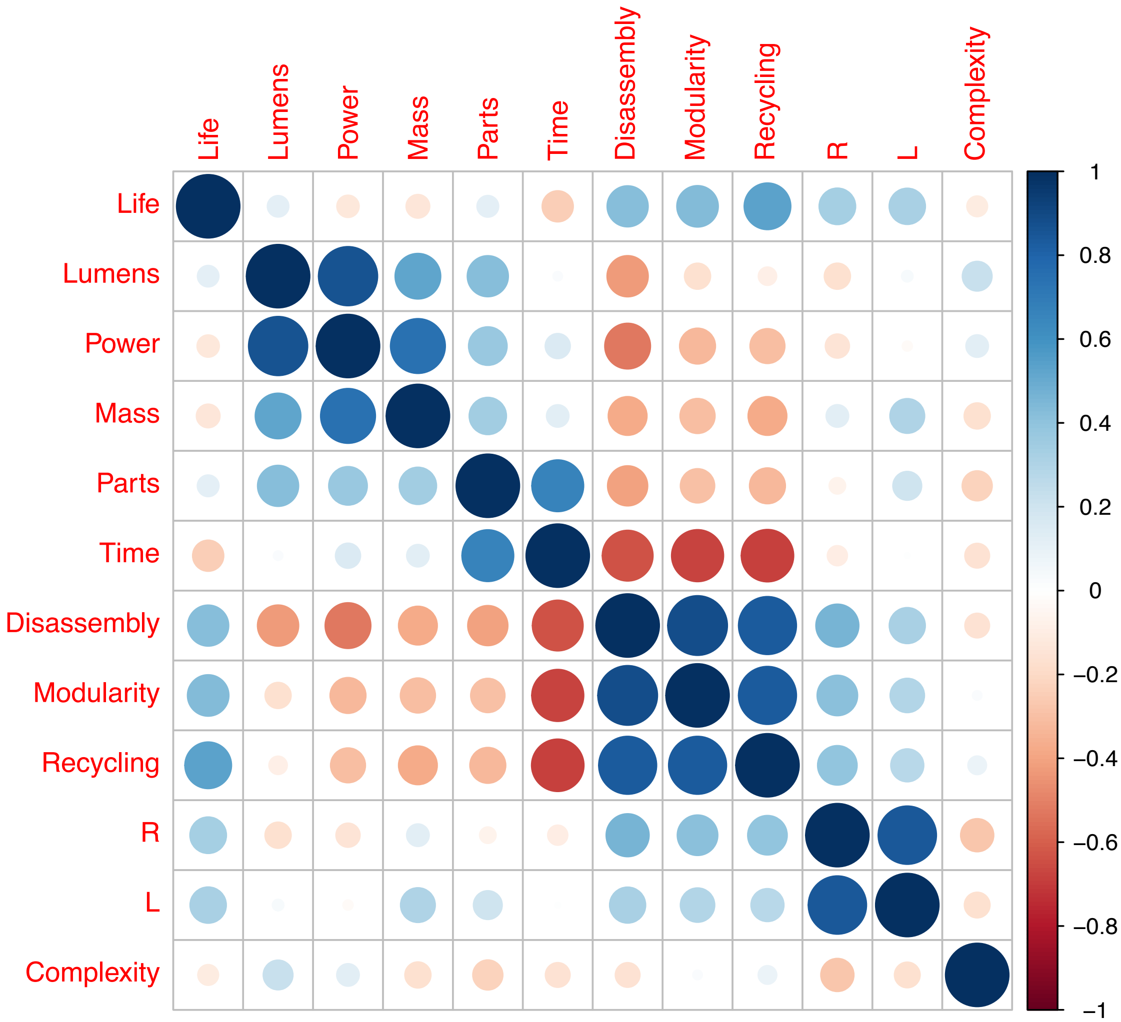


Figure 19: Correlation matrix for LED end of life parameters measured. The size of each circle is proportional to the correlation coefficient calculated.

In the correlation results, blue circles indicate the two variables are highly correlated (P=1), so each variable is highly correlated with itself as shown on the diagonal. Red circles indicated a low correlation (P=-1), and the size of the correlation is indicated by the size of the circle.

The analysis shows that R and L are highly correlated (P=0.84), a logical outcome since both values include the mass of metals in the products. Other variables that are highly correlated on the manufacturer side include mass and power (P=0.75).

The matrix also indicates that time required to disassemble is not strongly correlated with ease of recycling, ease of disassembly, and modularity. This result is reasonable for ease of recycling and modularity, but for the ease of disassembly this shows that the type of tools needed is not tied to the total disassembly time. In contrast, the total number of parts is correlated to disassembly time (P=0.67).

3.8 Examples of Positive and Negative Design Features

Among the variety of products analyzed, several design trends were noticed. Upon disassembly, the thermal epoxy posed the largest challenge in dissecting the bulb into its constituent materials. The epoxy must be meticulously pried off in order to uncover electronic components. Often the thermal epoxy acted as both thermal management and an adhesive for the driver inside the sink of the bulb. The part of the sink that adhered to the epoxy varied greatly in models that contained the thermal epoxy. Some models contained a plastic casing covering the driver. Others adhered directly to the heat exchanger.

The use of a metal heat exchanger itself prevailed as a trend in our samples. Its presence is key for the LEDs' ability to dissipate heat. Up to 58% of the heat dissipated in LEDs is dissipated through the exchanger [85]. Although the fin design (shape of the exchanger) varied, a metal exchanger was commonly present, and it was ubiquitously made from aluminum. From a sustainability standpoint, metal exchangers still have room for improvement. While useful in dissipating heat and providing structural support, metals used for exchangers, aluminum in particular, are more harmful at end-of-life than other LED components [71].

After disassembling and analyzing the entire product set, patterns of both positive and negative features arose among designs. Typically, concerns were attributed to complex designs with cramped components, large use of adhesives or epoxy, or difficulty accessing the LED driver. For instance, P02's complex design caused an invasive, time-consuming disassembly. Excessive force using a hammer and punch was required to remove the driver, and a Dremel tool was needed to gain access to the LED chip as shown Figure 20. Furthermore, the LED chip could not be removed from the heat exchanger.

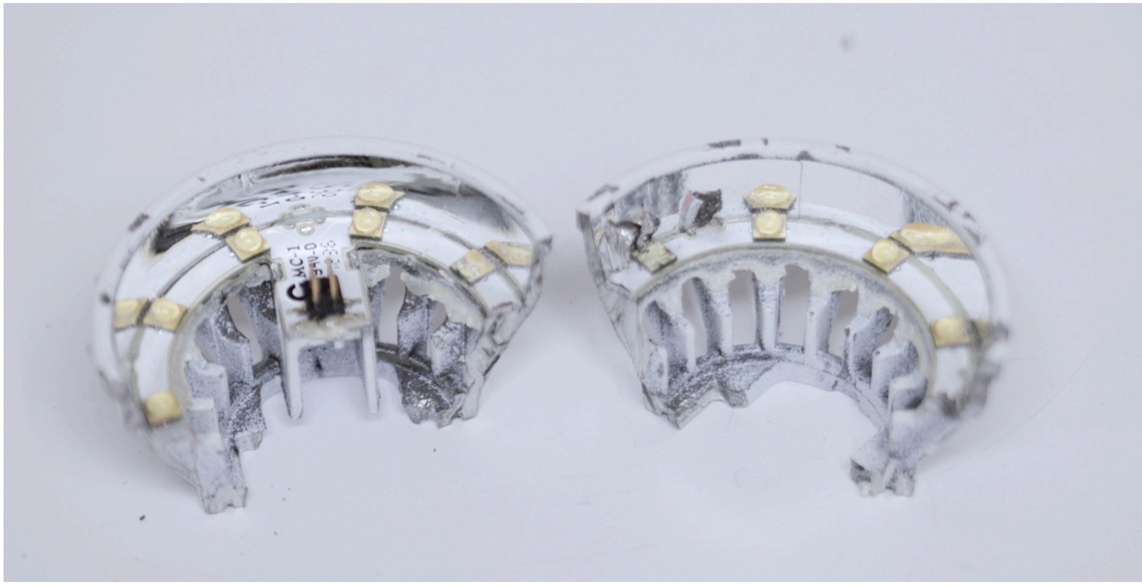


Figure 20: P02 product disassembly with heat exchanger in two parts. The sections required a Dremel tool for separation

P11 also required significant effort for disassembly. The design incorporated a complex plastic casing for the driver. The casing lacked practicality and impeded driver access. The casing had to be destroyed in order release the driver as shown in Figure 21. Though the casing did provide for an attractive aesthetic, its form inhibited the ability to recover component materials upon disassembly.

Figure 21: P11 Product Casing Made of Complex Plastic

To improve lighting products, designers of LED lighting should focus on creating modular products with accessible components that are easily detachable through the use of simple fasteners. Additionally, electronic connections should utilize PCB connectors over soldered wires and should aim to reduce thermal epoxy when considering heat distribution elements. P10 provides an example of the opportunity for a quick modularity upgrade. Soldered wires connect the driver and LED platform as shown in Figure 22. If a two-pin connector was utilized instead of soldering, this product could become easily serviceable in case of LED failure, the second-most common product failure mechanism [86].

Figure 22: P10 as an Example of Modularity

P02 (already noted for poor access to the LED platform) exhibited a small PCB connector (see Figure 23) that plugs the driver into the LED platform. This connector replaces metal wiring and creates higher modularity for the bulb. This design is unique for connecting the two most common components responsible for failure: the driver and LED platform [86].

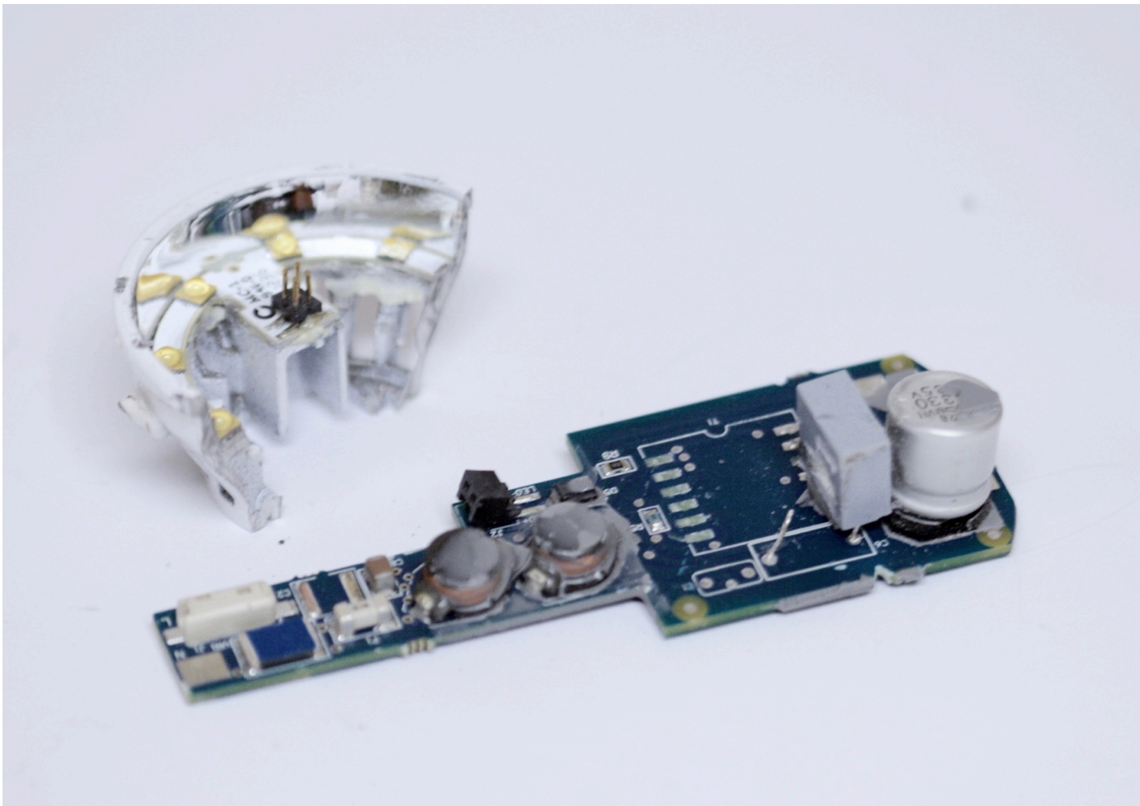


Figure 23: P02 product chip connector. This connector replaces metal wiring and creates higher modularity for the bulb.

The design of P03 provided an example of driver accessibility. The design used effective, removable fasteners (screws) and avoided thermal epoxy and adhesives as shown in Figure 24. These qualities allowed quick deconstruction with a screwdriver and prying tool. Without scraping thermal epoxy, separation of materials was simplified.

Figure 24: P03 product with removable fasteners and limited adhesives

3.9 Summary and Future Work

Throughout this section, the recent market for LED lighting products is critically examined and products' suitability for end-of-life processing as a result of design characteristics is assessed. This research builds on work completed in 2009 by Hendrickson et al. [15]. In the analysis done by Hendrickson, the authors proposed that manufacturers should (1) create products that can be easily disassembled, (2) incorporate replaceable parts, and (3) reduce the number of materials used. After 7 years of growth and evolution within the LED lighting industry, many of the same challenges still exist. The products analyzed in this study saw some improvements, including a lower average mass over time, but only 4 of 17 were scored as easy to disassemble. Most products included elements or materials that were difficult to isolate.

The market for LED lighting products is on the verge of a dramatic scaling. Before consumer uptake of LED lighting products increases further, companies and product designers should take seriously the concerns around designing for end-of-life. Taken as a single product, the design of A-19s can seem inconsequential. But when considered at the global market scale, the potential sustainability considerations become increasingly important. As products become more complex and electronic, as suggested by Katona et al. [65], the potential for end-of-life material recovery may decline if the suggested design principles are not followed by manufacturers. Evidence from our data set suggests that companies have prioritized efficiency, aesthetic design, and form factor over sustainability. Such decisions have led to an overuse of material and naturally, a higher cost for the bulb in comparison to equivalent incandescents. Praised for its green properties due to its high efficiency, an LED can be judged more completely on its environmental impact when including its material and end-of-life footprint.

After reviewing a broad group of A-19 lighting products we offer the following recommendations for lighting design teams and manufacturers.

- Create products that may be easily disassembled with modular elements that may be recycled. Quick release mechanisms in key areas of the products dramatically improve the chance of recycle. Minimizing glues and epoxy will further enhance the products for disassembly.
- Minimize the use of metal heat exchangers using modern thermal methods discussed by researchers. When metal heat exchangers are used they should be modular and easy to separate for recycle.
- Incorporate replaceable components, specifically the LED board that is most likely to experience thermal failure. These should be attached with quick release methods, and standardized within the industry if possible.
- Examine the use and end-of-life context of products during the design phase. Products should be optimally designed for the end-of-life strategy that most effectively preserves material given cost and location constraints. For example, if end-of-life strategies such as reuse or remanufacturing are deemed to be infeasible, products should be designed to optimize for recycling.

4 Challenges of Design, Manufacturing, and End-of-Life for Technologies in Developing Countries

Adapted with permission from: Product Manufacturing: Trade-offs, Challenges, and Strategies. (2015). Dzombak, R., Suffian, S., and Dornfeld, D. *VentureWell. Proceedings of Open, the Annual Conference*. National Collegiate Inventors & Innovators Alliance, 2015.

4.1 Introduction

Development engineering is an emergent multidisciplinary field that emphasizes creation and implementation of interventions that benefit individuals living in complex, low-resource settings [87]. The problems faced by communities in developing countries are numerous and include issues such as access to clean and safe sanitation, reliable and environmentally benign energy distribution, and secure food sources. Waste generation and management present additional challenges that are growing in significance as greater proportions of the population move to global urban cities and growth of the middle class occurs [88]. The level of waste within a regional area is usually in proportion to local average income, as waste is a major by-product of consumption driven lifestyles [89]. This means as incomes rise, waste generation does as well. In developing or low-income countries, this presents a particular challenge as the growth in waste generation often precedes infrastructure to manage and sort such waste. Without processing capability, either formal or informal, waste production can lead to significant greenhouse gas emissions and other public health impacts [90].

Designers and manufacturers must consider contextual constraints when creating products intended for use in low-income countries. Is there infrastructure to facilitate repair? Are replacement parts available? What can we expect in terms of end-of-life processing? These are some of the questions that must be asked during product design, production, and testing. Decisions made in the design and production phases have significant influence on the product's lifespan, use patterns, and fate upon obsolescence or failure.

Consideration of design decisions' consequences is of particular importance if the circular economy is to be implemented in developing or low-income countries [91]. In some respects, low-income countries are already employing closed-loop systems. In areas of scarcity, what materials and resources are available are used to their full potential and reused over time. The question then becomes, how might we leverage these existing environmentally beneficial practices and extend them as new products are introduced within local markets? How might strategies employed during product design facilitate the growth and expansion of a circular economy within developing countries and communities? To begin answering these questions it is critical to determine the factors that influence the sustainability of products over time and understand how such factors manifest during the design and manufacturing phases.

Furthermore, it is also critical to understand the current state of product design within development engineering in order to set a research and practice trajectory for the future.

Within this chapter, several themes related to sustainable product design, production, and end-of-life will be explored. First, the chapter background will provide greater context around the challenge of designing technologies for use in low-resource settings as well as the broader fields of both sustainable development and development engineering. A catalogue of factors that designers and manufacturers should consider when creating products is then presented. Also examined within the chapter are the various manufacturing strategies available to product designers as well as the benefits and detriments of each strategy. The last section involves analyzing a suite of products intended for use in low-resource settings in order to characterize their designs and suggest improvements. The contribution of this chapter is a list of necessary considerations when creating products, an analysis of current design features and suggestions of potential design improvements in the category of solar powered lanterns. The chapter closes with a discussion of future work and further areas of application.

4.2 Background

Approximately 2.2 billion people throughout the world live on less than 2 USD per day [92]. Challenges faced by impoverished populations result from food system vulnerability, nonexistent formal infrastructure, and nonfunctional healthcare systems, among many others. Multilateral institutions, non-governmental organizations (NGOs), private sector companies, and academic institutions each utilize different strategies to improve aspects of life in emerging countries such as large-scale investments, conditional-cash transfers, donated goods, and entrepreneurial ventures. The success of these solutions depends greatly on the structural, operational, and financial barriers that exist in each context.

Across Europe and the United States, multiple university programs have grown out of traditional design programs and become focused on altering the statistics on access to design [93], [94]. As Paul Polak wrote in his introduction to Cynthia Smith's *Design for the Other 90%*, "The majority of the world's designers focus all their efforts on developing products and services exclusively for the richest 10% of the world's customers. Nothing less than a revolution in design is needed to reach the other 90%" [95]. In the past decade, technology solutions have been lauded as a primary mechanism of change in developing countries. Appropriate technologies exist in nearly every sector and at every price point, including a $2000 car, $200 water pumps, $20 cell phones, and $0.25 diabetes test strips [96]. However, while design for the other 90% is beginning to happen, few products have led to significant impact [97]. Despite well-intentioned prototype testing in emerging markets, the majority of products fail to reach the commercialization stage. Many factors influence commercialization for technology ventures including access to capital, supply chain reliability, customer needs, and product characteristics [98]. Although decisions around product manufacturing greatly affect commercialization, use, and product end-of-life, they are often considered late in a design process or after the creation of high-fidelity prototypes.

Design processes often focus on the creation of prototypes, with less emphasis on the manufacturing and end-of-life implications associated with a given design [78]. Iterative design processes, like the one shown in Figure 25 excel at alerting designers the need to revisit assumptions and cater features to user needs. Iterative design processes however fail to draw connections between prototypes and possible avenues of scale. While design for manufacturability guidelines have long been established [99], they are not always integrated into the traditional design process. Integrating design for manufacturing principles enables one to consider product use, but also how the products will be manufactured, what resources are required, how material sourcing might influence the final cost, and the feasibility of end-of-life strategies.

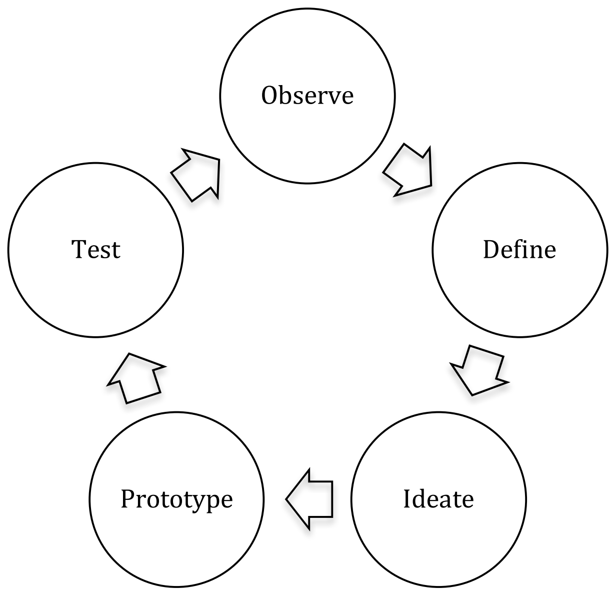


Figure 25: Example Iterative Design Process [78]

When creating products intended for use in emerging markets, affordability often drives design. However, the final cost to a consumer is determined by the entire system of a product and not just the production rate. Thus, it is critical that manufacturing be considered early in the design phase. Design for manufacturability prompts users to think about material selection, component parts, and time to market, as well as disassembly procedures and the product's end-of-life [100].

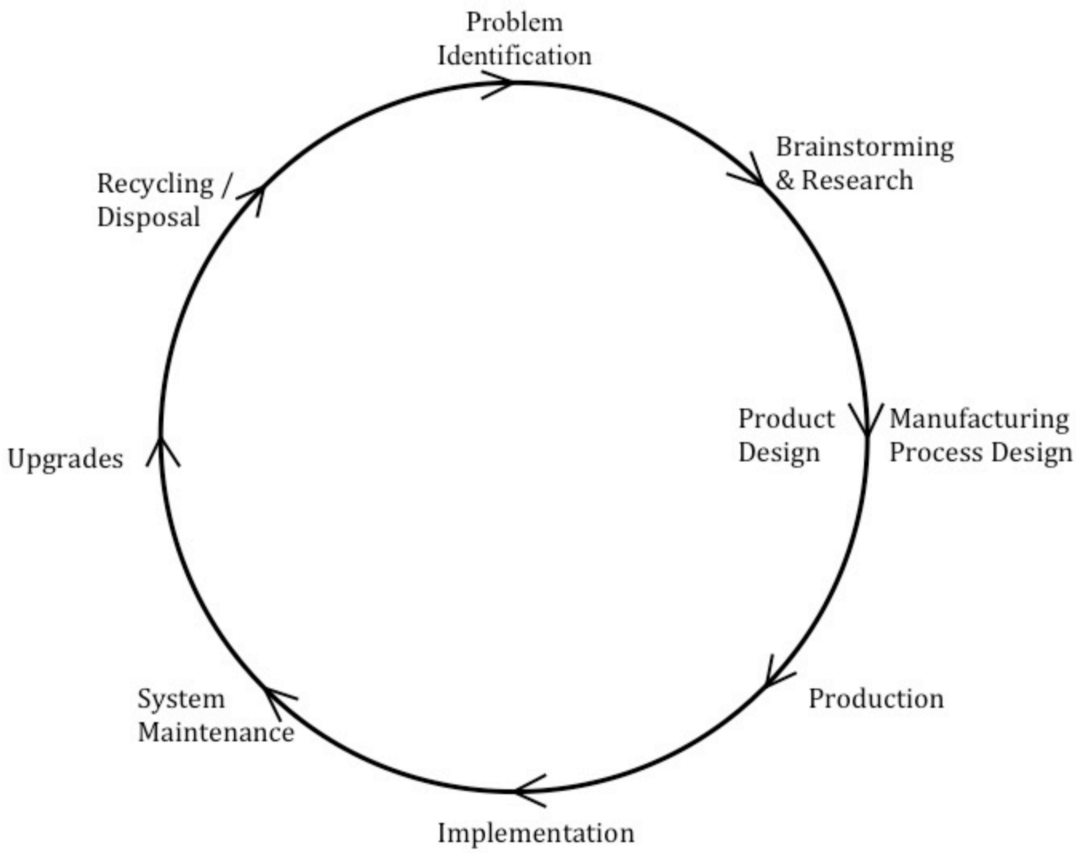


Figure 26: Product Life-Cycle Integrating Design for Manufacturing adapted from [101]

By viewing product design as part of a larger system rather than an independent process, the importance of manufacturing becomes rapidly apparent. Figure 26, adapted from Philip Koopman, shows product design and the manufacturing process as parallel and interdependent steps [101]. For example, imagine an innovator is working to create a spirometer to measure the lung capacity of individuals with upper respiratory infections. The problem definition phase revealed that removable mouthpieces are needed to prevent disease spread. It would be necessary to consider how to design the mouthpieces so that they can be easily manufactured and shipped in a sanitary way, ensuring that they reach the consumer in sterile condition. Further, it would be important to consider how multiple component parts might increase the device price point, and how to standardize the mouthpieces so that they are guaranteed to properly fit into the device.

Product manufacturing is an immediate precursor to the implementation of a venture. In some cases, the manufacturing facilities and end users are in different locations, and thus multiple challenges arise regarding the development of a successful and sustainable supply chain. Failing to develop this supply chain can prevent ventures from “crossing the chasm” to become thriving entrepreneurial endeavors [102]. In other cases where manufacturing is deliberately conducted close to the end users, issues of quality control and standardization across manufacturing plants may arise. However, many student entrepreneurs and development practitioners have little experience considering these cases that are necessary in order to manufacture products efficiently. The subsequent section elucidates the decisions individuals must face when designing and manufacturing products for use in resource-constrained environments. It will additionally provide examples of challenges faced when manufacturing appropriate technologies. Finally, commonly utilized manufacturing strategies will be discussed along with their respective benefits and challenges.

4.3 Issues, Trade-offs and Considerations

The manufacturing of appropriate technologies is a necessary step for entrepreneurs wishing to leverage a pilot into a mature venture. Decisions made around manufacturing dictate many social, technical, environmental, and financial facets of business operations. In the dynamic environments inherent to developing countries, changes and system shocks arise that influence a company's operations. However, entrepreneurs may mitigate chaos through decisions made during the design process. The following lists delineate important manufacturing considerations for entrepreneurs, academics, and students. This list is not all encompassing, but the hope is that such factors will spark conversation regarding certain issues and challenges that directly or indirectly influence the relative success of a venture's manufacturing phase. Throughout the set of factors, a common example of a solar food dryer will be used to elucidate the concept.

4.3.1 Technical

4.3.1.1 Material Selection

The materials that are used for the construction of a product impact final cost, usability, and lifespan. From a manufacturing perspective, material selection directs the required level of machining and processing. A vernacular material such as bamboo can be cut to size and used in a raw form [103]. However, products that incorporate metal components lead to an array of manufacturing challenges. How are components adjoined? Should welding be employed? What strength of connection does the design require? How durable does the design aim to be?

Example: A team of innovators is deciding what materials to use to create the frame of the solar food dryer. Aluminum is inexpensive and processed easily, but is prone to deformation. On the other hand, steel is expensive and difficult to work with. However, steel is extremely durable and can withstand stress induced by weather and the environment over time. Can users afford a higher upfront cost for a product that promises a longer lifespan?

4.3.1.2 Available Technology and Resources

The design complexity will dictate the technologies and resources that must be available in order to conduct the necessary machining and processing. While machining technologies are often available in emerging market contexts, it is not a guarantee and they are often less advanced. Thus it is often difficult to manufacture technologies in the location where distribution is intended. Further, once the manufacturing context is identified, one must also consider if a single manufacturer can perform all steps in the production.

Example: The design of a solar food dryer includes aluminum sheets to serve as thermal absorbers. The team has outlined a design requiring precise and detailed cuts to allow for air circulation and easy assembly, mandating the use of a water jet cutter. Thus, instead of manufacturing in the target context of Ethiopia, the metal sheets will need to be produced in India. An alternative solution would be to alter the design and either incorporate more standard sized and shaped sheets or alter the cuts so that they could be accomplished through stamping.

4.3.1.3 Replacement Parts

A common reason development technologies fail is a lack of compatibility between the design environment and the intended use context. For example, in developing countries 95% of medical devices are imported and of those, close to 96% are no longer working after 3 years [104]. A lack of spare parts was identified as one major reason why devices fail [105]. When creating a technology, designers need to consider what parts will need to be available in users' markets if and when the technology fails. If parts are not commercially available, how can a distribution system be designed to ensure replacement parts reach customers given supply chain constraints?

Example: The solar food dryer design includes a sheet of plexiglass over the collection chamber. While plexiglass is the ideal material to allow for light permeation, once cracked it can cause sub-optimal airflow as well as potentially allow moisture seepage. Replacement plexiglass is difficult to find in large sizes in emerging markets. The team therefore must consider how they can add mechanisms such as rubber bumpers or offer recommendations on dryer storage to protect against glass breakage. They may also want to partner with regional manufacturers or invest in a storage facility that stockpiles spare sheets.

4.3.1.4 Maintenance

Though replacement parts may be available, users of a technology may not be trained to perform the necessary maintenance or repairs. How can the design be modified to ease maintenance for the target users? Will the technology require a specialized maintenance team? If all users are concentrated in a single area, a dedicated service team may prove financially viable. However, if users are spread throughout multiple regions, can the technology be manufactured with an intuitive repair process in mind?

Example: Often repair knowledge for a technology is contained within a densely worded user manual. Over time, manuals get misplaced or thrown out, leaving the user without any instructions on how to improve a technology. Consider instead, for the solar food dryer, if instructions were painted on to the side of the device. The incorporation of pictures would simplify the instructions for users, but could complicate the manufacturing process.

4.3.2 Social

4.3.2.1 Local vs. Global

An important decision that entrepreneurs need to make is whether to manufacture technologies locally or outsource. Local manufacturing benefits the community by providing jobs and economic stimulus. However, entrepreneurs must be realistic about manufacturing within resource-constrained communities, as a lack of necessary support infrastructure can lead to an increase in overall cost and a decrease in quality control [97]. Outsourcing can lead to efficient manufacturing operations, though extending supply chains can cause unpredictable challenges such as import regulations, increased tariffs and increasingly complicated logistics.

Example: A team of innovators working on a solar food dryer decides to manufacture their technology in the same villages in which the dryer will be sold. The short, manageable supply chain enables increased transparency and brings economic gain to the community involved. However, the supply chain lacks robustness. The local markets run out of a critical material and do not know when the next shipment will arrive. Customers are lost because the dryers cannot be delivered according to planned schedules.

4.3.2.2 Employee Requirements

When deciding where to manufacture a product, it is important to consider the human capital necessary for operations. What skills must laborers possess? Who will manage daily processes? Despite high rates of unemployment in developing countries, a lack of trained workers can lead to low manufacturing productivity. This can significantly increase the manufacturing time compared to manufacturing in regions where higher-skilled workers are available.

Example: The solar food dryer team wants to make available a version that includes sensors to monitor whether optimal drying conditions are achieved. Such features require advanced features and electrical wiring that would prove unfamiliar to an unskilled worker. In order to guarantee high-quality production, utilizing large-scale manufacturing channels might prove more beneficial.

4.3.2.3 Worker Safety

Regardless of where manufacturing operations are located, worker safety is of critical importance to any company. In developing countries regulations are often unenforceable as a result of corrupt government officials and a lack of national infrastructure. This makes it easier to exploit workers and subject them to undesirable conditions. If a company is not operating in the same region as its manufacturing operation, it can be difficult to know what labor practices are involved during production.

Mechanisms must be designed in order to ensure that transparency exists along the supply chain.

Example: A solar food drying manufacturing facility is set up in a low-income community. Despite instructions by the venture to purchase worker gloves, employees are not provided with them and must use their bare hands. While hurriedly carrying the glass for a new solar dryer, a worker trips over debris and the glass breaks, cutting the worker's hand. If the manufacturing facilities are far from the venture's headquarters, random and unannounced auditing of the manufacturing process may be a necessary part of production.

4.3.3 Economic

4.3.3.1 Overhead Costs

Manufacturing costs encompass more than just the capital investment of the machines. Labor, materials, electricity, transportation, and rental costs all factor into the total cost of production. If electricity is unreliable, production efficiency will decrease which will increase costs. If manufacturing ecosystems do not exist locally, the overhead costs may prove significantly high as opposed to areas where resources can be shared between various firms.

Example: When attempting to source materials for the solar dryer, the team wants to find both material wholesalers and transporters locally so they can manufacture in close proximity to their user base. They find land space 30 km from the community they are working in and decide to try to establish operations there. The transportation company is unfamiliar with the proposed manufacturing location and therefore wants to charge a premium because they have no other stops in the area. The wholesalers nearby have 80% of the necessary materials and tell the team that they will have to import the remaining 20%. Should the team change their design to cater to what is locally available? Should they instead manufacture in a more established industrial center? What implications do these decisions have on the economic bottom line?

4.3.3.2 Standardization vs. Customization

Often consumers want to tailor aspects of a design to more directly meet their individual needs. While customization can lead to a highly satisfied customer, it can also raise product costs considerably because the company is no longer able to utilize economies of scale. Standardized products can contribute to highly efficient manufacturing operations; however, they may not appeal to a particular customer base. For example, the Jaipur Foot, a prosthetic foot manufactured in India, was previously customized for each amputee in need. The vulcanized rubber used to comprise the foot was heavy for users and hand-making each foot led to challenges with quality control. Therefore, the team behind the Jaipur foot began using injection-molded polyurethane in order to standardize manufacturing operations and increase the volume of feet produced. The polyurethane feet lack elasticity and are known to crack when users squat during defecation. Thus, despite improved manufacturing processes, design challenges persist

[106]. What is more important to prioritize for a given company? How different are user requests and what do they depend on? Gender? Income? Personal preference?

Example: When testing the solar food dryers with different potential users, the team receives conflicting feedback regarding the size of the dryer. Some users say that the size is too big and contributes to the increased cost being prohibitively expensive. Other users say that the dryer is too small and does not offer sufficient drying capacity. The company considers customizing each dryer to meet user needs, but ultimately decides to offer 3 different versions. Though they still may not satisfy some niche consumer preferences, they ultimately want to appeal to a mass market.

4.3.3.3 Quality Control

Often when obtaining materials in developing countries, one can purchase several supposedly "standard" copies of the same product and end up with significant variations in size and quality. Manufacturing processes that employ significant human input and unskilled laborers are typically less precise if measuring and cutting materials. Minimizing the number of steps in the manufacturing process as well as striving for a highly replicable design are two strategies to help control quality of a final product.

Example: When producing the solar food dryer frame, the team employs laborers to assemble multiple metal components. Because of skillset variability among the workers, the resulting products are of different quality, with some seeming sturdy and secure and others appearing to have loose connections. To rectify this, the team decides to eliminate worker input by utilizing pre-fabricated metal sheets the workers can instead bend into place.

4.3.4 Environmental

4.3.4.1 Embedded Waste

Ventures operating in resource-constrained environments must pay particular attention to minimizing waste. In these contexts, sufficient waste infrastructure does not exist and therefore practices such as uncontrolled incineration or smelting of electronic components are commonplace. These processes can prove extremely hazardous to worker health through the release of toxic emissions [107]. Entrepreneurs should consider what waste elements are embedded within their supply chain and attempt to see how they can reuse or ensure safe disposal of such byproducts.

Example: During the production of the solar food dryer, the team decides to cut the metal sheets to the proper shape by punching, in order to quickly assemble the final products. However, punching produces large quantities of scrap metal. The scraps are small and cannot be incorporated into the design. How can the manufacturing process be altered to prevent this step? Could a different machining strategy be used to achieve the desired metal shape?

4.3.4.2 Environmental Impact

The emissions associated with a given product can vary greatly depending on the energy sources utilized. If using photovoltaic (PV) cells or other forms of renewable energy, the emissions will be lower; however, the availability of power may prove variable due to a lack of storage, influencing the operation cycle time. If manufacturing in a country that uses coal as an energy source, the production will lead to higher levels of carbon released. The lifecycle energy input into a product is important to track because the long-term effects of climate change will be most intensified in developing countries.

Example: When deciding whether to manufacture locally or outsource, a team wants to assess the full environmental impact of their product. For resource extraction through decommissioning, they assess both the material and energy inputs for each stage of the production process. This reveals that the variability in the electricity in their target context will lead to significantly less efficient operations. Depending on the size of their operations they could either invest in a PV system along with a backup generator, pay to offset the carbon emissions associated with outsourced manufacturing, or determine if a change in materials could help to lower the overall product energy input.

4.3.4.3 End-of-Life Considerations

A product may reach end-of-life because of functional obsolescence, product performance degradation, or technical obsolescence, when new products render the original technology useless. No matter the reason, every product will eventually lose its utility and be disposed. What is the assumed product lifespan? Can it be repurposed into a new product? Can it be easily taken apart? Will it have to be placed in a landfill? Can elements be recycled?

Example: When deciding on options for the transparent part of the solar dryer, a team considers either using a more durable, imported plexiglass or a locally available glass. While the plexiglass may increase the product lifespan, the local glass has more opportunity to be repurposed. How will users dispose of the product? What potential is there for reuse?

4.4 Strategies for Manufacturing

Many of the decisions faced during the manufacturing stage are connected to the underlying tension of local versus outsourced manufacturing operations. Ultimately, the decision of where to locate manufacturing operations requires analysis of company priorities, available resources, financial viability, and business transparency. Hybrid models that include outsourced and local operations exist and have been used successfully in bringing products to market while simultaneously creating economic stimulus within communities. The following section details three manufacturing strategies and contains examples of how such strategies have been employed in the past.

4.4.1 Local Model: Local Manufacturing + Local Assembly

Manufacturing locally can yield significant benefits to the community but success hinges on the level of infrastructure that exists in the area where the venture is located (see Table 5). Some small-scale manufacturing infrastructure could be available and offered by local universities or technology institutions. For example, Gearbox, a maker space in Nairobi, provides tools and equipment for fabrication, electronic building, and rapid prototyping [108]. Gearbox provides the opportunity for individuals to move from concepts to prototypes to final products, but is not intended for manufacturing at scale. There has been a recent surge in the availability of 3D printers throughout emerging markets. If 3D printers are available, they can assist in the manufacture of products with minimal waste. Printers require the availability of printing materials and electricity that are frequently unavailable in resource-constrained contexts. Local manufacturing can succeed if it is possible to leverage an informal labor market for manufacturing operations, such as jua kalis in Kenya [109]. Rather than create a single manufacturing facility, these independent machinists can be contracted to construct products in batches. This would allow for more geospatially distributed product availability, which could improve resilience to certain local externalities such as power outages or weather-related transport issues.

Table 5: Benefits and Considerations for Local Model

Benefits	Considerations
• Community economic benefit • Job creation • Low transportation costs • Manageable supply chain • Lower Tariffs	• Availability of necessary resources • Skill of labor pool • Electricity reliability • Quality control • Regulation • Overhead costs

4.4.2 Hybrid Model: Outsource Manufacturing + Local Assembly

Hybrid manufacturing models serve to effectively leverage available community resources while also reaping the benefits of an integrated global supply chain (see Table 6). For example, after struggling to have the stoves fully manufactured in Darfur due to a lack of materials and equipment, the team behind a low-cost cookstove decided to shift their manufacturing operations to India. The design for the stove is now stamped onto metal sheets for India and then along with supplemental materials, shipped as flat kits to Sudan. Once in Sudan, trained workers can follow guides on the metal sheets to assemble the stoves without advanced tools and prepare them for distribution [110]. This strategy constrains the design because it requires minimal assembly once on site. For example, the team wanted to include a latched door because it increases the efficiency of the stove; however, the moving part would decrease the durability of the design [111].

Table 6: Benefits and Considerations for Hybrid Model

Benefits	Considerations
• Use of local labor • Job creation • High quality control • Manufacturing efficiency • Fast cycle time	• Disparate supply chain • Lack of oversight • Import tariffs

4.4.3 Import Model: Outsource Manufacturing + Outsource Assembly

If working in an area with minimal infrastructure and resources, outsourcing both manufacturing and assembly may prove to be the only viable option (see Table 7). If a majority of the raw materials for a product are not locally available, the benefits of local manufacturing may be outweighed by the added complexity of the manufacturing supply chain. For example, while cell phones and related technologies are widely used even in the most rural environments, it is not feasible to create local manufacturing or assembly facilities with the same degree of standardization or quality control as those that can be purchased from mass-manufacturing companies. Importing is also a usefully strategy for technically sophisticated products. For example, medical devices with intricate electronic components require manufacturing to be performed with specialized equipment that can achieve high degrees of precision or can maintain a sterile environment.

Table 7: Benefits and Considerations for Import Model

Benefits	Considerations
• High quality control • Manufacturing efficiency • Fast cycle time • Less expensive production	• Disparate supply chain • Lack of oversight • Import tariffs

4.5 Summary of Manufacturing Considerations

The manufacturing and processing needs for a venture depend on product type, company scale, available resources, and priorities. Regardless of the complexities involved in creating a sustainable manufacturing strategy, these considerations must be woven into the initial design process in order to ensure that technologies will fit into a larger venture ecosystem. Failure to think systemically during the design phase can lead to significant implementation barriers. Consequently, the proper use of these considerations in design will allow ventures to evolve their ideas into sustainable, scalable products. Of critical concern within this dissertation research are the implications of product design and manufacturing for end-of-life as well as the associated environmental impacts. In the section 4.6, deeper analysis of end-of-life suitability of an appropriate technology design is considered.

4.6 Assessment of LED Solar Lanterns

Solar-powered lighting has the potential to make vast global impact as more than 1 billion people lack access to electricity. Light sources can make significant improvements in households' education prospects and work productivity [112]. The Solar Portable Light (SPL) market is expected to grow rapidly over the next decade, with the sales volume to reach over 25 million in 2018 [112]. The design and sustainability of SPLs have benefitted from the technology improvements that have occurred in the photovoltaic, battery, and lighting industries [112]. Currently, the largest cost of SPLs is the PV cells (29%), followed by housing and assembly (18%). With current trends it is expected that by 2020, housing and assembly will represent 40% of the cost of the SPL [112]. Recently, an assessment of SPLs was conduced by MIT's Comprehensive Initiative on Technology Evaluation (CITE). CITE found that the upfront cost for most SPL products was still too high for the intended users [113], thus showing the critical need for further cost-savings in the product design.

Though CITE's analysis touched on all aspects of the product's lifecycle, they did not go into depth in any one life-cycle phase [113]. On the production side, the aspects considered included (1) number of vendors (2) production planning and (3) location of facilities. For the aftermarket and end-of-life considerations, CITE examined (1) warranty duration and (2) warranty type. Their analysis consisted of several product attributes such as brightness, cost, luminous range, and water resistance, but did not consider the manufacturability, number of parts or material choices. This chapter will complete the same product analysis as described in Section 3.4 for four solar lighting products: the d.light S300, the SunKing Solo, the WakaWaka Light, and the UniteToLight all shown Figure 27.

	
S01: d.light S300 [114]	S02: SunKing Pico [115]
	
S03: WakaWaka Light [116]	S04: UniteToLight [117]

Figure 27: Solar Portable Lanterns Included in Study

4.7 Product Analysis Results and Discussion

Despite all products aiming to serve a similar function, the form factors of the SPLs are vastly different, as is the construction of each. Though they are intended for use in developing countries, all of the SPLs could also be purchased from within the U.S., either direct from the manufacturer in the case of UniteToLight, or via Amazon for the rest. Further information about the SPL products analyzed is shown in Table 8, with data collected either from online product specifications or from the CITE Evaluation Report [113].

Table 8: Summary of the SPL Products Analyzed

Product Label	Cost ($)	Rated Wattage (W)	Rated Lumens (lm)	Efficiency (lm/W)	Charge Time (hours)	Rated Lifespan (years)
S01	36.79	1.6	110	68.75	13.3	7
S02	19.99	0.350	25	71.4	8.2	5
S03	59.99	0.5	60	120	17.7	10
S04	20.00	3.84	20	76.2	17.9	2

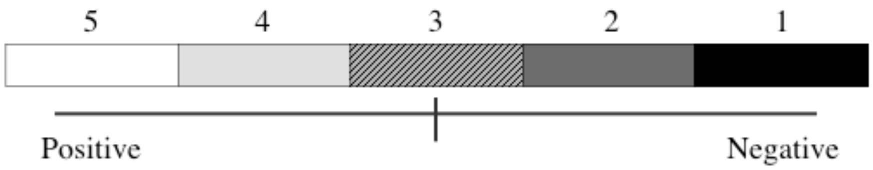
The products analyzed represent a range of what is available within the SPL market and thus provide a diverse sample set. As shown in Table 8, the purchase cost ranges from $20 to $60. To note, these prices are what it costs to purchase the products themselves, however the intended consumer in a developing country may be offered a lower price point, as many of the SPL manufacturers employ a Buy-One Give-One (BOGO) model. When the BOGO model is employed, the prices listed reflect the purchase of a single product. The products all have significantly different expected life spans, with S03 expected to last approximately 10 years and in contrast, S04 is only expected to last 2 years due to degradation of the battery. The assessment of the SPL design is shown in Table 9. The rubric can be found in Appendix 1. Table 10 provides the results of the scaled assessment.

Table 9: Raw Scores for SPL Product Assessment

Product Label	# of Parts	Time of Disassem. (min)	Ease of Disassem.	Modularity Level	Ease of Recyc.	Recovery Potential R (%)	Material Complex. H
S01	17	22	1	1	1	42	1.33
S02	16	10	4	3	3	76	1.12
S03	12	37	1	1	1	15	1.62
S04	15	42	1	1	1	5	1.76

Table 10: Scaled Scores for SPL Product Assessment

Product Label	# of Parts	Time of Disassem. (min)	Ease of Disassem.	Modularity Level	Ease of Recyc.	Recovery Potential R (%)	Material Complex. H
S01							
S02							
S03							
S04							



Due to the small size of the products, they are all comprised of relatively few parts. However, the ease of separating and recovering the components proved challenging for all but one of the products analyzed. The products assessed are highly durable and purposefully designed to withstand rugged conditions. They are designed to last and, hopefully, not break. Therefore, the SPLs have few characteristics that lend themselves to end-of-life processing. When discussing end-of-life considerations with the product manufacturers, all said they expect that the SPLs would either be landfilled (if an option) or incinerated following use. For that reason, each manufacturer aimed to design the product for as long as possible, even raising the price point to enable use of higher quality materials. This is consistent with the design for manufacturing principle of trying to keep materials in use for as long as possible, rather than upgrade frequently. Despite that intention, the expected lifespan of S04 remains only 2 years, meaning that many of these products would be used over time.

Most of the companies offering the SPLs do not have a permanent presence in the communities that are in need of the SPLs and so options for maintenance or repair are limited. Products S01, S03, and S04 all were unsalvageable following the separation of components. They were not modular and so if someone attempted to repair the product given a level of failure it would be rendered useless. In the case of S01, specialized tools were required to separate the component pieces without destruction of the product itself.

Figure 28: S01 Example of Product Requiring Specialized Tools

As shown in Figure 28, S01 exhibited modular features including the use of screws to attach the product housing. For the exposed screws, the screws chosen though had a pin in the center meaning that conventional screwdrivers could not be used to unscrew them. The other housing screws were embedded far down within the product making them inaccessible and challenging to remove. While the product itself was characterized by a difficult disassembly, S01's solar charger was in fact quite modular and easy to disassemble as shown in Figure 29. The solar charger featured 3 main body pieces held together through the use of 6 screws. As the panel may have to be cleaned from time to time to remove dust and dirt build up, it makes sense that the housing around the panel be easy to disassemble. Given the fact that the charger may be taken apart and reconstructed over time, the connectors used for the solar panel wiring were surprisingly weak. As connections are a key failure point for most technology products, this is an area that could be redesigned for increased ruggedness. The connection is shown in Figure 30.

Figure 29: S01 Solar Charger as Example of Modular Design

Figure 30: Example of Weak Connection Point

The final note for S01 was the number of adapters included in the product kit. A key feature of SPL is that the products include a USB port as well as a second microport for cellphone charging. When purchasing the product, the light is accompanied by a set of 5 adapters, shown in Figure 31. Though each piece is small and could be assumed inconsequential, the manufacturer could shift their sales model for individuals to request which adapters they wanted instead of assuming every customer wanted all adapters. This however can be expensive to manage due to the inventory implications and need to have more detailed order tracking, thus introducing a tradeoff between costs and environmental impacts.

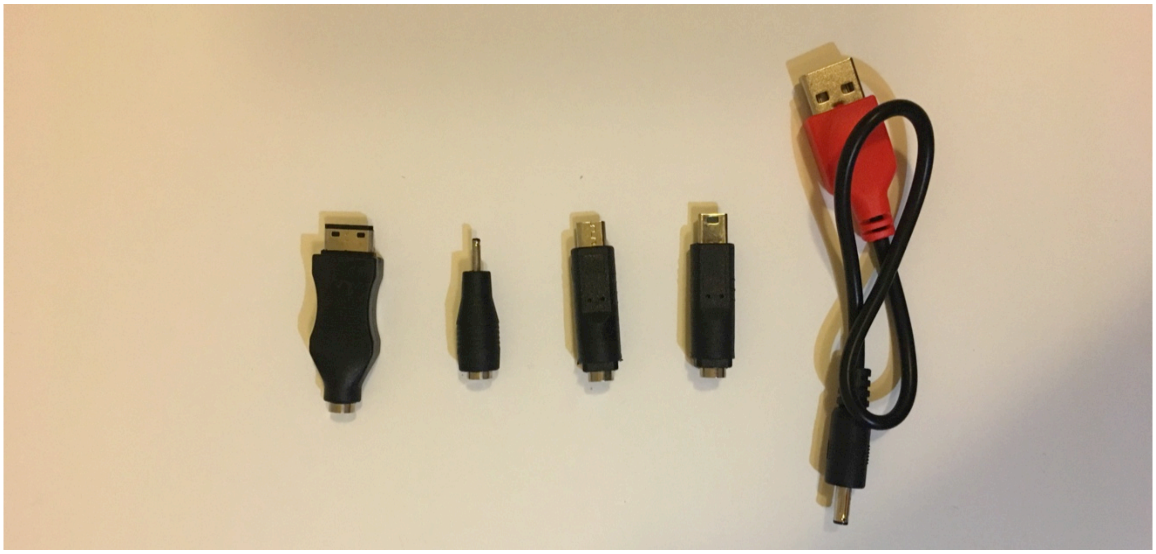


Figure 31: Adapters Included in S01 Product Kit

Similar to product S01, products S02 and S04 proved difficult to disassemble due to their ruggedized build. In the case of product S02, shown in Figure 31 such durability made sense as the product had a long expected life of 10 years. S02 had no visible disassembly points or areas to remove the casing and so pliers were used to pull apart the outside casing. One item to note is that though the LEDs are covered with a clear plastic, the material chosen does not diffuse the light, producing a very bright light that is harsh at times. If no end-of-life options are available that could enable a user to preserve the materials over time, then the next best option is to use a product for as long as possible. S02 provides a good example of an electronic product built to last.

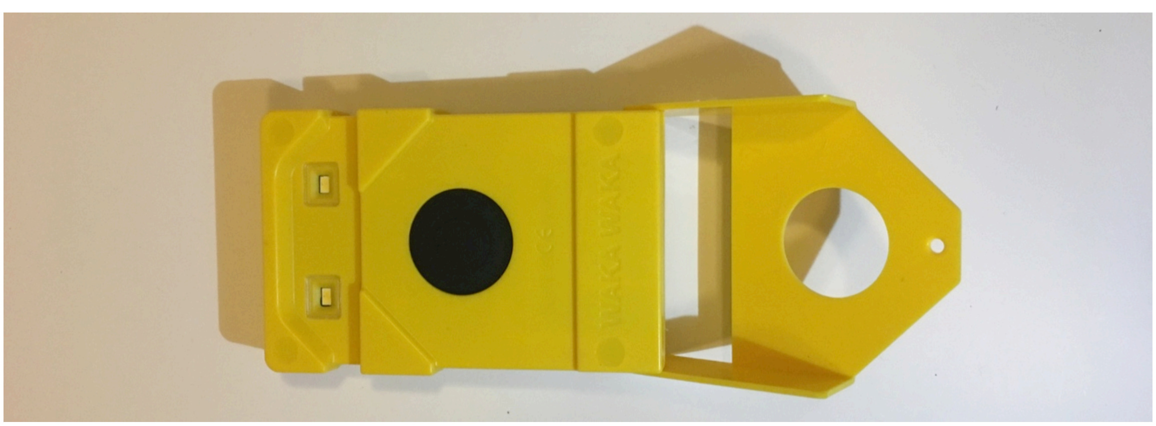


Figure 32: S02 as an Example of Durable Product Design

In contrast, S04 was also difficult to disassemble with no clear ways to remove the individual components. However, the product itself is only meant to last for 2 years. Given the fragility of the components used and the poor connection points, it is hard to imagine the product would make it a full two years without requiring repair. Any repair would also be challenging because the product is not modular. S04, shown in Figure 33 provides an example of a poor design that is not durable or easily repairable.

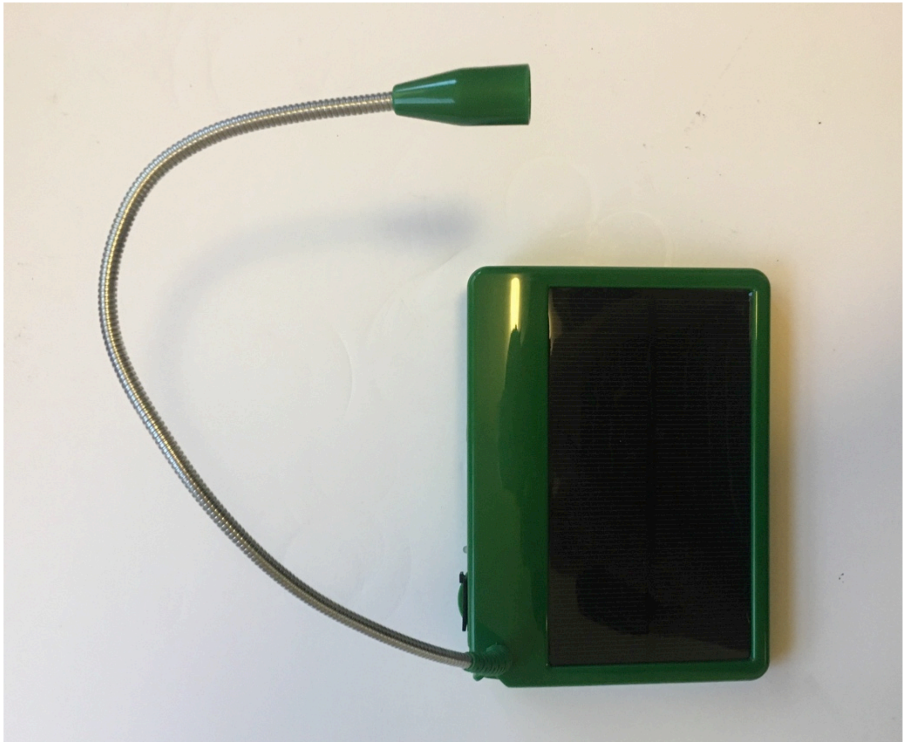


Figure 33: S04 provides an example of product with fragile components

S03 is the only example of a product suited for end-of-life processing from the SPL product set. The wire stand was easy to pop on and off, both enabling different use scenarios as well as material recovery following product end-of-life or failure. The parts of the plastic housing for S03 were connected by 4 screws, making the disassembly efficient. Within the housing all of the individual components are accessible and removable as shown in Figure 34. In particular the battery was easy to replace if new one was needed in the future. Wire connections were attached through the use of plastic connectors, an example of durable design. Furthermore, as shown in Figure 35, the components were further separable if recycling options were available for the plastic housing at end-of-life.

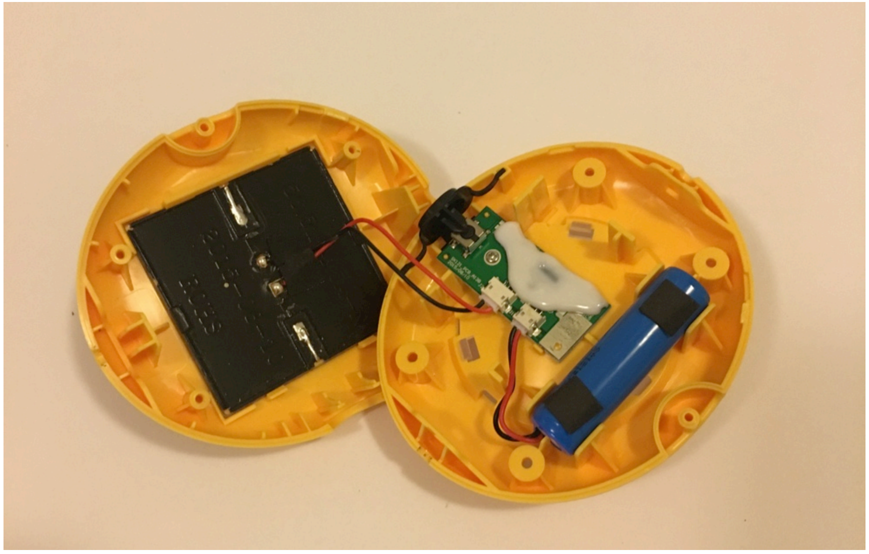


Figure 34: S03 as Example of Repairable Design

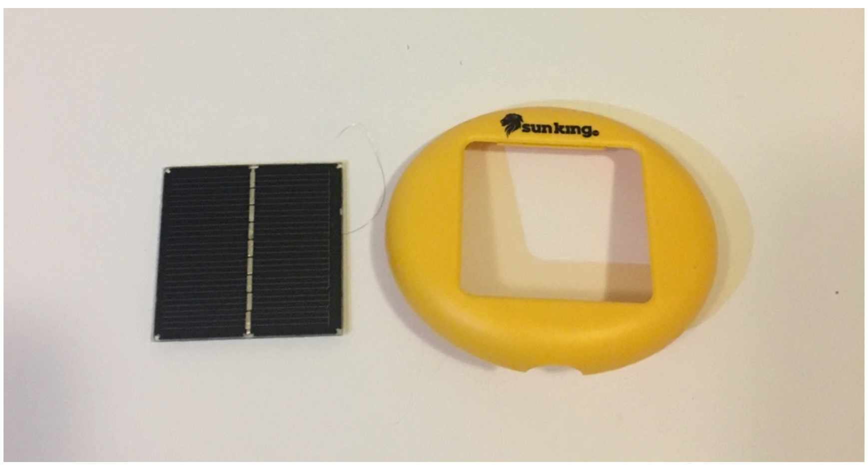


Figure 35: S03 Separable Components

4.8 Chapter Summary and Future Work

Within Chapter 4, several factors were explored pertaining to the life-cycle of products intended for use in developing countries. First, considerations when manufacturing appropriate technology were outlined. The case study of a solar food dryer was used in order to elucidate how such considerations might be made come into questions during manufacturing decision-making. Next the benefits and detriments of three commonly employed manufacturing strategies were examined as a means of helping designers better understand the options that are available when moving from the design to production stage. Finally, four solar powered lanterns that target markets where affordability is important were analyzed to assess their suitability for end-of-life processing including repair, maintenance, and material recovery. Only one product was considered modular in design, however two others showed traits of extreme durability, thus manifesting design for manufacturing and circular design principles.

In the future, the first part of this work could be extended to include a survey of designers and manufacturers, to better understand how industry prioritizes the considerations outlined. It would also be beneficial to collect data from practitioners about the cost differentials between the various manufacturing strategies to help others weigh the trade-offs when deciding which manufacturing pathway to pursue. Further work could also encompass a more detailed life-cycle assessment of the products analyzed to assess the true environmental impacts associated with manufacture, use, and end-of-life of the solar powered lights in question. Understanding the environmental impacts of technology manufacture, use, and failure in areas without waste infrastructure could provide guidance on how to make appropriate technology more sustainable in the future.

5 Understanding the Roles of Design and Context in End-of-Life Management Decisions for LED Street Lights

5.1 Introduction

In 2012, the EPA estimated that over 44 million street and roadway lights were in use throughout the United States [19]. At that time, only 3% of the total installed luminaires were LED; the majority of products in use were either high pressure sodium or metal halide luminaires [19]. However, over the past 5 years the product portfolio used in the U.S. has begun to quickly shift towards LED. Local, state, and national governments recognized the opportunity to replace their lighting infrastructure to high efficiency LED products with the promise of a long lifespan and quality light output [118]. Despite their high upfront cost, street light infrastructure upgrades have a relatively short return on investment relative to other capital infrastructure projects and could lead to significant cost savings in markets with a high volume of installed luminaires [119]. Furthermore, as street lighting can constitute 60-80% of the electricity costs for a given municipality, finding ways to more efficiently meet regulated illumination levels is a top priority for many [120], [121]. Cities set a given level of light output per unit area as well as required illumination hours based on traffic patterns, accident history, neighborhood safety, and a number of factors. Intersections requiring brighter light for a longer period of time have higher costs than a light that is only required to be on until midnight, for example. As reduced energy use can directly reduce environmental emissions, the benefits of installing high efficiency technologies are numerous [70].

As consensus grows on the effectiveness of LED lighting technology as an energy saving technology, the question becomes not if conventional lighting products should be replaced but when. Though installation of LED luminaires appears as a straightforward decision due to the cost and environmental benefits, technology management decisions are complex and guided by multiple factors. As shown in Section 2.4, decision processes remain complex throughout the entire life-cycle of the lighting product. Decisions on maintenance, replacement, and disposal are also highly dependent on budget, presumed effectiveness, and contextual culture. In order to understand how technology decisions are made, one must examine stakeholder incentives, contextual policy, and competing organizational priorities, among other factors.

This chapter begins with an assessment of current product design within the street lighting space, using the developed design assessment model to analyze three products currently in use by municipalities within the United States. Too often within the academic literature, it is assumed that cost is the only factor driving technology management decisions. In reality, the decision-making context is far more complex and varies across geographies and between stakeholders. To better understand the decision-making space around street light installation and upgrade in practice today, interviews were conducted with 19 stakeholders in an attempt to empirically characterize the factors influencing street lighting technology management decisions. Key findings and major themes from interviews are presented in Section 5.3. Finally, the chapter concludes with a summary of work completed and outline of future work. The contributions within this chapter include: (1) characterization of current street lighting design as well as guidelines for design improvement (2) examination of the system in which street lighting management decisions are made and an agenda for future areas of research and (3) insights of the socio-technical challenges faced by stakeholders at each life cycle phase. This work provides analysis of the real-world conditions that frequently constrain implementation of the “optimal” strategy. The goal is that understanding contextual constraints can prompt the research community and industry to determine mechanisms by which consumers can overcome barriers preventing them from making environmentally optimal decisions.

5.2 Design Assessment and Tear-Down

In order to understand technology management decisions in the context of end-of-life processing, it is first critical to determine what comprises the technology itself. Three different street lighting products were analyzed. Though the set is small, the products provide a representative sample of what is available on the market and what materials are incorporated within the product design. All of the products analyzed were purchased from a lighting distributor and are all currently installed by at least one municipality in the United States. Two of the products (SL1 and SL2) are from Cree Inc. and manufactured in North Carolina. The third product is sourced from Leotek, a California-based lighting company manufactured in San Jose and Mexico. The product set is shown in Figure 36.

SL 1: Cree	SL 2: Cree	SL 3: Leotek

Figure 36: Street Lighting Products Assessed

The summary of products can be found in Table 11. Despite a higher lumen output, the 2017 product is 6% lower in cost than the 2015 product, consistent with industry trends [122]. The expected product lifespan is growing over time, with products on the market today that can last up to 100,000 hours or close to 20 years. Due to the fact that products have not yet been installed for that long, it is too early to determine if they will in fact last their entire expected lifespan. Manufacturers are guaranteeing products for 10 years and usually offer a warranty within that range.

Table 11: Summary of Assessed Street Lighting Products

Product Label	Year Sold	Cost ($)	Rated Wattage (W)	Rated Lumens (lm)	Efficiency (lm/W)	Rated Lifespan (hours)
SL1	2015	280	42	3819	90.9	50,000
SL2	2016	263	25	2722	108.8	60,000
SL3	2017	225	87	8300	95	60,000

Figure 37 gives an overview of the components by mass in each of the assessed products. The compositions of the two products by Cree (SL1 and SL2) are highly similar with only a few differences between product years. The biggest difference between the products has to do with the thermal management. The Leotek product has a large aluminum heatsink separate from the housing in order to passively cool the product over time. The heatsink for the Cree lights is considerably smaller, and contains both passive and active (small fan) cooling elements. Beyond the thermal management, the other two significant categories in terms of material use are the power supply, which encompasses the driver, wiring, and epoxy, as well as the metal housing. In the United States, street lights are specified to require brushed chromium steel housing to promote product durability, which therefore is a significant portion of the product by mass.

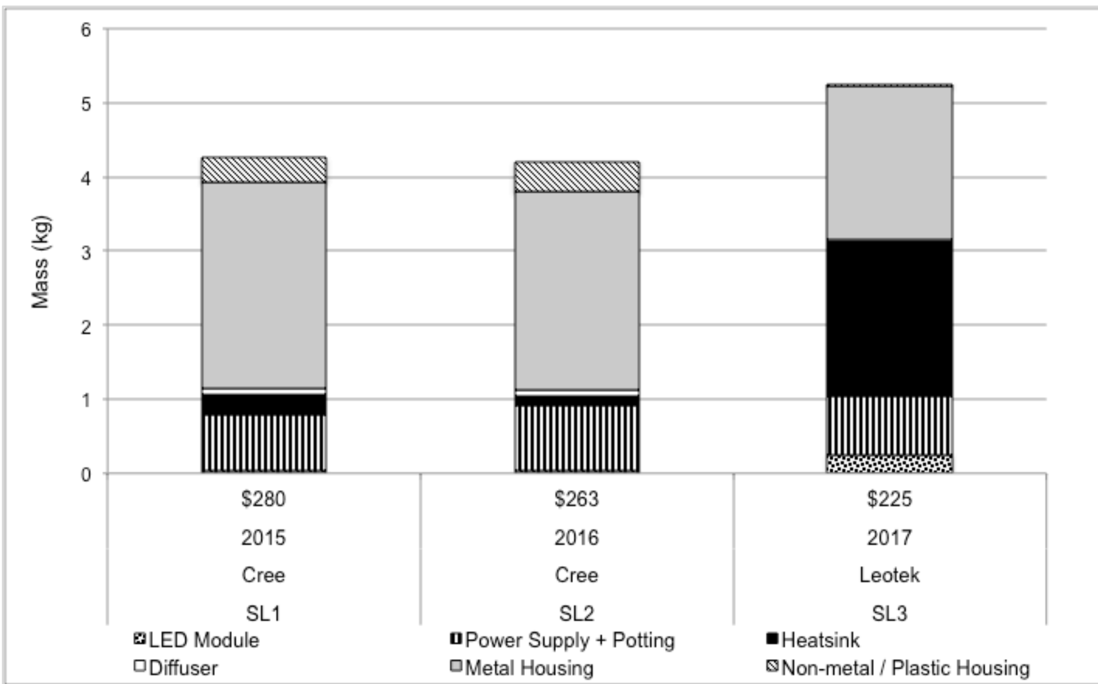


Figure 37: Breakdown of Product Components by Mass

The design and characteristics of the street lighting products were assessed using the methodology outlined in Section 3.4. As seen in Table 12, the Cree products had fewer than half of the number of parts as did the Leotek product, however, are still inherently complex products. The scale and design of the products are more modular than their A-19 counterparts, though room for improvement still exists. The potential for material recovery is high within the street light products, given the fact that the housing and components are primarily metal. The metal components are able to be separated and recovered, though SL3 required more effort to do so when compared with SL1 or SL2. Table 13 provides the scaled assessment for the street light products. Though the street lights performed better within the assessment when compared to the A-19 products, no characteristic was rated as a “5” or fully positive trait. The number of parts is understandably high due to the complex nature of the product. As street lighting products become more complex due to the integration of safety and monitoring systems, it is expected that the total number of parts will continue to increase.

Table 12: Raw Assessment for Street Lighting Products

Product Label	# of Parts	Time of Disassembly (min)	Ease of Disassembly	Modularity Level	Ease of Recycling	Recovery Potential R (%)	Likely Recovery L (%)	Material Complexity H
SL1	43	30	4	4	4	77.44	69.95	1.34
SL2	43	42	4	4	4	74.38	64.84	1.38
SL3	106	108	3	3	4	81	79.2	1.67

Product Label	# of Parts	Time of Disassembly (min)	Ease of Disassembly	Modularity Level	Ease of Recycling	Recovery Potential R (%)	Likely Recovery L (%)	Material Complexity H
SL1								
SL2								
SL3								

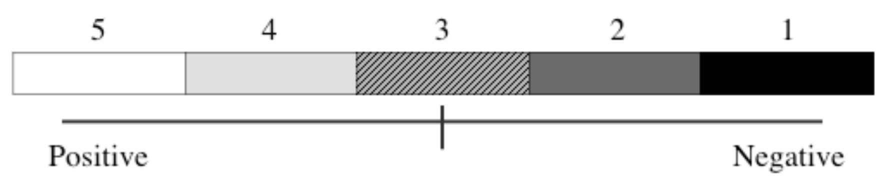


Table 13: Scaled Assessment for Street Lighting Products

There are several design features across the street lighting products that could be modified in order to increase the suitability for end-of-life processing. The first is the accessibility and design of the power supply. Across all products, accessing the driver proved challenging with multiple steps requiring some advance removal tools. As the driver is the most common failure mode within LED street lights, it would make sense that the products be designed to accommodate such failure and facilitate repair. For the products examined, when the driver fails the entire fixture is replaced. As the metal housing is durable with a long lifespan, it would be preferable if the fixture could remain installed and only the failed component be replaced over time. Furthermore, once extricated, the driver is encased in a steel container and covered in epoxy, as shown in Figure 38. While these features are intended to assist with thermal management, they impede any potential for material or component recovery.

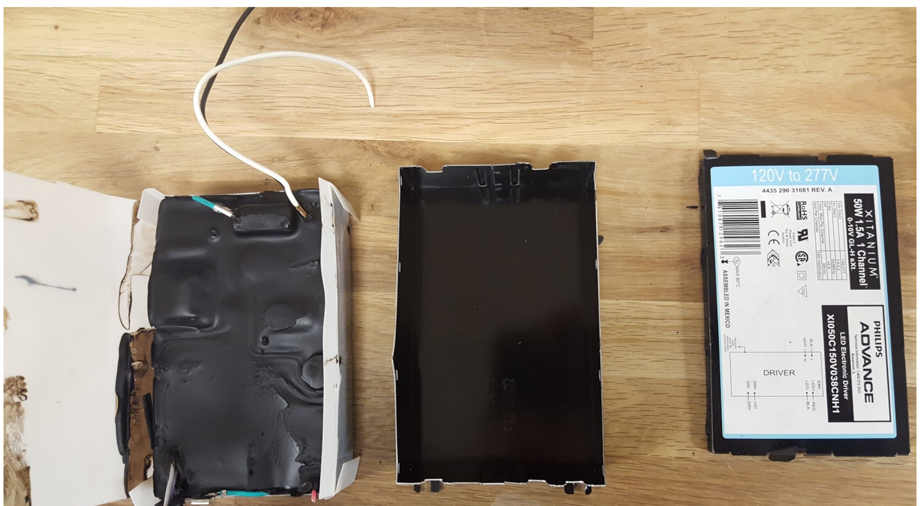


Figure 38: SL 01 driver requiring multiple steps to remove

All of the products analyzed exhibited traits of easily disassembled design within the internal framing. The internal bracketing pieces used could be removed with only a wrench or screwdriver. However, further improvement could come from the standardized parts. As shown in Figure 39, two different metal components were used to perform a similar function. If more standardized parts were used, the potential for remanufacturing would increase, as would the number of salvageable components.

Figure 39: SL 2 Design standardization for metal components could increase to promote remanufacturing potential

Another design principle that could be adhered to by street lighting OEMs is avoiding the use of mixed materials. Across all of the products, instances of mixed-material products were seen, which compromises the components ability to be recycled or reused over time. Figure 40 and
Figure 41 both provide examples of mixed-material usage within the products analyzed.

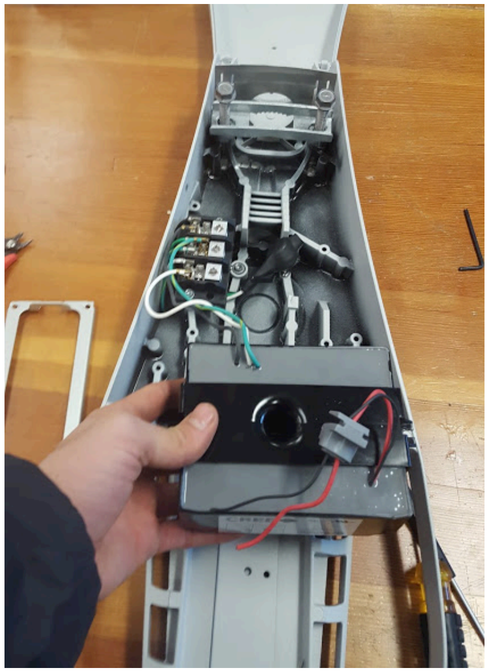


Figure 40: SL 2 driver casing mixing plastics and metal

Figure 41: SL 3 adaptor example of mixed materials

In addition to the potential design improvements noted, the products exhibited several traits that should be replicated in future products. Product SL 3 is designed so that the housing could be reused over time if municipalities returned the product to the manufacturer following use. As light output scales across different categories, the same housing structure may be used for the power supply and electronics. In this design, the aluminum plate is both the thermal management mechanism as well holds the LED module in place. Such a design feature encourages direct material reuse at end-of-life. While the driver and power supply housing were not designed to allow for component upgrade over time, the LED module in SL 3 facilitated replacement if needed. Shown in Figure 42, the LEDs are protected by a thin rubber sheet (likely to prevent water damage) as well as an aluminum plate. Both layers are easily removed, making the LED module accessible.

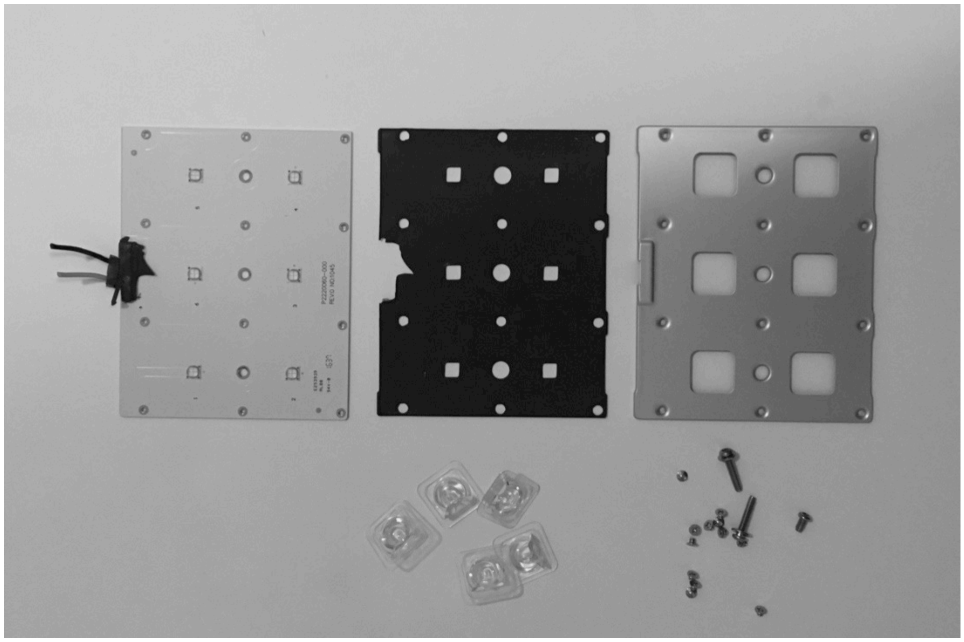


Figure 42: SL 3 housing for LED module facilitates repair and upgrade over time

5.3 Factors Influencing Technology Management Decisions

Decisions regarding when to buy, install, maintain and replace technology are influenced by multiple factors. While some may desire the lowest cost option, others may prioritize aesthetics, or convenience. In order to understand how practitioners prioritized these factors and the context of technology management decisions in the street lighting industry, interviews were conducted with stakeholders at different life-cycle stages. The goal of the interviews was to understand when and how technology management decisions are made and by whom. Table 14 summarizes the number of interviews conducted with stakeholders representing each life-cycle stage. A total of 21 interviews were conducted.

Table 14: Interview Summary

Life-Cycle Stage	# of Interviews
Design	4
Manufacturing	2
Use (Management and Maintenance)	7
Reuse	1
Remanufacturing	3
Recycling	2
Landfilling	2

Each interview provided insight into the decision-making process. In the design phase, interview subjects were individuals who either scoped purchasing decisions and provided product requirements, or worked for an OEM and were responsible for an aspect of the product design. Four of the interview subjects served as the primary decision-maker for purchasing and managing the entire fleet of street lights in a given area. Those individuals were able to provide detailed information about the cost and specifications for the lights they managed as well as the trajectory of the lights following product EOL or functional obsolescence. For the reuse phase, the interview conducted was with an individual who managed redistribution of piloted LED street lighting products. Representatives from three different remanufacturing companies were consulted, that either currently remanufactured lighting products or were looking to add lighting to their product portfolio. Finally, municipalities currently sending their products to recycling or a landfill connected the researcher with the individuals they worked with to collect and dispose of products.

5.3.1 Interview Process

The interview process was approved by the University of California, Berkeley's Office for the Protection of Human Subjects and the approval form can be found in the Appendix 3. Interviews were conducted either in-person or over the phone depending on the preference of the subject. The goal of the interviews was to gain understanding about the decision-making processes of product and system designers in the lighting industry to determine the need for tools that better suit decision-makers' needs. Participants were identified through faculty and student networks, individuals met through conferences or personal acquaintances, or through online searches of relevant organizations including local municipalities and stakeholders along a product supply chain, e.g., recycler, remanufacturer, etc.

Interviews were conducted using the interview guide attached in Appendix 2. The questions revolved around current EOL processes for LED street lighting products as well as expectations for technology change moving forward. Subjects were also asked about the key factors driving technology management decisions. In each section below, key quotes are included to elucidate the influence of the factor followed by a discussion about the broader implications of each factor.

5.3.2 Interview Results

The interviews indicate that decision-making around street lighting installation, use, and disposal depends heavily on the context of the installation. As one subject said, “If you spoke to 20 different utilities you’d get 20 different answers to the question of how do you dispose of the product.” The main drivers of EOL decisions are covered in the following sections.

5.3.2.1 Role of Product Design in Influencing Decisions

“For LEDs, we need to make sure the system is designed to be serviceable [or repairable] so that if a power supply or LED array fails it can be easily replaced. This means that the LED is only truly failed when there are no longer replacement parts available or when the efficiency of new technology is so high that the economics of total replacement are justified.” – Government Agency, Program Manager

The newly installed LED luminaires are fundamentally different from previous technologies including high pressure sodium or metal halide. In the past, when one part of the lamp failed, the entire product needed to be replaced. In contrast with LEDs often what is failing are the electronics driving the operation; the core illumination elements remain intact even when the driver fails. However what was unclear to the interview subject was whether or not the design of the products purchased were easily repairable, i.e., whether the driver was easily accessed and replaced. Every product purchased by those interviewed has a 5-10 year warranty and currently many municipalities are replacing products prior to the warranty ending. When a product has failed for any reason beyond easily repairable fixes such as the photosensor malfunctioning, it is returned to the manufacturer and replaced onsite with an entirely new fixture. Though convenient to fix the problem through replacement, this handling is accompanied by both economic and environmental costs; it was unclear to the subject if those costs were truly necessary.

“Out of 5000 lights we've had 8-12 fail. When we get a call that the light is out we send someone out. The problem could be a connector problem or a wire problem. If the light can't be fixed on site then we take it back to our facility, where it sits until we get a few failures. Then our contractor takes them back to [the manufacturer]. I'm assuming not too much is wrong with the lights so they still have a lot of value.

We're reaching the 10-year life on [some lights] they're hanging in there but for how long?" - City Government, Senior Electrician Supervisor

For most of the municipalities included in the interviewing process, operating budgets are of high concern and employees are looking for savings in every corner possible. Municipalities pay a flat rate cost for the lights and the warranty, but are unsure of how the new LED products will perform over time because it is an entirely new technology to them and is fundamentally different than prior technologies. At present, the research supports the notion that lumen depreciation is not a proxy for luminaire lifetime, however the true lifetime of products on the market today remains unclear [123]. If more transparency was embedded into the product design about mechanisms for serviceability and upgrade potential, municipalities would be more incentivized to retain, repair and reuse products for a longer period of time. However, many OEMs have adopted the strategy of planned obsolescence, where they induce repeat customer purchases by creating products with low durability [124]. A corporate strategy of planned obsolescence is at odds with a strategy to build modular products that are easily repairable by the customer. If companies are to make a commitment to more circular practices this is a tension that will need to be resolved.

5.3.2.2 Role of Economics in Influencing Decisions

“If you have the money, you want all of the lights to be wirelessly connected to a central server, we just don't have enough lights for that to make sense. Dimming and motion detection would be a great cost savings, that power would be metered. With street lights we pay a flat rate... so there aren’t any cost savings right now to dim.” - City Government, Senior Electrician Supervisor

Two key points regarding the influence of cost are brought up here. First, similar to how the early adopters of LED street light luminaires paid a higher capital cost in order to be industry leaders, the same is true for the emergence of control systems. Less than 5% of all current LED street light installations are connected to advanced wireless control systems [125]. Controls have the potential to expand the value that roadway lighting offers through the addition of security features as well as the potential to lower costs through improved operational management [31]. Some of the lights that have been installed already are “controls-ready”, meaning when the municipality or utility decides to connect the fixtures to a central server, the products will not need to be replaced. However, not all installed products are controls ready and many would need to be replaced if the decision were made to establish a fully-connected lighting system. This could lead to replacement of products far sooner than their expected lifespan.

The second point raised is that of the payment structure for electricity costs. Currently, many municipalities pay a flat rate for electricity costs. Though the flat rate decreased when users replaced traditional technologies with LEDs, they still pay the same daily rate if a light is on for 5 hours at night or 12 hours. While control systems have the potential to decrease energy expenditures further as users could lower the illumination levels in the summer when there is increased daylight, there’s little incentive for users to implement further energy saving mechanisms as they are not paying for direct usage. One thing that was repeatedly cited was that changing the rate structure with utilities represented a major barrier to further potential energy savings.

“We looked at retrofitting our older copperheads but it's more economical to buy new with the way fixtures are evolving. The lamp itself costs $100 to retrofit and for another $50 I could get a new fixture with a far lower failure rate. Plus with so many fixtures we

have bargaining power - We give our own specifications and the manufacturers work to meet them. It's an interesting market." – City Government, Project Director

Those making decisions about upgrading street lighting infrastructure recognize how quickly the technology and market is changing. In contrast to the previous example, for those that do pay for direct energy use a high incentive exists to pursue all energy saving opportunities. Despite installing products with a long lifespan, the products on the market were sufficiently better to warrant replacing all of the previously installed lights. This signals how sensitive decision-making processes are to cost-saving opportunities. Furthermore, in this example all of the replaced pilot lights were recycled despite there being significant residual value in the now obsolete products. Had the decision maker been aware of options for remanufacturing, he or she may have been able to gain further economic and environmental value from the initial investment.

5.3.2.3 Role of Technology Change in Influencing Decision

"The vast majority of these 1st and 2nd generation LEDs are going to be pulled out well before they fail; Cheaper LEDs and higher efficiency are going to drive the rate of change. As you add digital devices that is going to drive the wattage up." – Government Agency, Program Specialist

Several of those interviewed had worked in the street lighting industry for over two decades. They saw the rise (and current fall) of fluorescents as well as the replacement of incumbent technologies with several generations of new products. This led the individuals to have strong opinions about where the industry was headed and use such to inform their decisions about technology management. The individuals who anticipated that the early installed fixtures would be replaced prior to failure also had thought about piloting remanufacturing projects or finding rural areas who had not yet upgraded their lights that may be interested in purchasing the 1st or 2nd generation fixtures at a lower upfront cost. One of the challenges that arose was that in the gap between initial purchase and first replacement, the market cost had dropped so significantly that little opportunity existed for savings when comparing a 3-year old product and a current generation model. As the available products become more technologically sophisticated in the coming years and customized to the use-context, reuse in alternative settings may become an even harder challenge.

"My rule of thumb is I wait until the 4th generation of a technology is out – that's usually around the time all the issues have been worked out and the cost has come down." – Higher Education, Assistant Dean

Industry experts often have rules of thumb developed over time that they do not know how to check against the current market. In this example, the interview subject spoke about how he was excited by the prospect of metal halide products when they emerged in the market and the early generations he had purchased failed soon after installation. From that experience, he had formed the rule that he wouldn't purchase a technology until at least the 4th generation was available. In the context of street lighting, that rule has both benefits and considerations. On the one hand, waiting to upgrade may allow for control system technology to evolve, product quality to improve, and price points to drop. However, in the interim the municipality may miss out on significant energy and cost savings that would have been achieved with a decision to upgrade. Either way, industry experts are seeking tools and guidance for when they should make the decision to invest in a new technology, which is one value this dissertation can provide.

5.3.2.4 Role of Policy in Influencing Decisions

"In places where people are environmentally conscious, regulations are followed; in rural areas – disposal rules aren't followed and no one enforces regulation." Program Manager, Utility

Policy initiatives have been noted as an important driver towards a circular economy, particularly in Europe and China [53], [55]. Policy can help to prompt adoption of more sustainable behaviors or enable a new technology (e.g., renewable energy technologies) to achieve competitive status in a market relative to existing technologies [126]. Adoption of more efficient lighting technology in both consumer and commercial sectors was spurred by initiatives to phase out older products as well as those containing harmful chemicals (e.g., mercury in compact fluorescent lights) [127], [128]. Governments have also implemented significant policy changes to better manage the emergence of waste electric and electronic equipment (WEEE) with varying degrees of success [129], [130]. As the quote here elucidates, often the challenge with regulations is in the enforcement. The interviews revealed that disposal strategy for lighting technology is highly contextualized. In places with an environmentally progressive city or state government, municipalities were more likely to have programs set up to ensure that recycling of all product components happened. In places with fewer resources or minimal enforcement of disposal regulations, municipalities were more likely to pursue the disposal strategy that was most convenient which meant landfilling of the street light fixtures. Information about potential challenges associated with lighting product take-back can be taken from programs aimed at collecting fluorescents and compact fluorescent lights (CFL), of which the recycling rate remains between 20-40% despite being regulated as hazardous waste due to their mercury content [131]. The main explanations for the low rate of CFL recovery include a lack of customer knowledge about regulations as well as where to recycle lights and the inconvenience of recycling relative to disposal into landfill [131].

"Advancement of controls technology has been rather spotty. Out of the 60 projects I've worked on I would say only 2 adopted controls. There's no federal position that will recognize controls as a meter. Until the rate structure changes control systems won't be adopted. And they're still expensive - the technology is really in it's infancy. – Construction Industry, Property Management Director

The issue with charging a flat rate for electricity consumption is both an economic concern as well as a policy concern. Controls have the potential to be another disruptive technology within the lighting industry facilitating lower energy consumption and providing enhanced services such as internet and security to communities when installed [31]. However, for municipalities to upgrade to new technology, the legal frameworks that incentivize adoption (e.g., changes in electricity rate structure to reflect real time consumption) should be in place [125]. Often government policy is reactive rather than proactive, meaning that the legal framework to enable a technology's full adoption follows invention. The time delay inherent in those steps, however, can hinder the progress towards more sustainable systems.

5.3.2.5 Role of Public in Influencing Decisions

"People do complain about the color of the lights and the temperature - they don't like the change from yellow to white light.. so that is something that may drive product turnover." – City Government, Project Director

As with any infrastructure decisions, the public plays a key role in influencing project development. Any system changes, no matter how large or small, can generate a significant public response. Early adopters purchased products with a color temperature of ~4000 K (a measure of light color), resulting in cool, blue-tinted light and raising public concern around glare when driving and light pollution [132]. In several cases, negative response to the newly installed LEDs has prompt rapid replacement for newer products. As described by Jeff Hecht in IEEE Spectrum, "Just months after the city of Davis, Calif., installed 4,000-K LED street lights in 2014, a high volume of complaints prompted officials to spend $350,000 to replace 650 of those new lights with less-efficient 2,700-K LEDs [133]." Several cities have done similar replacements to satisfy citizens. Beyond the cost implications, it's important to understand the environmental consequences associated with product turnover.

I also worry about the social consequences of dimming or a light out. We're already being sued for a light being out that caused a car accident. - City Government, Senior Electrician Supervisor

Often government agencies can be slow to act because they need to ensure buy-in across a large and diverse group of stakeholders. Missteps can slow down project implementation or jeopardize allocated funding. In the case of LED street lights, many cities wanted to quickly upgrade to LED fixtures in order to have the public recognition as a public leader. However, adoption of further technology upgrades such as control systems is not without concern. One city government employee mentioned how dimming, which has been well lauded as a cost-saving opportunity, could be accompanied by increased security concerns. This necessitates further study of the consequences (both positive and negative) of technology upgrade decisions.

5.3.3 Interview Results Summary

The interview results showed the variety of factors influencing the technology management decisions for street lighting. Those in public-facing roles mentioned more frequently the influence of critical pushback to decisions, while those in the private sector highly emphasized the need for cost-effective decisions. Additionally, several of the interviewees had specific "rules-of-thumb" to follow, which may or may not represent the most cost and/or environmentally friendly decision. The ways that different stakeholders approached the product EOL proved particularly of note. Decisions were highly dependent on the regulations in place or the perceived benefit that could be obtained by choosing a given EOL strategy (recycling or remanufacturing). At the present, most interview respondents said that they expect LED street lights to be dealt with in the same way as conventional street lighting products: the majority are recycled with some products still going to landfill following obsolescence. This finding motivated the need to examine potential EOL trajectories in depth, with the hope that by quantifying both the cost and emissions associated with each, one could determine strategies to motivate behavior that preserved material longer and prevented unnecessary environmental impacts.

5.4 Chapter Summary and Future Work

This chapter provided an assessment of current street light product design using a novel method of design assessment. The goal of this assessment was to analyze products currently in use by municipalities within the United States in order to determine their suitability for EOL processing. Such work provides insight into the gap that exists between the literature on design for environment and sustainability and the products in the market today. While design strategies for product sustainability are known, they are not being implemented by OEMs. Also in this chapter the results of 19 stakeholder interviews were presented. The interviews yielded information on the system dynamics influencing technology management decisions within the street lighting industry. Understanding why and how technology management decisions occur in the context of street lighting provides researchers with a sense of where more work is needed if more environmentally beneficial decisions are to be made in the future. A key area of future work identified is the role that rate structure plays in influencing utilities and municipalities to adopt controls technology. While control systems could provide significant benefit in terms of energy efficiency as well as improved community safety and accident monitoring, charging a flat rate fee for total energy consumption provides little incentive to upgrade technology. Overall, the work conducted within this chapter could be improved by including a larger number of products within the analysis set. Due to the high value of the products and limited research budget, fewer products were obtained than previously expected. Analyzing a larger number of products could increase the generalizability of the work. Furthermore, expanding the scope of the environmental analysis to include more outcomes would also be beneficial in the future.

6 Characterizing Cost and Environmental Impacts of End-of-Life Pathways for LED Street Lights

6.1 Introduction

Understanding the environmental impacts associated with various EOL strategies including repair, reuse, remanufacturing, recycling, and landfilling can help to guide more sustainable technology management decisions. In light of the growing push for sustainable manufacturing and a circular economy, it is increasingly critical to understand the life-cycle cost and emissions associated with product systems in order to determine whether proposed closed-loop systems truly are sustainable. [134], [135]. Often the EOL phase is assumed to be inconsequential, considering the environmental burden falls primarily in the use phase for many products, however, as energy efficiency increases and constraints on raw materials grow, the environmental impacts associated with products' end of life becomes increasingly important [136].

The relative importance of the EOL phase has been studied in the context of evolving technology products. Gutowski et al. [137] studied the energy use implications for a large suite of products, taking technology trends into account. They found that remanufacturing has a small positive effect on the total product lifecycle footprint during periods of rapid product efficiency changes. Krikke et al. [138] analyzed the effects of choosing between alternate EOL strategies (repair, recycling, and remanufacturing) and saw that the benefit of an end-of-life strategy for copy machines depended on the quality of the returned product, the time owned, and the level of use during ownership. The authors suggested that take-back prior to machine failure could extend use over a longer period, by allowing for the upgrade of parts and redistribution. They further found that expanding the allowable distance for returns (i.e., accounting for the carbon consumed when transporting a farther distance) was environmentally worthwhile if the transported product was remanufactured and redistributed.

Full life-cycle assessments are available in the literature for both the manufacturing of LEDs as well as the use phase and disposal of LEDs [38], [71], [139], [140]. However, none of the studies examine end-of-life strategies other than recycling, though all stress that more work is needed in the area of end-of-life decision making for LEDs. This chapter includes (1) a characterization of the environmental and economic impacts associated with different end-of-life strategies for LED street lighting products and (2) the results of a simulation analysis to understand the impact of various use and EOL scenarios.

6.2 Life-Cycle Assessment and Life-Cycle Costing Methods

Life-cycle assessment (LCA) is used throughout many sectors and applications to determine and quantify impacts associated with a process, product, or service. Decision-makers use LCA to identify the largest sources of impacts in order to find opportunities for impact reduction. In LCA, one examines how materials and products move throughout various life-cycle phases. Phases can include raw material extraction, material processing, manufacturing, distribution, use, and end-of-life. Examination of all life-cycle phases can lead to a more accurate evaluation of impacts incurred [141]. According to the LCA standard 14040, issued by the International Organization for Standardization (ISO), key components of an LCA include: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation [142]. Defining the goal and scope enables one to ensure that the study remains feasible by imposing assessment boundaries. Following that, one must collect supply chain data in order to determine the energy and material demands of each life-cycle stage. In this analysis, environmental assessment will be limited to carbon emissions. Life-cycle cost assessment (LCCA) is also employed, to understand the trade-offs between cost and emissions for end-of-life strategies. LCCA follows a similar methodology as LCA, however, inventory is taken of costs incurred rather than emissions generated [143].

Several researchers have promoted LCA as a key tool to analyze the environmental implications of proposed circular economy models [50], [144]–[147]. LCA, particularly when combined with LCCA, helps to elucidate the realities and challenges associated with closed-loop systems that proponents of the circular economy aim to create [148]. Often studies conducted using the methodologies can reveal that environmentally optimal systems are cost-intensive, or that despite investment into a system change, the environmental impacts remain the same over time [148].

LCA and LCCA are further relevant to understanding the circular economy as over the past two decades, the academic community has debated and put into practice guidelines for dealing with common challenges encountered in evaluating closed loop systems, including coproduct allocation, reference states, and material reuse [147], [149]. As the circular economy is a relatively new area of research, few researchers thus far have used LCA and LCCA in this context [145], [149]–[151]. When studies have been conducted, the approaches have been varied. Hashimoto et al. [150] and Peters et al. [145] both used attributional LCA. Employing an attributional approach means conducting a system analysis that traces impacts to the individual processes and materials that comprise a given scope (e.g., the specific components of a product) [152]. Alternatively, consequential LCA is used to study the changes in impacts caused by proposed decisions if proposed changes significantly influence the rest of the economy [149], [152].

In this decision-making context, attributional LCA is used to understand how product design can influence the accessibility of various end-of-life strategies. (If instead the analysis had been conducted to examine the effect on all street lighting products in the US, a consequential LCA methodology would have been used.) All of the process steps will be assessed for inputs including labor, energy, and materials and outputs including costs in USD ($) as well as emissions (kg-CO_2) and emission factors will be used to quantify the GHG footprint of the individual end-of-life strategies. The functional unit of comparison here is a single LED lighting street lighting product, specifically the Leotek 87W product (SL 3). Equations 7.1 and 7.2 show the method to calculate the GHG footprint and cost of each pathway and capture the overall impact (cost or environmental) of the system scoped in the analysis.

$$E_{strat} = \frac{\sum_{i=1}^{P}\left\{\sum_{a=1}^{M} m_{a,i} \cdot e_{f_{a,i}}\right\} + \left\{\sum_{b=1}^{W} w_{b,i} \cdot e_{f_{b,i}}\right\} + \left\{\sum_{c=1}^{R} r_{c,i} \cdot e_{f_{c,i}}\right\}}{X}$$

Eq. 6.1: Total Emissions

where:

- E_{strat} is the total CO_2 footprint of the system included in the analysis scope [kg $CO_{2\text{-}eq}$]
- P is the total number of processes
- m is an individual material used in a given process
- M is the total number of materials
- r is the energy utilized in a given process [kWh/process]
- R is the total amount of processes that consume energy
- w is the waste generated in a given process
- W is the total number of waste sources
- e_{fa} is the emission factor associated with a material manufacturing [kg $CO_{2\text{-}eq}/kg_{material}$]
- e_{fb} is the emission factor associated with waste generated by a process [kg $CO_{2\text{-}eq}/kg_{waste}$]
- e_{fc} is the emission factor associated with resources (energy) used in system [kg $CO_{2\text{-}eq}$/kWh]
- X is the number of products processed

$$C_{strat} = \frac{\sum_{i=1}^{P}\left\{\sum_{a=1}^{M} m_{a,i} \cdot c_{f_{a,i}}\right\} + \left\{\sum_{b=1}^{L} l_{b,i} \cdot c_{f_{b,i}}\right\} + \left\{\sum_{c=1}^{R} r_{c,i} \cdot c_{f_{c,i}}\right\}}{X}$$

Equation 6.2: Total Costs

where:

- C_{strat} is the total cost impact [$]
- P is the total number of processes
- m is the material used in a given process
- M is the total number of materials
- r is the energy utilized in a given process [kWh/process]
- R is the total number of energy uses
- l is the labor employed in a given process
- L is the total number of labor uses
- c_{fa} is the cost of an individual material per unit mass [$/kg]
- c_{fb} is the hourly labor cost [$/hr]
- c_{fc} is the cost of energy consumption per kWh [$/kWh]
- X is the number of products processed

6.3 Data Sources and Scope

Collecting inventory data posed several challenges due to limitations in available data. A key method for overcoming data shortages involved contacting stakeholders including manufacturers, users, recyclers and remanufacturers and directly in order to conduct interviews. Table 15 shows the key data sources used by the study.

Table 15: Key Data Sources Used in Inventory

Inventory Component	Data Sources
Material Production Costs	Industry Specification Data Manufacturer Interviews and Earnings Statements: Philips [153] Cree [154]
Transport Distances	Municipality Interviews, Manufacturer Interviews
Transport Emissions	Ecoinvent V3.1 [155]–[157] Municipality Interviews Taptich 2014 [158]
Labor Requirements and Costs	Manufacturer Interview, Municipality Interviews, National Labor Statistics [159]
Material Production Emissions	Product Teardown, Ecoinvent V3.1 [156], Ciceri 2009 [160], Tahkamo 2015 [140]
Efficacy Projections	U.S DOE SSL Program [161],
Electricity Prices	U.S. EIA [162]
Control Systems Penetration	PNNL [125]
Emissions Factor	U.S. EPA eGRID [163]
Process Models	Stakeholder Interviews

A key data source used throughout the subsequent analysis is the inventory of materials that comprise the street light product. The inventory was constructed via a bill of materials (BOM) from the product tear down. Manufacturers were contacted to ask for a BOM however the only information provided was high level product statistics such as mass, efficiency, and size. As municipalities reported a higher usage of product SL 3 when compared to SL 1 and SL 2, SL 3 was used to model the scenarios. The complete bill of materials and corresponding processes for the manufacturing of a sample street lighting product as modeled in Ecoinvent v3 is shown in the Appendix 4.

In order to assess across all end-of-life strategies, the scope of the analysis is cradle-to-cradle, meaning that following use all impacts are accounted for to the point of a second product being distributed. The process flow diagrams used throughout Section 6.4 reflect the system scope.

6.4 Process Flow Modeling of End-of-Life Options

6.4.1 Manufacturing

To ascertain the cost of components, available industry specification sheets and product marketing materials were used to understand the costs to the consumers. Next, earnings statements were used to understand the average profit margin for manufacturers within the industry. The profit margins within the lighting industry are relatively low compared with other electronic markets, leading manufacturers such as Cree and Philips to separate their lighting products into standalone company divisions. After a baseline of costs were obtained, two manufacturers were interviewed and asked to see if they agreed with the relative proportion of component costs as they were unwilling to share information about their direct costs. Overall this allowed for analysis of the difference in costs between product components. The results of the manufacturing cost analysis are show in Figure 43. The error bars indicate the range of potential costs given available data. The total cost to the consumer for the light shown is $240. The power supply proved to be the most expensive component, followed by the metal housing and the LED module.

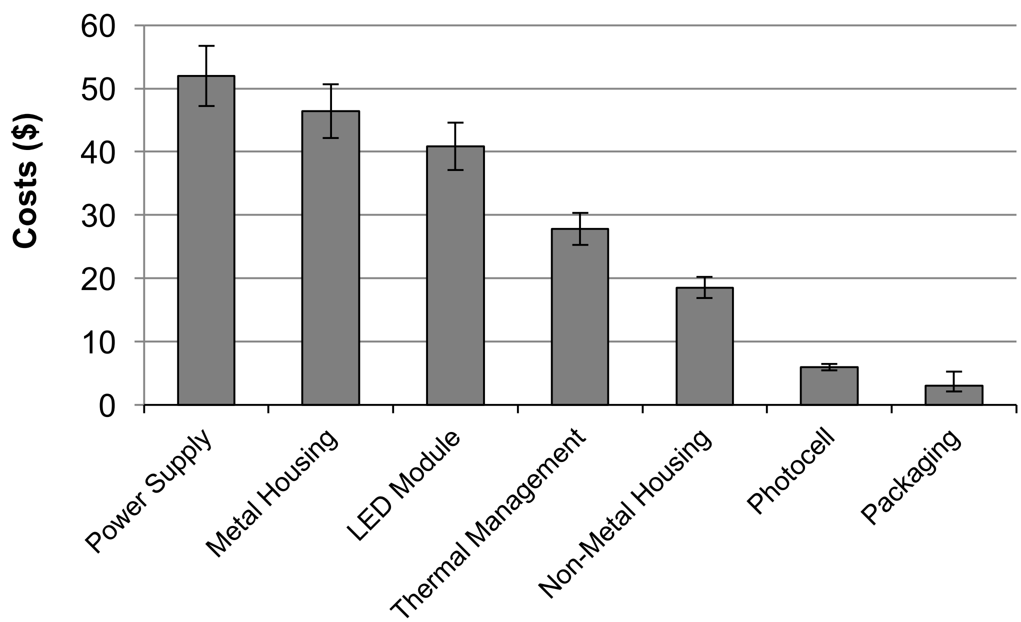


Figure 43: Component Costs for 2017 87W Leotek Street Light

The total costs for LED street lights have declined dramatically since their introduction to the market over 8 years ago. The expected reduction in manufacturing costs can be seen in Figure 44 using data from the U.S. Department of Energy [161]. According to the DOE and the manufacturers interviewed, what is supposed to decline most significantly is the cost of the LED module, accompanied by reductions in the cost of the thermal management and power supply. However, the costs reductions are based on the cost per kilolumen of light delivered and so do not reflect the costs of integrated components from the rise of control systems, which could increase the overall product cost depending on the number of auxiliary functions added to light delivery.

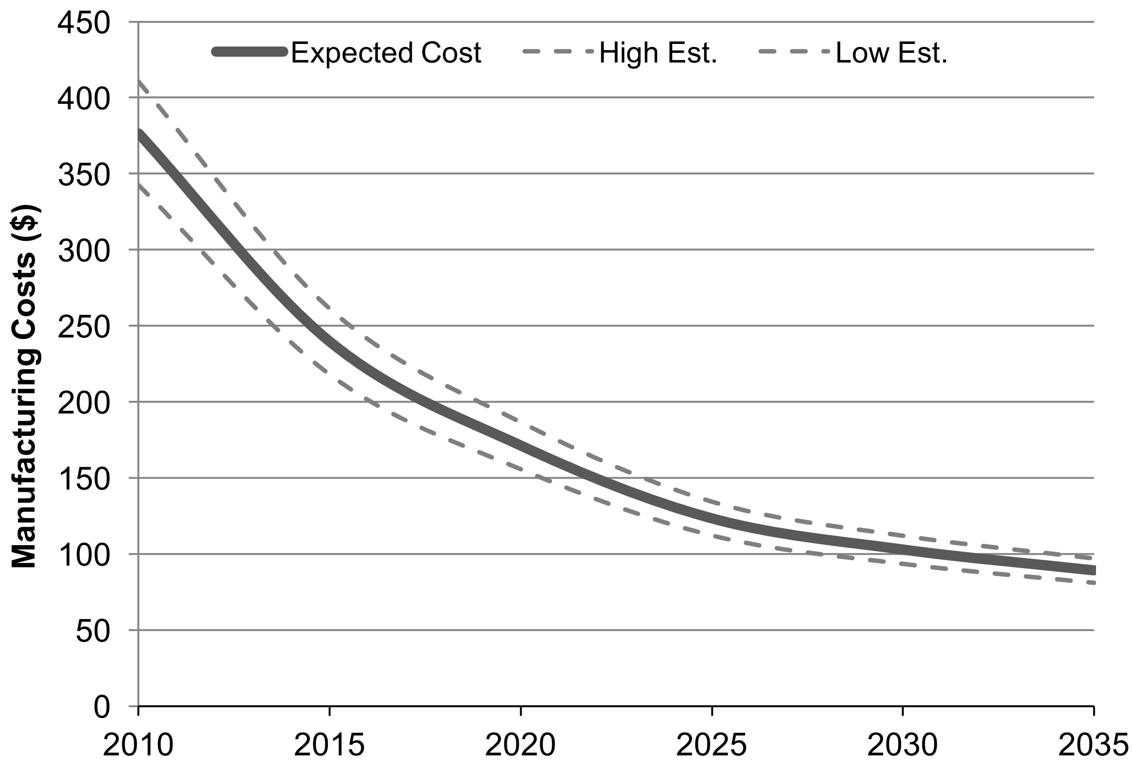


Figure 44: Expected Decline in Manufacturing Costs [161]

On the environmental side, carbon dioxide emissions from manufacturing were estimated using the material inventory (Appendix 4) and the Ecoinvent v3 database [156]. The results of the environmental analysis can be seen in Figure 45. The error reported with the analysis comes from uncertainty around particular materials used (e.g., specific types of metal components) as well as a range of absolute values provided from data sources for emission factors corresponding to individual processes (e.g., aluminum processing). The most emissions-intensive component is the metal housing, followed by the power supply and the thermal management (or cast aluminum heat sink). The non-metal housing and LED module have little contribution to the overall environmental impact of the product manufacturing.

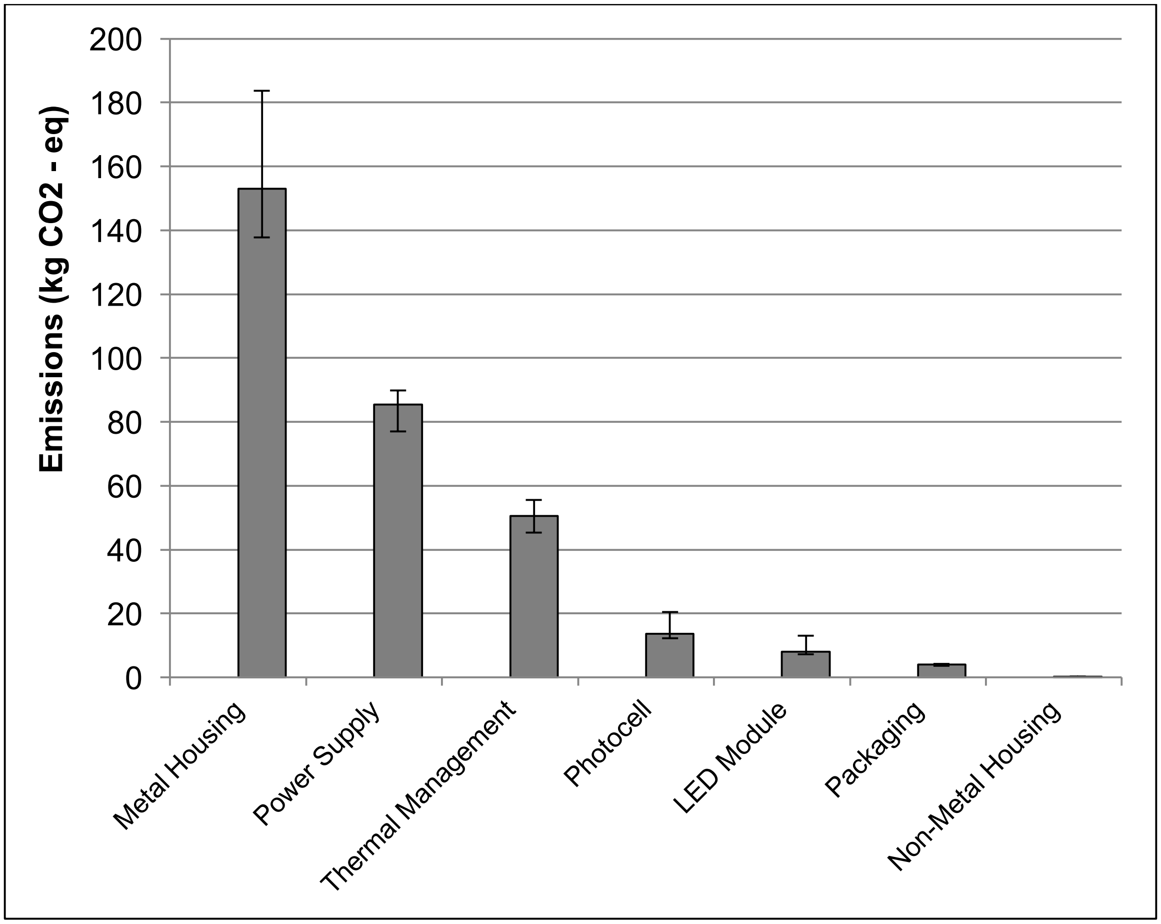


Figure 45: CO_2 Emissions from Manufacturing for 87W Street Light

The differences between the cost and emission profiles are important within the context of technology management as the most cost-effective decision will not necessarily be the most environmentally-effective decision and vice versa.

6.4.2 Use

Street lighting products are used on average for 12 hours per day. The associated costs and emissions are the highest impacts within the use life-cycle phase, particularly when manufacturing and end-of-life costs are amortized over a long expected life span. As this dissertation is examining implications of various technology management strategies, it is critical to understand the impacts incurred throughout all phases.

6.4.2.1 Expected Growth in Efficacy

The reason why LED lighting technology is still evolving so rapidly is because the efficacy (i.e., lumens produced per kwh of energy consumed) of new products on the market continues to rise over time. Two potential projections of efficacy are shown in Figure 46, with data sourced from the U.S. DOE [161]. Following the logarithmic scenario is both conservative and unlikely. It would come into effect if a different technology emerged that replaced the need for innovation in the LED market. However, while diode efficacy has increased by over 50% since 2010, system efficacy or luminaire efficacy has only risen by approximately 20% during the same time period [31]. As reported by Katona et al., the system wide-efficacy has also declined between product years as manufacturers aimed to lower manufacturing costs and use fewer LEDs to achieve the same light output, sacrificing operational savings [31].

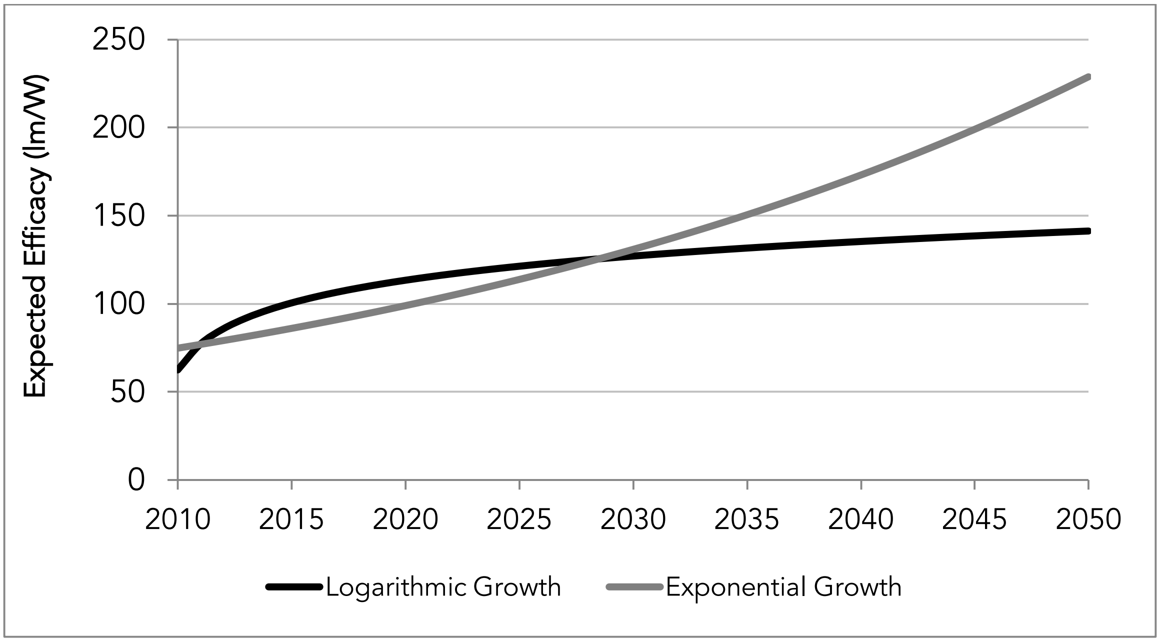


Figure 46: Projected Efficacy Increases (lm/W) from U.S. DOE [161]

The other major factor influencing use-phase energy consumption is the implementation of networked control systems, more accurately called luminaire-level lighting controls (LLLC). According to the Northwest Energy Efficiency Alliance (NEEA), LLLC can provide potentially 50 percent energy savings [125]. The capabilities of an LLLC include:

- Dimming
- Distributed control that facilitates remote measurement and verification
- Sensors for monitoring light-level, motion, and energy use

Currently, the penetration of LLLC is low among municipalities, with adoption levels below 5% nationwide. Though the savings could be up to 50%, the overall efficiency will depend on political (rate structure), technical (system), and market (technology) factors. Scenarios of annual use phase efficiency given expected efficacy changes is shown in Figure 47. For products purchased between 2010 and 2025, the implementation of LLLC could yield significant energy savings. For products purchased after 2025, the expected lighting efficacy in products at that time is high, however, small savings summed across a large product fleet will be substantial as well. It is critical though to remember the potential for the rebound effect to manifest as the system efficiency increases over time. Across the energy sector, as financial savings are realized through increased efficiency, consumers can either increase their energy consumption or use the savings toward non-energy services. Choosing the former is known as the rebound effect, the magnitude of which can negate previously achieved energy and emission savings [164].

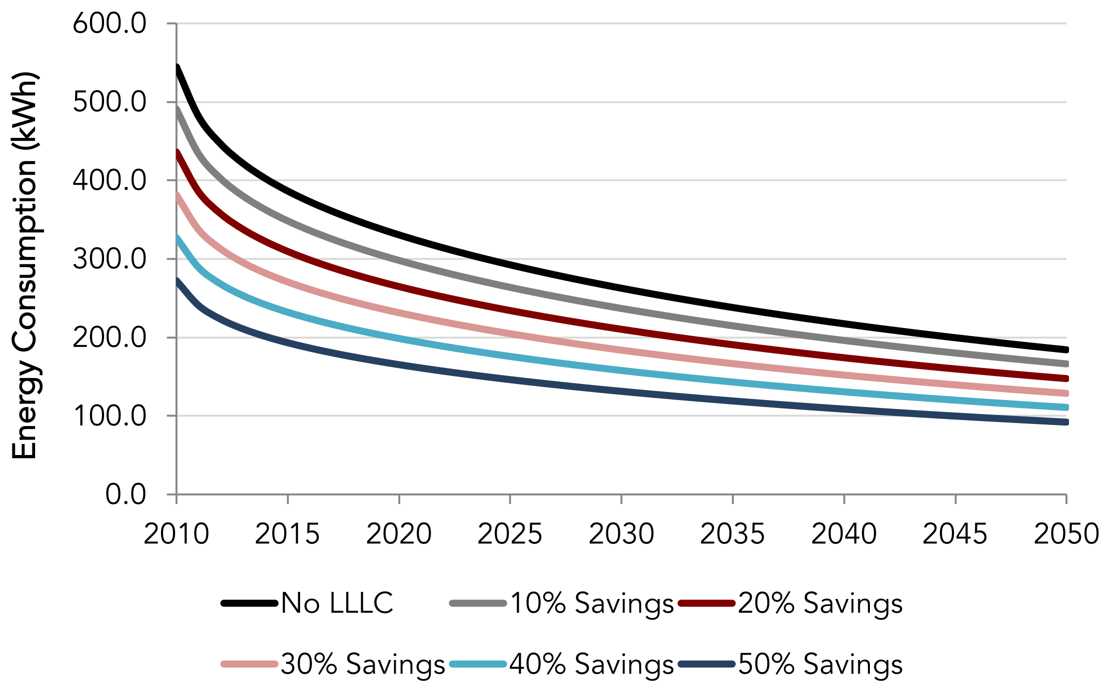


Figure 47: Energy Savings with LLLC Implementation

6.4.3 Reverse Logistics

Following use, the next step is reverse logistics, or the steps required to move the product from its use site to the appropriate processing facility. In order to understand the logistics required four scenarios were examined that represented geographically diverse regions within the U.S. The four scenarios also represent different infrastructure ownership and management models including municipality ownership, utility ownership, and ownership by the local Department of Transportation. Ownership influences how the products are managed and handled as well as how far the product must travel for end-of-life processing. The data shown in Table 16 provide a summary of the average distance required between the installation site and the necessary processing facility that the location uses or would use. Data for the table was collected from the interviews with the municipalities and stakeholders. The table also provides insight in the current end-of-life practices of the various locations. As the table shows, currently recycling is the primary end-of-life option used across the four locations. Location A uses remanufacturing in a higher proportion as they are close to the manufacturing facility and thus any failed products are remanufactured and returned to the install site. The only location that is landfilling products (Location D) is in a rural area where regulations around end-of-life processing are not strictly enforced. Outreach is happening by local governments to promote at minimum recycling of products in order to avoid landfilling. However, in rural areas where regulatory oversight is low it is unclear whether EOL trajectories will change over time. Throughout the following end-of-life strategies analysis, Location A is used as the example scenario due to the highest level of detailed data provided by the municipality. Transportation ended up being largely negligible throughout the cost and environmental analysis however was included for completeness.

Table 16: Current Reverse Logistics for Four U.S. Locations

	EOL Strategy				
	Repair	**Reuse**	**Remanufacturing**	**Recycle**	**Landfill**
	Location A				
Transport (mi)	10.0	51.3	42.4	30.0	51.0
Current %	-	0%	30%	70%	0%
	Location B				
Transport (mi)	15.0	150.0	333.0	365.0	150.0
Current %	-	0%	15%	85%	0%
	Location C				
Transport (mi)	10.0	285.0	115.0	50.0	85.0
Current %	-	0%	0%	100%	0%
	Location D				
Transport (mi)	30.0	75.0	100.0	85.0	75.0
Current %	-	0%	0%	55%	45%

6.4.4 Repair

Figure 48 provides the process flow diagram for repair. Repair enables a product to stay in use for the expected duration of the product lifespan. In the context of street lighting, events that would warrant repair represent a compromised state of the light, rather than a full failure, e.g., the light output is diminished or is operating at less than optimal efficiency, or the light is on/off when it should be the opposite. If any of those events occur, a worker is dispatched to the installation site, and checks to see if any of the quick repairs fix the issue. If yes, the light is back to the normal state. If not, the light is taken down and replaced with a new product, and the failed product is returned to the distribution facility (often a municipality building). The costs and associated emissions of the repair process are shown in Figure 49 and Figure 50, respectively.

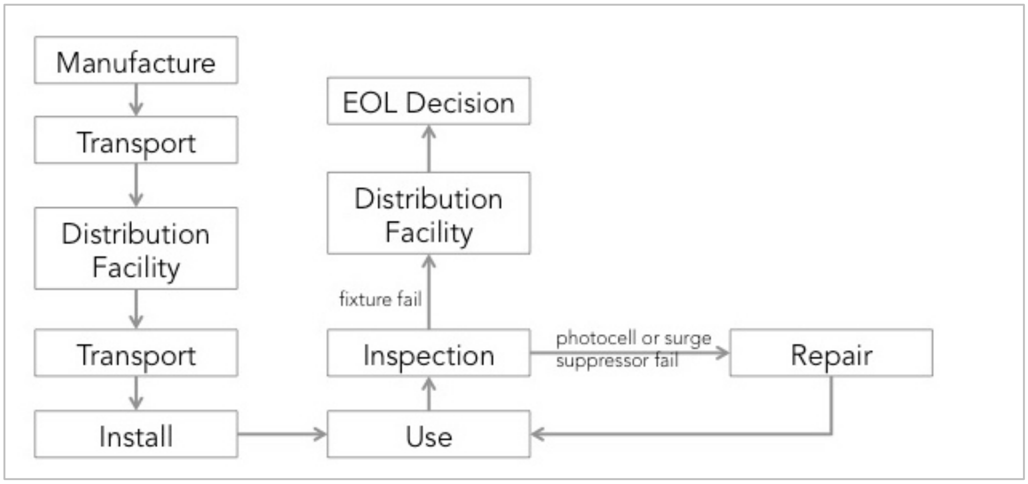


Figure 48: Process Flow Diagram for Repair

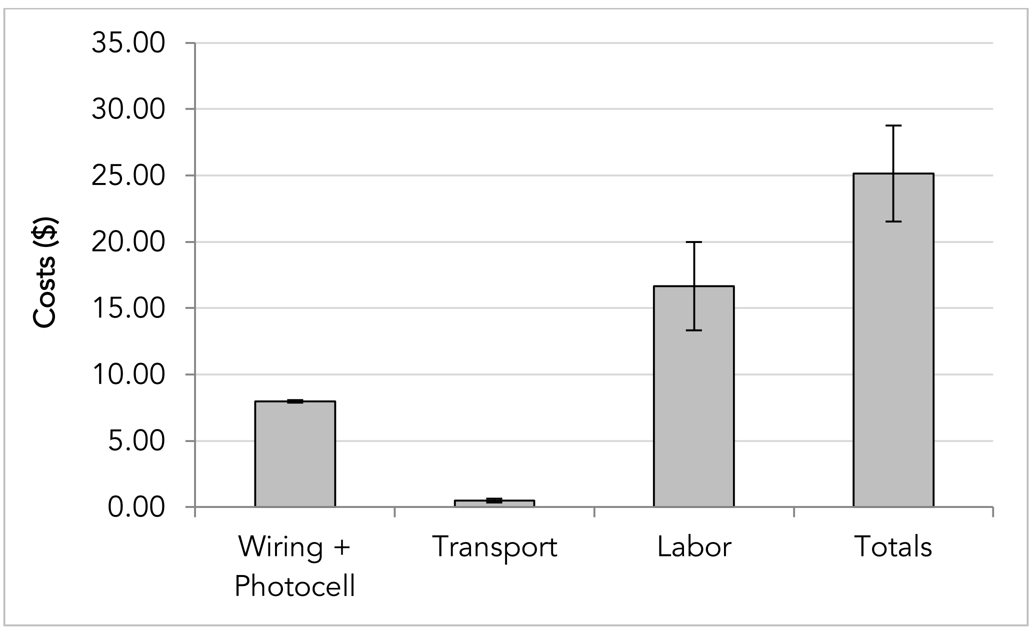


Figure 49: Costs Incurred During Repair

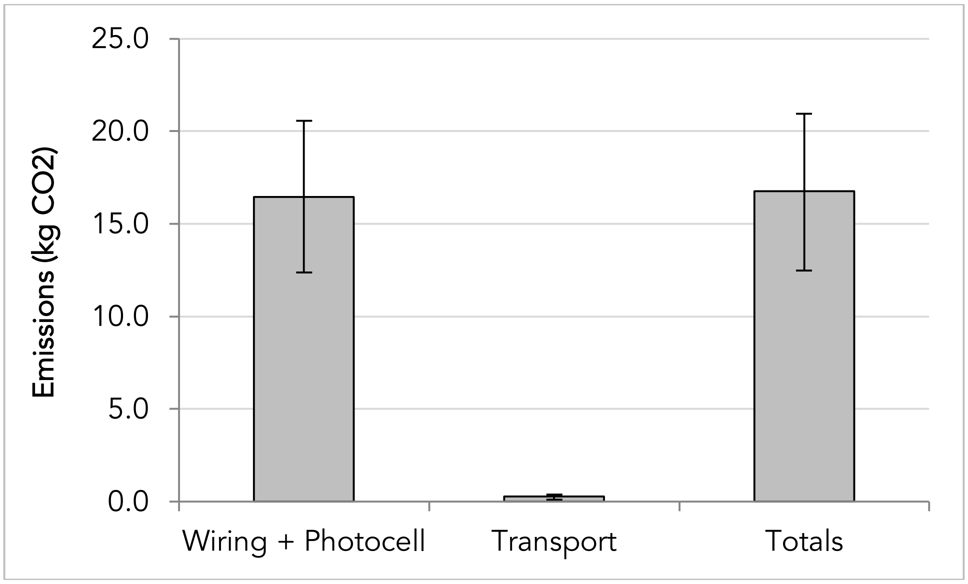


Figure 50: Emissions Incurred During Repair

Among the costs incurred, labor costs involved with paying the worker to inspect and repair the product are the main cost components, followed by the cost of the replacement materials. If an inspector goes to repair a light, they typically replace the photocell or daylight sensor while up there as they tend to fail easily and this prevents future issues. On the emissions side, the only notable source of emissions is producing the replacement materials.

6.4.5 Reuse

For reuse to be viable, the product is replaced out of consumer preference rather than a technical failure. In the consumer products industry, often reuse occurs when a customer purchased the wrong item and returns it to the store out of the box. Retailers will quality-check the product before reselling or redistributing. A similar process is followed for commercial products; Figure 51 provides the process flow diagram within the street lighting context. Here, the original user will return the light to the original equipment manufacturer. The product will then be disassembled, cleaned, checked once again for quality, packed and redistributed. The only difference between reuse and remanufacturing is that in reuse the yield is 100%, meaning all of the components within the product can and are reused.

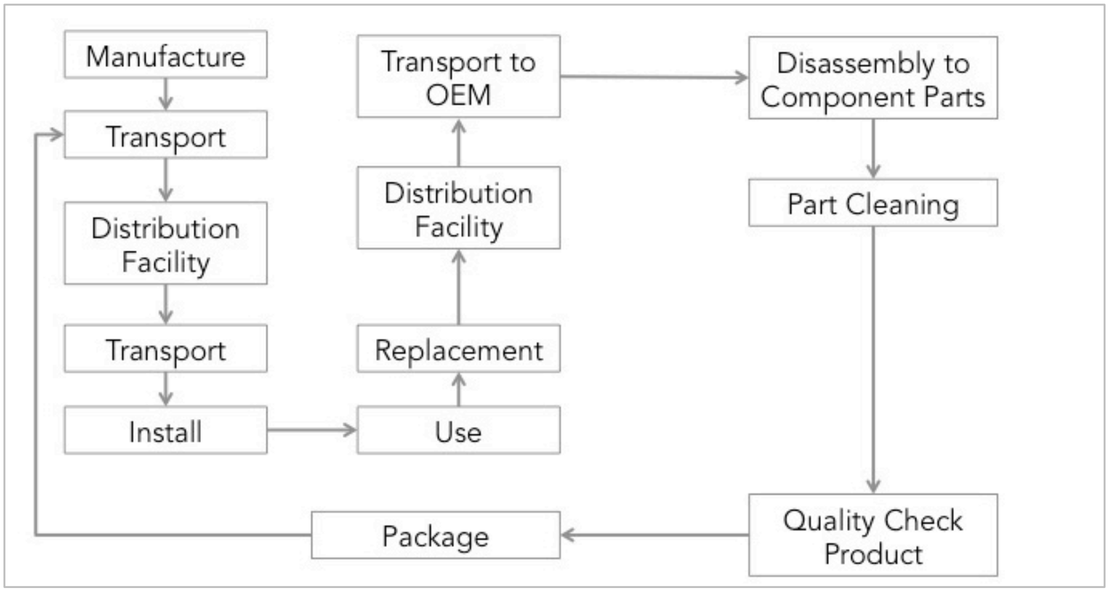


Figure 51: Process Flow Diagram for Reuse

Figure 52 and Figure 53 show the costs and emissions incurred through reuse. The process of disassembly and part cleaning is almost entirely manual, making labor the major cost. The emissions associated with reuse are low; with the packaging process constituting the largest fraction. Overall both cost and emission impacts with reuse are considerably lower than other strategies because the material integrity is preserved and thus manufacture of new products is avoided, assuming the product can be successfully redistributed.

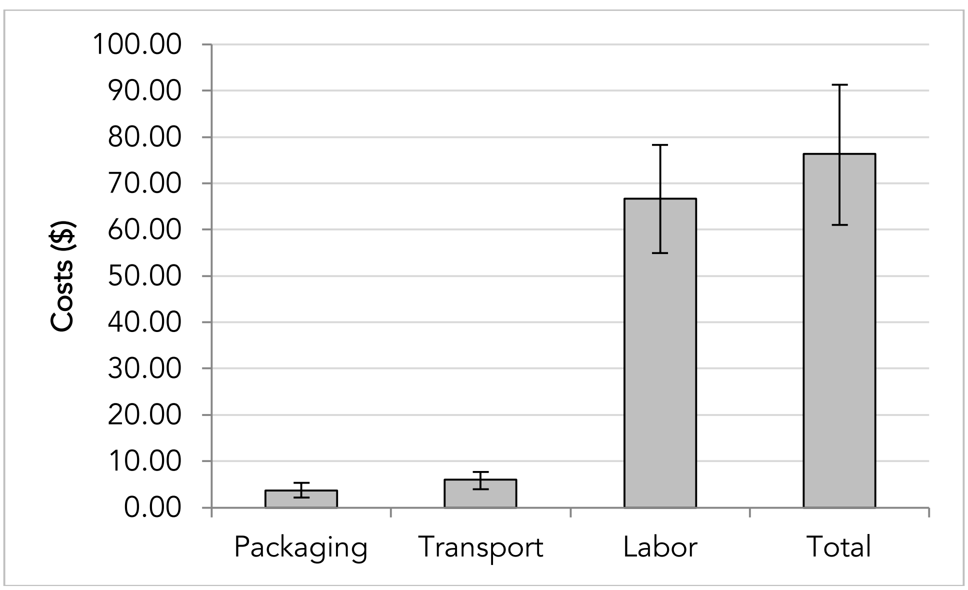


Figure 52: Costs Incurred During Reuse

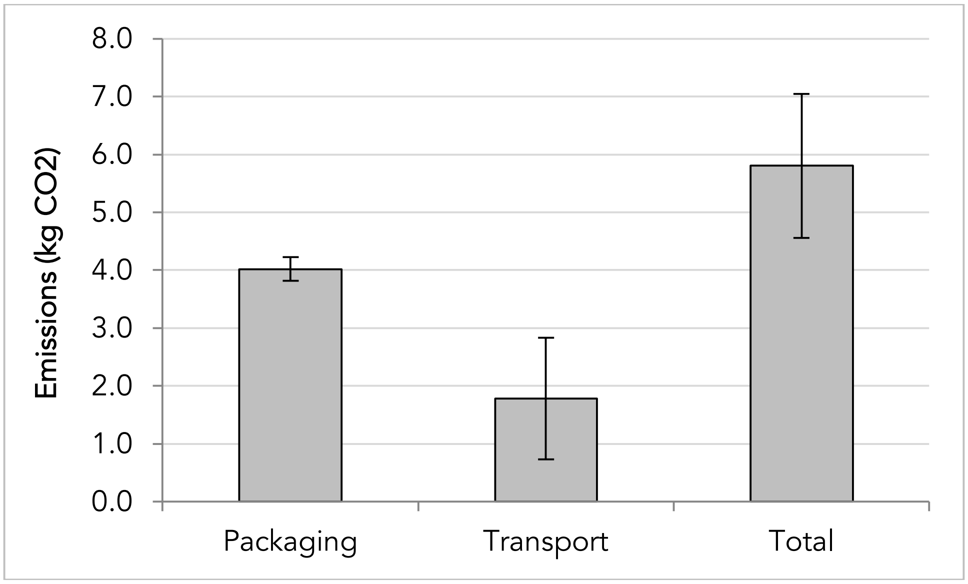


Figure 53: Emissions Incurred During Reuse

6.4.6 Remanufacturing

The process flow diagram for remanufacturing, as shown in Figure 55, is similar to reuse. The differentiator is the product yield. Components that cannot be directly reused are recycled and those that can be reused are cleaned. Then the new components are combined with the salvaged ones, the newly assembled product is quality checked, then packaged and shipped.

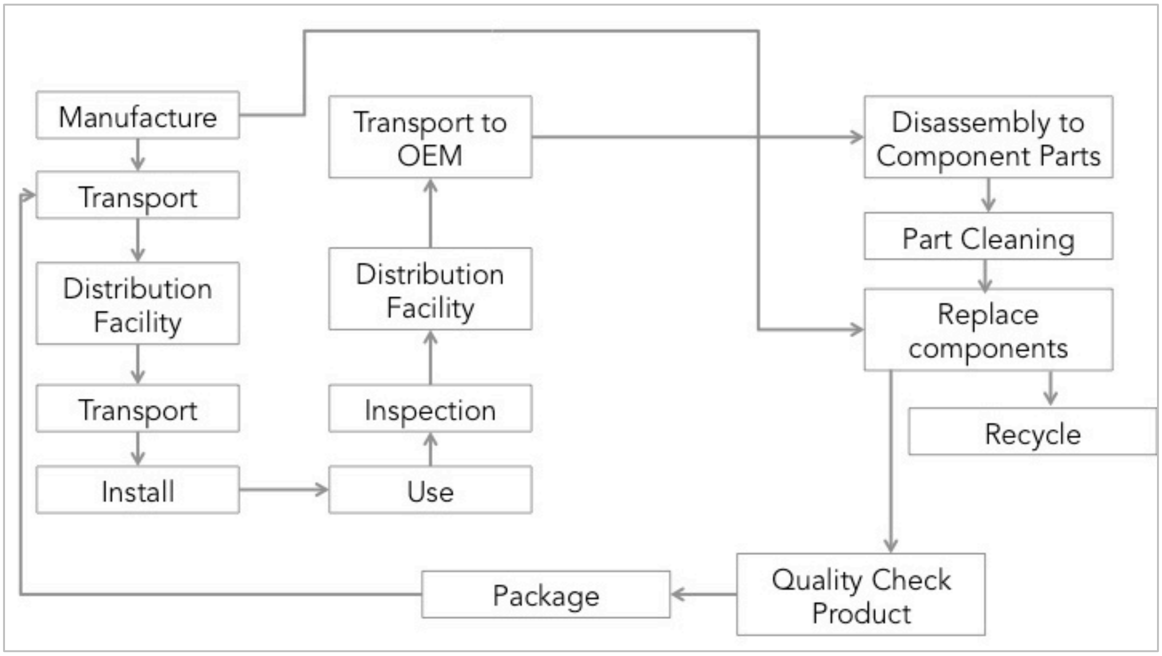


Figure 54: Process Flow Diagram for Remanufacturing

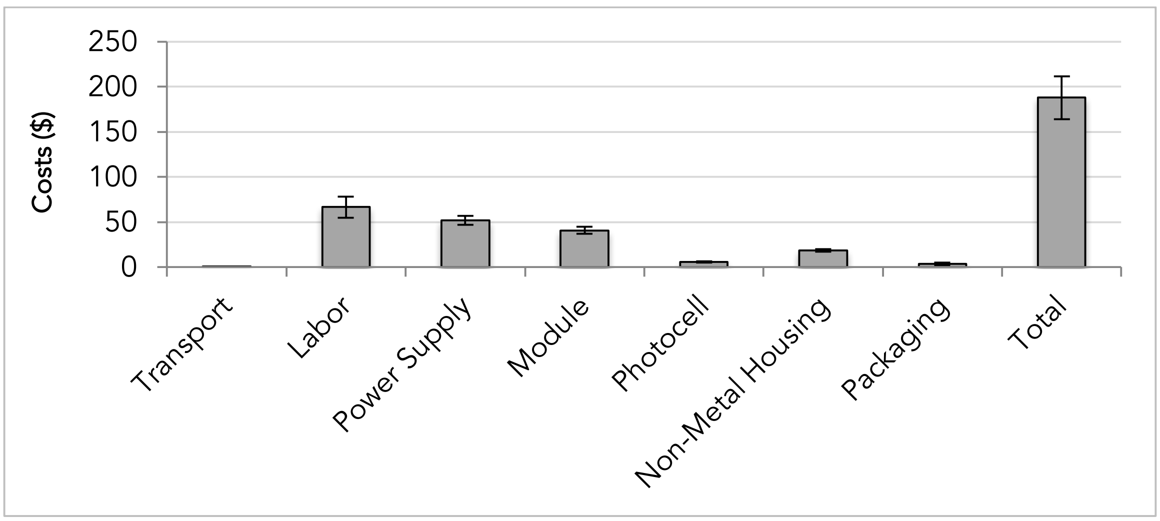


Figure 55: Emissions Incurred During Remanufacturing

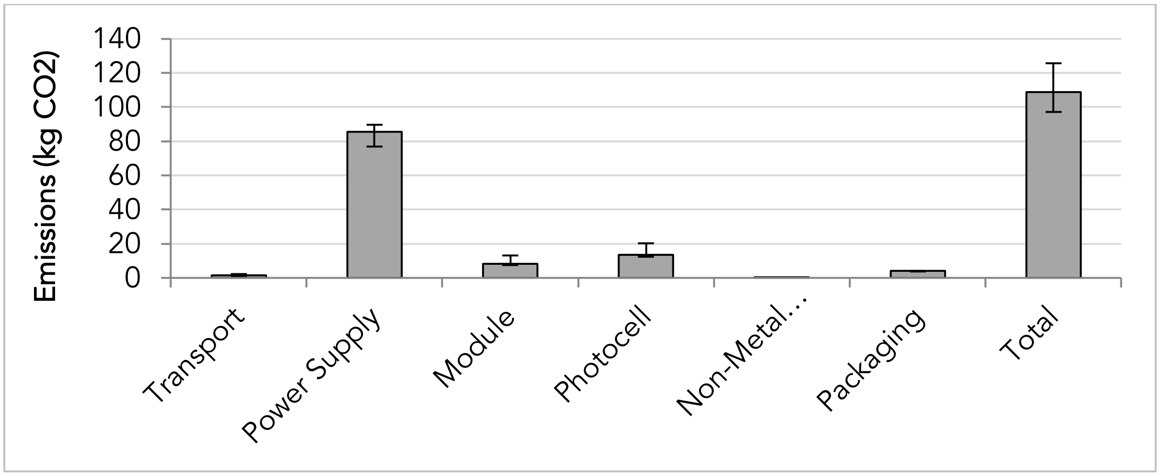


Figure 56: Emissions Incurred During Remanufacturing

As shown in Figure 55 and Figure 56, the costs and emissions incurred during remanufacturing are highly dependent on the product yield, though labor also influences the total cost. The main components that are salvageable within the street lighting product are the metal housing and the thermal heat sink. Particularly if they are designed to integrate with future products, remanufacturing of both can represent a significant emissions savings. However, the power supply, which is an emissions-intensive component, is not able to be remanufactured in its current form and is sent to hazardous waste recycling upon EOL. If sub-components of the power supply could be salvaged, further emission savings would be possible.

6.4.7 Recycling

Recycling is currently the main end-of-life strategy used within the street lighting industry and the process flow diagram is shown in Figure 57. When products fail or are replaced, they are returned to the local distribution facility and the component parts are separated to the best of the ability of the lighting manager into hazardous and non-hazardous recycling. If recycled, the components sent to non-hazardous recycling include the thermal management as well as the metal and non-metal housing. The electronics and power supply are sent to hazardous recycling. The costs and emissions are entirely dominated by the replacement materials needed. Table 17 provides an overview of how the costs change according to the recycling process yield assuming all of the non-hazardous materials listed are recycled.

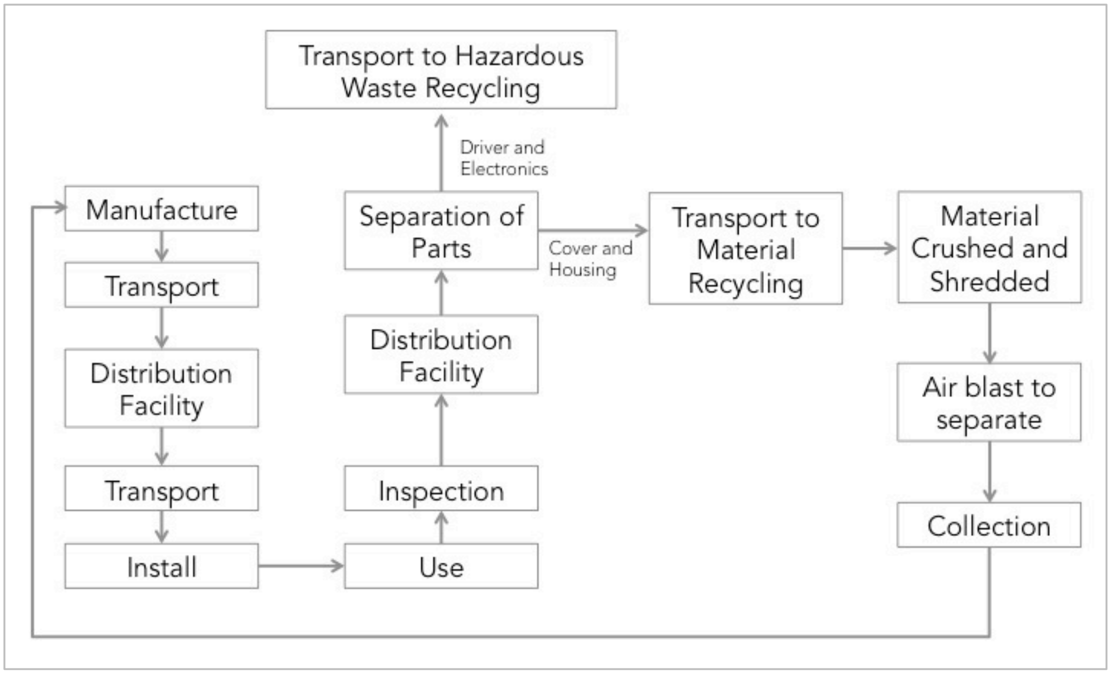


Figure 57: Process Flow Diagram for Recycling

Table 17: Possible Recycling Yields and Resulting Material Replacement Costs

Recycling Yield	Mass Fraction Recycled	Amount Virgin Material	Material Replacement Cost ($)
0.3	0.19	0.81	181.08
0.4	0.26	0.74	176.33
0.5	0.32	0.68	171.58
0.6	0.38	0.62	166.84
0.7	0.45	0.55	162.09
0.8	0.51	0.49	157.34

6.4.8 Landfill

A small proportion of currently installed street lighting products end up in the landfill, primarily due to existing commercial waste regulations. However, where regulations are not enforced enforcing behavior is challenging. The process flow diagram for landfilling is shown in Figure 58. The costs incurred throughout this process only involve the landfilling charge per kg of product disposed as well as the cost of material replacement, which in this case would be an entirely new product. As this analysis is only tracking carbon dioxide emissions, the environmental impacts associated with landfilling are incomplete. There are no direct carbon emissions associated with landfilling outside of transportation. If other environmental metrics including ecotoxicity and material scarcity were tracked landfilling would be determined as an even more environmentally detrimental option.

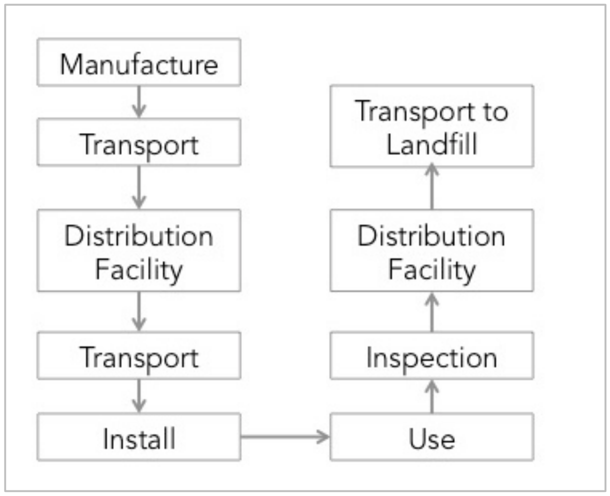


Figure 58: Process Flow Diagram for Landfill

6.5 Results and Discussion

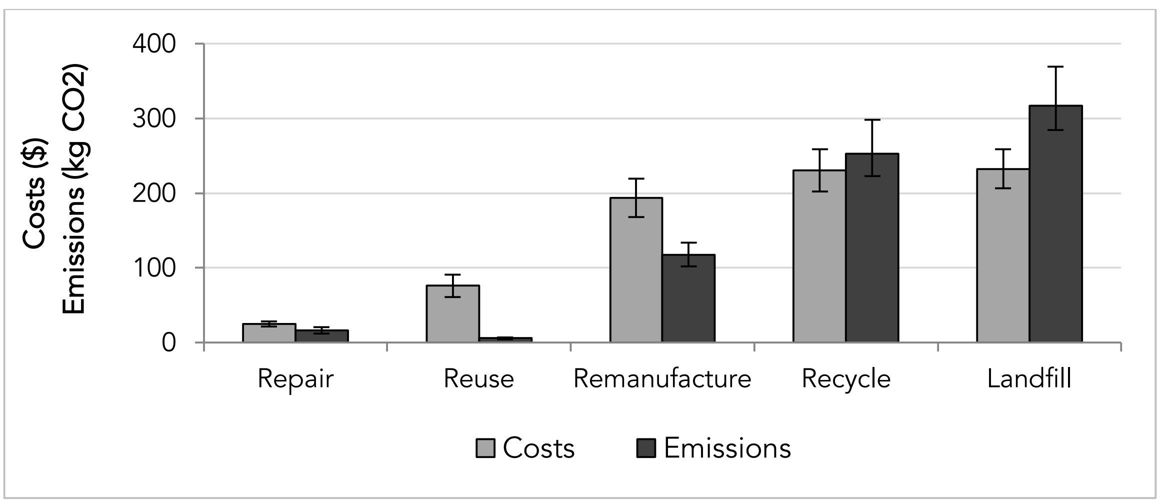


Figure 59: Comparative Analysis of End-of-Life Options for 87 W Leotek Street Light

Figure 59 provides a summary of the total costs and emissions associated with all end-of-life options for an 87 W sample street lighting product. The emissions and cost intensity of an end-of-life option follow the amount of material that is preserved over time as well as the amount of effort needed to recover materials. Though recycling is environmentally preferable over landfilling, the costs are nearly the same due to the low fraction of material that is recovered through recycling. While repair and reuse provide significant cost savings when compared to landfill or recycling, remanufacturing is only a marginal cost improvement. This is because of the labor involved in the remanufacturing process.

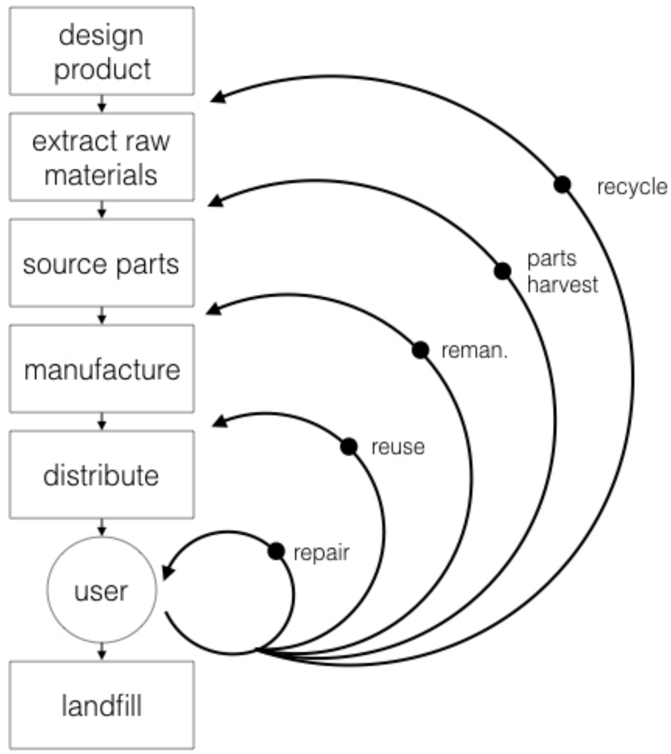


Figure 60: Circular Product System and End-of-Life Paths, Adapted from [1], [79]

The results shown in Figure 59 quantitatively support the ideas behind the circular product system diagram shown in Figure 60. Utilization of the inner loops, or repair and reuse, is encouraged within the circular economy as a means of extending product use times and maximizing resource utilization. However, few examples are available in either the academic literature or in case studies where all potential end-of-life options for a single product are quantitatively analyzed and compared from both a cost and environmental perspective.

Overall the summary provides insight into the incentives for pursuing an alternative end-of-life option. A challenge that still exists is that for most products, the cost and environmental differential between end-of-life options is unknown. Even among industry members, while the cost impacts are well-known, knowing how to calculate environmental impacts of materials and material usage remains an enigmatic process for many. This work provides a methodology for assessing the impacts associated with each path that can be extended to other products in the future. Finding ways to disseminate the benefits of material preservation as well as helping manufacturers know where they should prioritize component recovery potential could significantly help to increase the utilization of end-of-life options such as reuse and remanufacturing.

6.6 Simulation of Use and EOL Scenarios

Using the cost and emissions inventory, a series of simulations were run to understand the financial and environmental implications of potential replacement strategies. The scenarios simulated were chosen based on the results of the interviews discussed in Chapter 5. During the interviewers, the subjects responsible for purchasing revealed that the major ways purchasing happened was that either the manager (individual in a private organization or a collection of individuals in a public context) had a set rule to follow, e.g., replace every 5 years, or they waited until a product was technically or functionally obsolete and then facilitated replacement. Thus, the simulations show the result of set replacement schedules as well as the result if one kept the product installed throughout its entire expected lifespan.

The interviews also revealed that at present, the majority of products are recycled at end-of-life. However, new business models that sell light as a service rather than as a physical product are making end-of-life strategies such as reuse and remanufacture significantly more viable. In general, a service-based business model is that which emphasizes selling performance rather than a physical product [4]. When selling services, companies focus on optimizing utilization on and exploit resource efficiency to gain financial advantages and higher competitiveness. They do this by retaining ownership of the physical product and selling access to it over time. The potential benefits of lease-based businesses include fewer products and resources consumed and therefore, a reduction in associated emissions [165], [166].

In the lighting industry, Philips and other major OEMs have begun to pilot selling light as a service, guaranteeing a lux level (light per unit area) over a defined period of time [167]. As described by Calhoun et al. from the Rocky Mountain Institute, "The widespread adoption of 'Light as a Service' can dramatically accelerate the growth of the nascent LED retrofit industry toward its $63 billion potential, while having a material impact on the decarbonization of…buildings [168]." Selling light as a service would enable upgrading, reuse, and remanufacturing of products over time. However, each of those options comes with a constrained period of opportunity. From the interviews with remanufacturers and manufacturers, as well as from the literature on degradation, assumptions could be made around the viability of the end-of-life options.

Whereas statistical degradation was well-defined for incumbent street lighting technologies, with LEDs there are more factors to consider. Due to the fact that LEDs are sealed, dirt plays less of a role in lumen depreciation compared to high-pressure sodium or metal halide lamps [169]. LED products are less likely to fail catastrophically (i.e., produce no light) and instead exhibit parametric failure, slowly reducing light output over time. This can come as a result of the degradation of any system component including the LED array, the thermal management, the power supply electronics, as well as connection points [169]. At this time, a standard method for characterizing the per thousand hour degradation of LED street lights does not exist according to the Department of Energy. Within this work, the deterioration rate, d_o is set at .00685 / thousand hours in line with DOE estimates if no maintenance is performed. Within the model, performing maintenance assumes that the product is cleaned and resealed, and both the wires and photocell are replaced, as such are the common maintenance activities performed by industry. Maintenance is modeled to reduce the product deterioration, $\Delta d(k) = d_o - d(k)$, where d_{min} is .0022 and *d(k)* is defined by $d_{\min} \le d(k) \le d_o$ following the methods employed by Lee et al. [170]. While the deterioration rate in this context models the parametric failure, catastrophic failure is also possible, particularly in the first year of operation [171]. The result of these assumptions is that reuse is only viable if the product itself is less than 3 years old and remanufacturing if the product itself is less than 5 years old.

The purpose of the policy simulation is to show the costs and emissions incurred if one were to follow a rule of thumb and the products performed as expected, without seeking a means of optimality. Thus, a large number of scenarios are examined in order to assess the differences in impacts between proposed strategies. The results of the simulation are calculated by setting the decisions at each stage in the time horizon and then through accounting for costs and carbon emissions based on the inventory completed.

The results for all scenarios are shown as follows. The simulation runs for 10 years, and starts in a year during which all products are new. For work on when a new product should be purchased based on changing technological characteristics see Ochs et al. (2014) [172]. Figure 61 presents the results for the scenario where the product is replaced every 2 years and then reused in a different setting. Following replacement the newly installed product and it's corresponding energy usage represent the expected efficiency for a technology manufactured in that year. The repair status listed indicates whether or not the simulation took into account maintenance done on a product while installed. If 'No Repairs' is listed it means the scenario does not incorporate the cost of maintenance or repairs. Figure 62 shows the results for scenarios where the product is manufactured at EOL following 2-, 4-year replacement periods. Here the results show that while replacement every 4 years is a significantly more cost-effective strategy than replacing every 2 years, it is only marginally more effective from an environmental standpoint. This is because the expected gains in energy efficiency during the time period are non-trivial. Figure 63 and Figure 64 respectively show the results for scenarios where the product is recycled and landfilled at EOL. In both cases, the results show that the best cost and environmental option is to keep the product for it's entire useful life, in this case the full 10 years. This is an expected result as any financial or material benefit for recycling is small and it is non-existent when the product is landfilled at EOL.

A comparison across all scenarios run is shown in Figure 65. This allows for analysis of how different use and EOL scenarios result in different cost and environmental impacts. The results show that the lowest overall cost option is to keep the installed product for the entire 10 years of its useful life followed by recycling or landfilling at EOL (because at 10 years of age remanufacturing and reuse are no longer viable EOL strategies). However, when examined in terms of emissions, the least carbon-intensive option is to replace the product every 2 years and reuse the hardware at EOL. Due to the fact that the use phase is the predominate source of environmental impacts for LED street lighting, there exists an environmental incentive to upgrade to the newest technology that consumes less electricity during the use phase. This strategy proves particularly advantageous if it is possible to reuse the product in full (e.g., in an area that has not yet upgraded its lighting infrastructure.) If the product cannot be reused in full because of a broken part or a saturated reuse market, the results in Figure 65 show that upgrading to a new technology and remanufacturing the original product provides lower carbon impacts when compared to keeping the originally purchased product for its full life.

The results presented from the simulations indicate that there may be emissions-reductions associated with the implementation of ‘light as a service’ business models. As the market stands now, it does not make sense for lighting product managers and purchasers to pursue a frequent upgrade policy because of the capital costs associated with purchase and installation as well as the uncertainty of the reuse and remanufacturing markets. If a single entity retained ownership of the product and collected it with the intent of reuse and remanufacturing, the functional life could be extended for the materials comprising the products and customers could get better access to higher efficiency products over time.

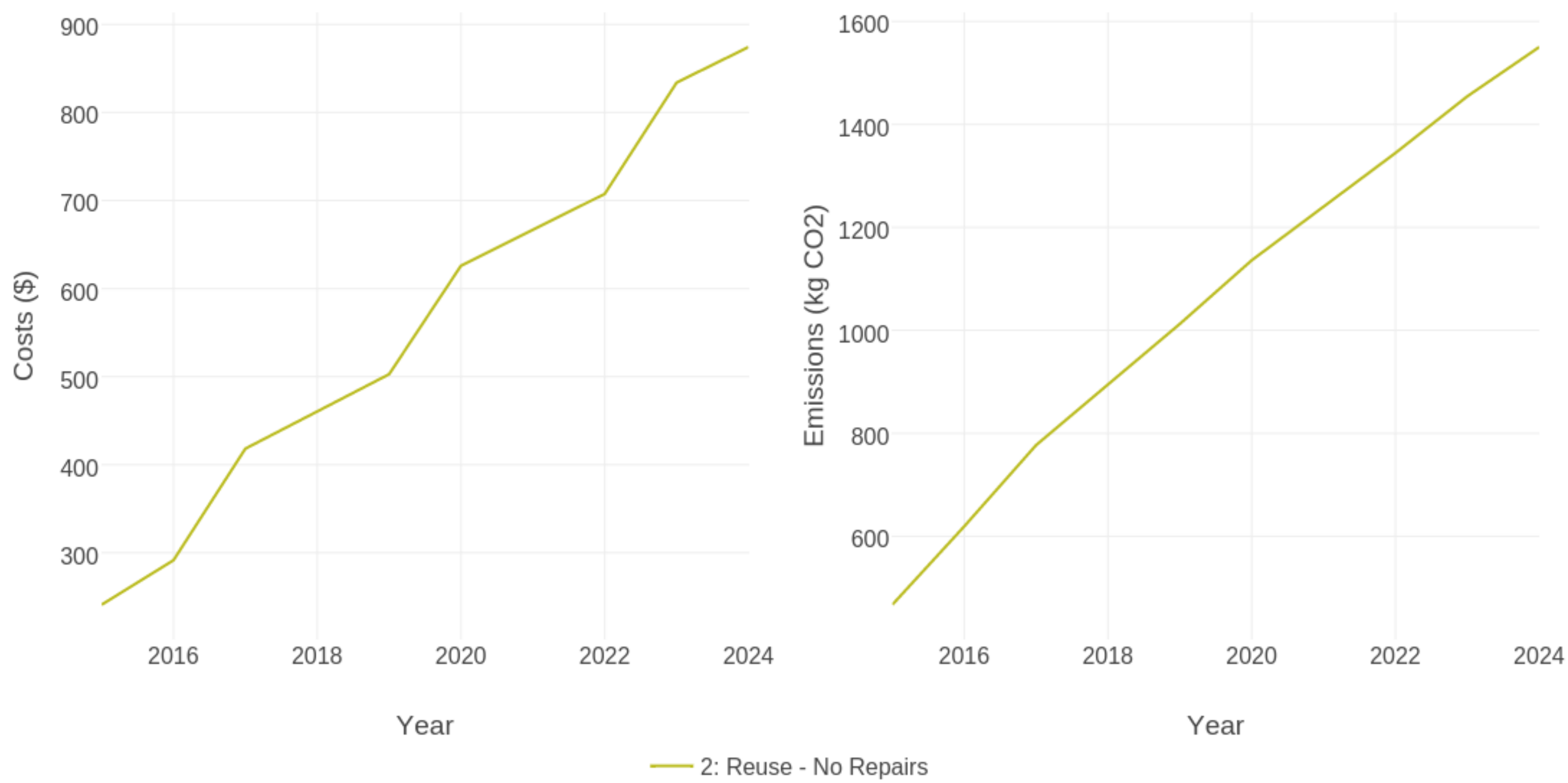


Figure 61: Reuse Scenario Analysis [# indicates frequency of replacement e.g. 2- product replaced every 2 years]

Figure 62: Remanufacturing Scenario Analysis [# indicates frequency of replacement e.g. 2- product replaced every 2 years]

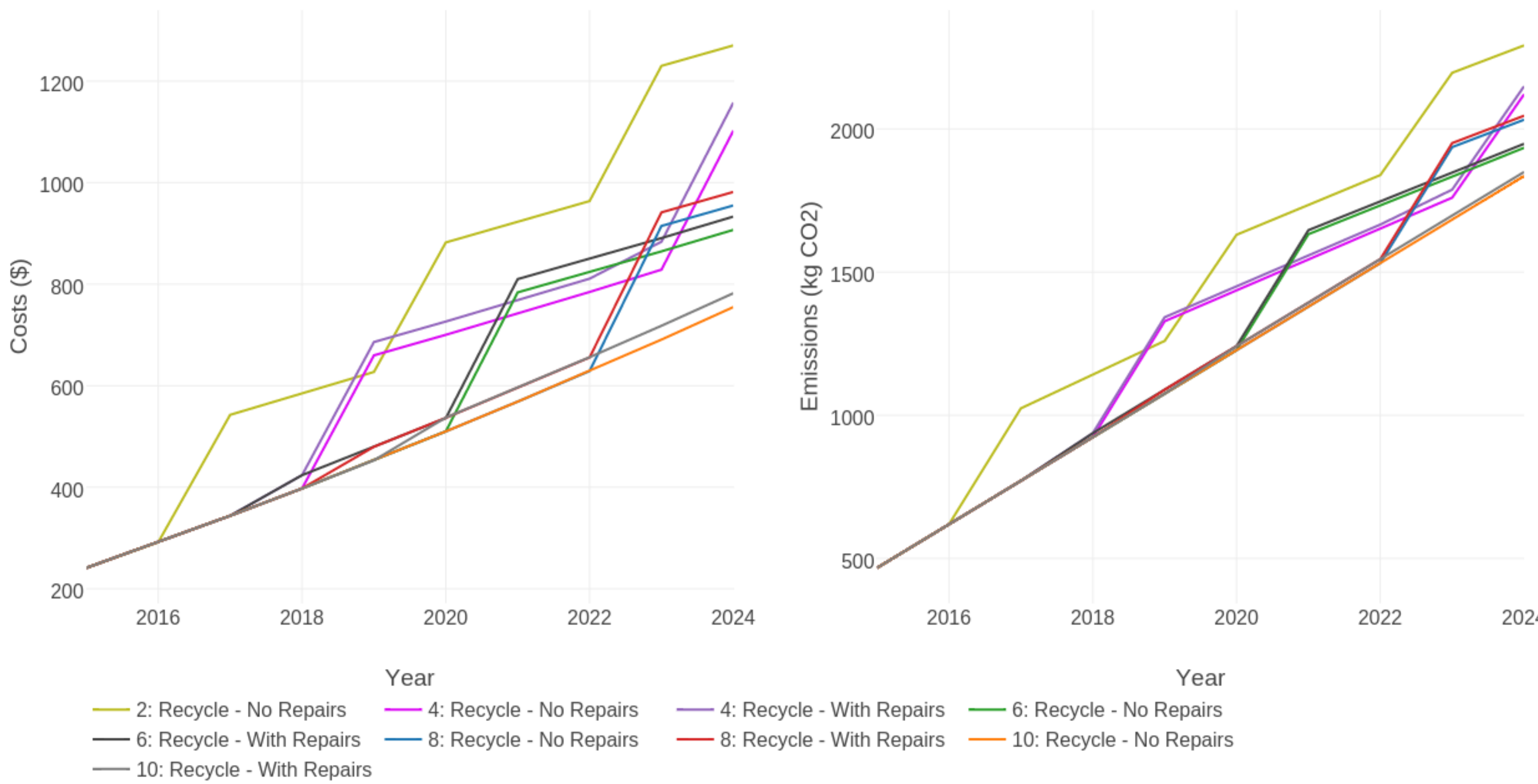


Figure 63: Recycling Scenario Analysis [# indicates frequency of replacement e.g. 2- product replaced every 2 years]

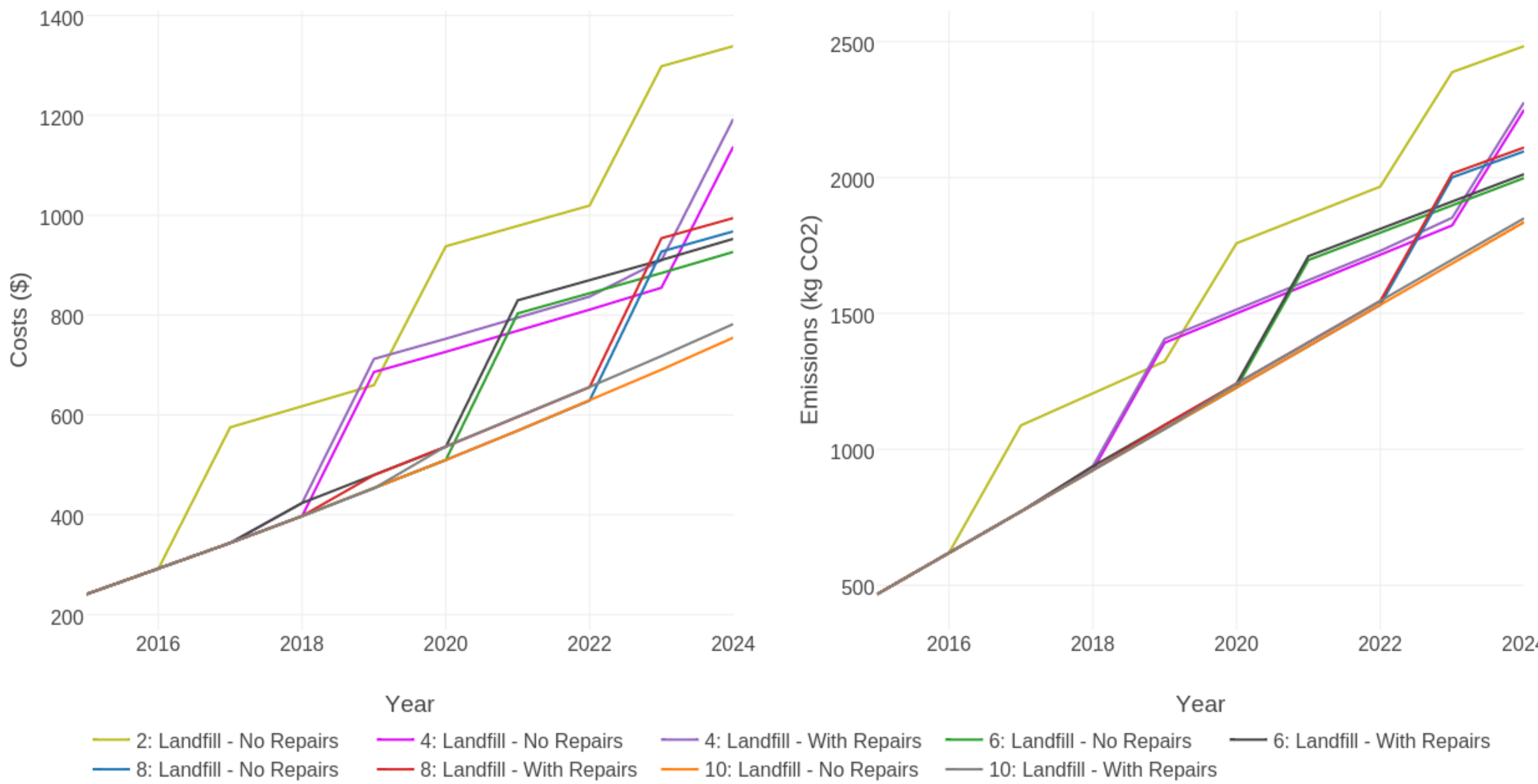


Figure 64: Landfill Scenario Analysis [# indicates frequency of replacement e.g. 2- product replaced every 2 years]

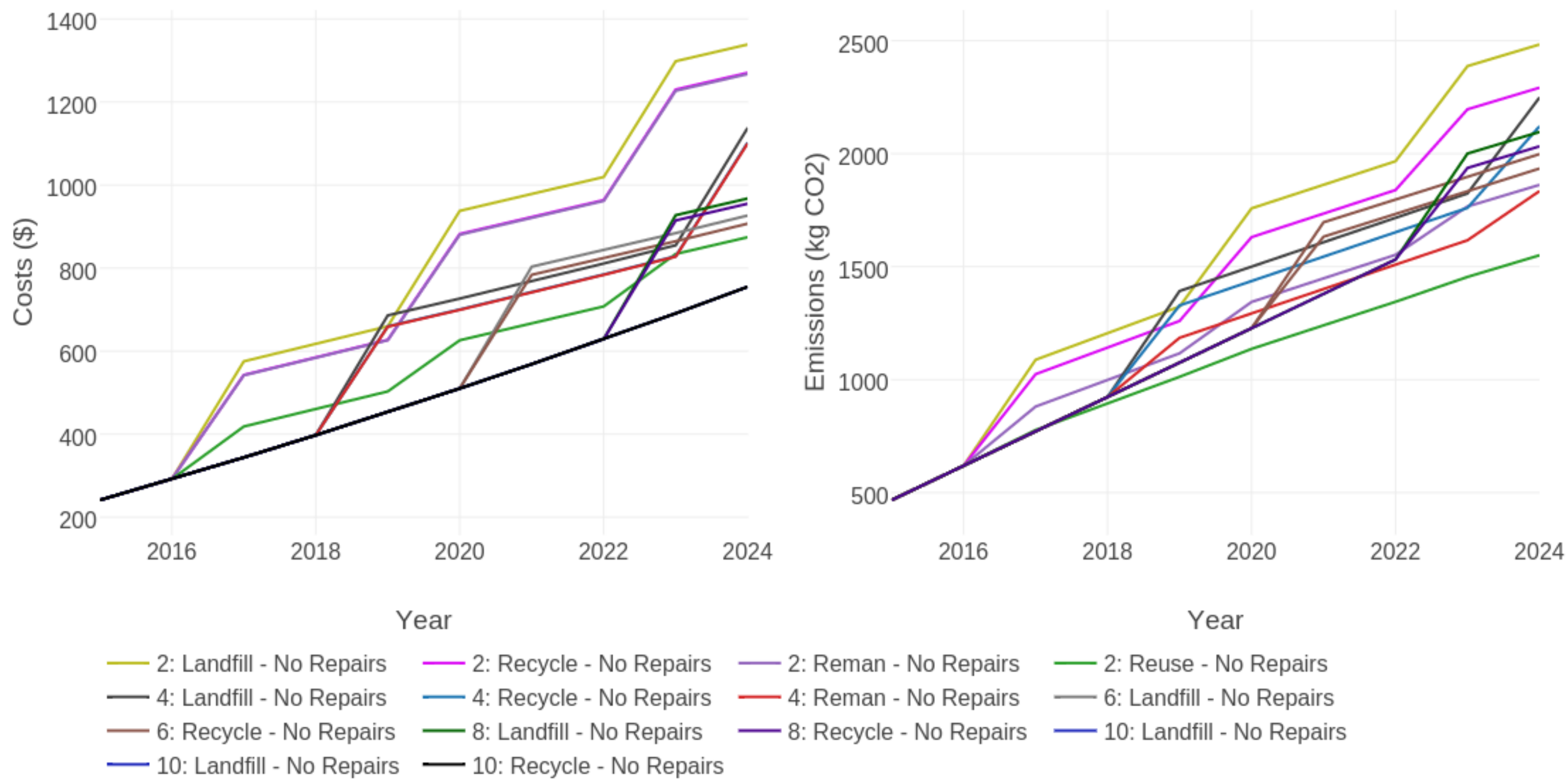


Figure 65: Comparison of EOL Scenario Analysis [# indicates frequency of replacement e.g. 2- product replaced every 2 years]

6.7 Analysis Limitations

Several limitations of this work exist. The impact inventory was conducted based on a single product. While SL 3 is a standard product used in many locations and by many municipalities, a wide variety of street lighting products exist within the U.S. today. Furthermore, the end-of-life process flow diagrams were constructed with the input of many stakeholders throughout the decision-making process however abnormalities could exist. The data to comprise the inventory was pulled from a diverse set of sources as shown in Table 15. If one wanted to improve data used for the study, a key focal area would be on the manufacturing process data, specifically material production costs, labor requirements, and typical transportation distances. While manufacturers contacted through this work provided general information around their process, they were resistant in providing specific process information, as that is core intellectual property. This is why it was critical to perform the product tear-downs to get a detailed understanding of all the materials comprising a specific product.

The simulations could be improved in several ways. For one, a greater number of simulations could have been run and presented that show the entire spectrum of use and EOL decisions. Additionally, a higher level of detail around the particular location in which the decisions are taking place could have been integrated in order to show the exact results for a single setting. The intent of such a tool is that decision makers will follow the process described and take steps to evaluate both the cost and environmental implications of technology management decisions under their jurisdiction. Furthermore, the simulation assumes the product will perform as expected and does not take into account the probability of failure or the discounting of future decisions.

6.8 Chapter Summary and Need for Future Work

The goal of this chapter was to characterize the cost and environmental impacts of use and end-of-life pathways for LED street lights. The work described here provides a novel contribution because throughout the lighting literature, EOL paths are often assumed to be only recycling and landfilling, or are left out of analyses entirely. This chapter provides a framework for assessing the economic and environmental impacts associated with alternative EOL strategies including reuse and remanufacturing. Furthermore, the chapter provides analysis around ‘light as a service’ business models, which can be employed by OEMs to make alternative EOL options viable for consumers. The simulations conducted show that while having set rules for replacement schedules can yield some benefit, often the option that minimizes economic impacts is far different than that which minimizes environmental impacts. The next steps for this work are to integrate the findings into a decision-making model that will help to elucidate the cost and environmental implications of technology management strategies. Other possible extensions of this work would be to assess how the results vary across different products installed in different geographic contexts. Such a study could help to answer the degree to which technology management strategies need to be contextualized to a given location, which could in turn influence policy initiatives. Additionally, it would be helpful to understand the potential size of the reuse market. The work presented here assumes that reuse is a viable option, however eventually the reuse market would potentially saturate. Understanding and integration of such market dynamics would strengthen the characterization of the reuse EOL strategy.

7 Markov Decision Process for LED Street Lights

7.1 Introduction

Consumers and manufacturers have seen the cost of LEDs rapidly decline over the past two decades, following the predication of Haitz et al. in 2000 [29]. Haitz proposed that the evolution of LED technology would follow a similar path to silicon-based processor technology, on which Moore's Law is based [173]. Accompanying the decrease in production cost for LEDs has been a growth in the lumen output per unit of energy consumption, or luminous efficacy with annual new products on the market and an increasing product lifespan. Within the street lighting sector, the quick evolution of technology paired with increasing appreciation of energy efficiency has led decision-makers to examine when should they upgrade technology as well as how long should they plan to keep products installed. Given the high volume of products purchased by street lighting customers, small gains in energy efficiency can yield to significant potential energy savings and reduced operating costs. For street lighting purchasers and operators, including municipalities and utilities, optimizing technology management can yield significant cost savings. Street light operation represents 60-80% of the electricity costs for municipalities, thus creating a strong incentive to adopt energy efficient products. However, cost-optimal decisions are not always environmentally optimal, when considering products' entire life-cycles.

In order to understand the total impacts of a given technology management strategy, a holistic approach should be adopted [135]. Management of technology in the context of street lighting involves designing the product requirements, material sourcing, manufacturing, installation, use, maintenance and repair. Once the product is replaced, management extends to reverse logistics and end-of-life processing. Throughout each phase, managers must rely on imperfect information to analyze trade-offs between capital costs of upgrades, potential savings from reduced energy consumption, public opinion of infrastructure changes, and uncertainty around the environmental benefits and consequences of end-of-life strategies. A tool is needed to elucidate the implications of decisions and reduce uncertainty for managers. The goal of such analysis is to determine a policy that minimizes expected costs and emissions for the system over a fixed time horizon.

Determination of an optimal technology management policy can be found through the use of a Markov decision process (MDP), which integrates probabilistic models to predict infrastructure degradation and the effect of maintenance and repair. It is commonly used within applications of sequential decision-making, particularly when uncertainty plays a role within the decision [174]. MDP has been widely employed throughout the literature to aid decision makers when examining wind farm management, pavement resurfacing, electric vehicle charging, equipment replacement, and sustainable product management [170], [175]–[179]. However, within the lighting industry, MDP has not been previously used to model replacement strategy in connection to EOL pathways. The model developed here is also novel in that it analyzes both economic and environmental impacts, as opposed to only one impact category. In this work, an MDP is used to evaluate the optimal replacement strategies for street lighting products and will additionally connect the result to the optimal EOL product trajectory, taking both costs and carbon emissions into account.

7.2 Background

Many researchers have studied the question of when to optimally replace products due to changes in efficiency, technology availability, and expected component failure [180]–[182]. Optimal replacement in the transportation industry in particular has been extensively examined [183], [184]. In the context of products, researchers have begun looking at optimal replacement but typically from either a cost or environmental perspective. For example, Intelkofer et al. examined the effect of varying lifespan on total life-cycle emissions [185]. Kim et al. put forth a planning framework to help decision-makers determine replacement schedules based on expected failure mechanisms and the environmental implications of disposing [186]. They did not consider any end-of-life strategies besides landfill and recycling. Meng [187] and Jun [188] examined this space by optimizing for the lowest cost end-of-life strategy. Both authors stated their work could be enhanced through the inclusion of environmental metrics.

In this work, cost and environmental implications of replacement decisions are analyzed here through stochastic dynamic programming. The critical advantage of using a Markov Decision Process (MDP) model is that the method incorporates the probability of degradation and failure of technology products as well as potential random failures. LED street lighting is subject to varying weather conditions that can lead to unexpected degradation of component parts and product failure. An example MDP model is shown in Figure 66 and a full description of the model can be found from Sutton and Barto [189]. The outside box represents a given time step. The circles represent the state (s) at the time step. The squares show the action (a) that is pursued at the time step. The diamond represents the reward (R) that is incurred and the triangle shows the transition probability function, which models the uncertainty of the next state, given the current state and action. Within the system modeled here, the transition probabilities and reward function are time dependent, though often both are time independent.

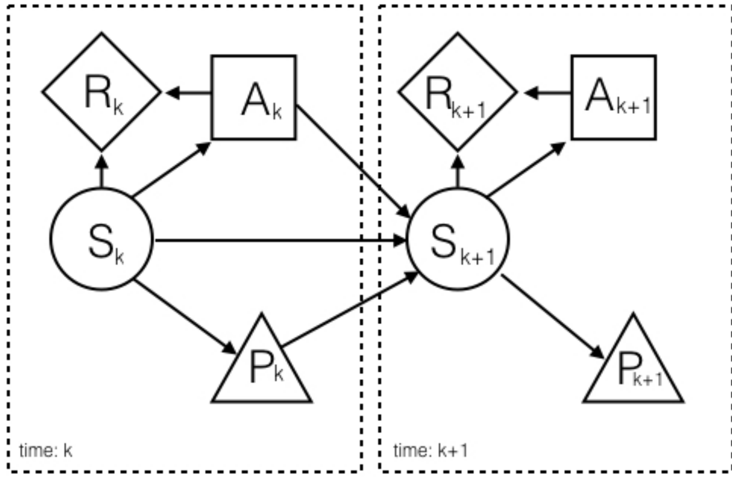


Figure 66: Model Markov Decision Process, Adapted from [175]

The model itself contains the Markov property, which entails that given the present state, the future state is independent of the past. As shown in Figure 66, the model is comprised of five primary components (S, A, P, R, γ).

- *S*: a finite number of system states
- *A*: a finite number of actions. The action taken influences both the reward at the current time-step, t, as well as the state in the future time step, t+1
- *P*: a transition probability matrix that is both action and state dependent. P(Y|X) is defined as the probability of event Y given event X. As such, the transition probability matrix is defined as $P(s' \mid s,a) = \Pr\{S_{t+1} = s' \mid S_t = s, A_t = a\}$.
- *R:* the reward function. Given the state and action at a time point, the agent receives a positive reward or benefit, or a negative reward or cost.
- γ : A discount factor, γ , of greater than 0 but up to and including 1 may also be incorporated to discount rewards in future time periods.

In a finite-time horizon MDP, the model is also defined by the number of time periods, N, that the study wishes to include. At each time step in the MDP, the state is assessed which influences the system to make decision A. Decision A moves to the next state S_{t+1} as determined with probability P. The value function $v_k(s)$ is the expected reward of a policy if the system starts in state *s*. The value function can be calculated according to the Bellman equation shown by Equation 7.1. The value function maximizes the reward at each time step while also summing the value function incurred at future optimal states. The optimal policy is that which maximizes the value function over the time period. The equation is solved recursively; the governing equation at the final time step in the period is shown in 7.2.

$$V_k(s) = \max_{a \in A}\left[R_k(s,a) + \gamma \sum_{s' \in S} P(s,a,s')V_k(s')\right] \qquad \text{for } k = 0, 1, \dots N$$

Eq. 7.1: Bellman Equation

$$V_N(s) = R_N(s)$$

Eq. 7.2: Value Function at Final Time Step

7.3 MDP Model Development for Street Lighting Management

The MDP model was used in this work to analyze product replacement in the context of LED street lighting as well as elucidate EOL strategy for the obsolete technology. The data source for the costs and carbon emissions associated with each state are sourced from the life-cycle assessment conducted in Chapter 6. A 10-year time horizon was chosen for examination, as it is a realistic estimation of the horizon decisions in the street lighting industry are based upon. An assumption is made that a usable product could fall in one of 3 States of Health (SOH), representing (1) good working condition, (2) a damaged state where the product remains repairable or (3) a critical failure state, where the product is beyond repair. The states as modeled here encompass both the level of light output and the condition of the physical product. For example, a model of higher resolution could separately model the state of the physical components (i.e., the metal cover, and the driver) as well as the quality of light that is produced. Here, both aspects were modeled together with these 3 representative states. Luminaires that degrade to less than 70% of initial lumens delivered are considered at end-of-life and are replaced. Potential for catastrophic failure (SOH 3) is modeled through the transition probability matrix $P_{k.}$ Catastrophic failure could occur if the light were struck by lightening or a car crashed into the pole causing the light to fall and shatter. It could also occur if the electronic components become significantly corroded due to weather exposure.

A total of 165 states, *s,* were modeled. At given time point, k, the installed light could be age [1:10], in year [1:10], and in SOH [1, 2, 3]. However, many states are considered inaccessible, e.g., if you are in year 8, you cannot have a product that is 10 years old. The model assumes that a new product is purchased and installed in the first time period examined. In each subsequent time point, there are 6 possible decisions made as shown in Table 18. Each decision is associated with both cost and environmental rewards that are state-dependent. The resulting reward matrix is then shaped as [States x Actions]. Notation in the reward equations is as follows: C represents the economic cost incurred, M is the value received upon material recovery, E are the environmental emissions (CO_2) incurred, and A are the emissions avoided upon material recovery.

Table 18: Decisions Available and Associated Cost and Environmental Rewards

Decision	Action	Reward	
1	Do Nothing	$	C_{use}[year-age]
		CO_2	E_{use}[year-age]
2	Maintenance	$	C_{use}[year-age]+C_{main} [year]
		CO_2	E_{use}[year-age]+E_{main} [year]
3	Replace + Reuse	$	C_{use}[year-age]+C_{new} [year]-M_{reuse}[SOH, age]
		CO_2	E_{use}[year-age]+E_{new} [year]-A_{reuse}[SOH, age]
4	Replace + Remanufacturing	$	C_{use}[year-age]+C_{new} [year]-M_{reman}[SOH, age]
		CO_2	E_{use}[year-age]+E_{new} [year]-A_{reman}[SOH, age]
5	Replace + Recycle	$	C_{use}[year-age]+C_{new} [year]-$M_{recycle}$[SOH, age]
		CO_2	C_{use}[year-age]+E_{new} [year]-$A_{recycle}$[SOH, age]
6	Replace + Landfill	$	C_{use}[year-age]+C_{new} [year]-$M_{landfill}$ [SOH, age]
		CO_2	E_{use}[year-age]+E_{new} [year]-$A_{recycle}$[SOH, age]

The model further incorporates a set of state and action dependent transition probabilities. The transition matrix is as follows:

$$p_{ij} = \Pr[X_{k+1} = j \mid X_k = i], \quad k = 0,1,\ldots N-1, \quad i,j \in s$$

The transition matrix was built using the results of a survey conducted by the DOE with manufacturers on expected failure rates of new products [171] and confirmed through data points collected from interviews conducted with lighting product managers. From current data, of newly installed products 5% will fail upon initial installation, and 3% from each year after until year 5. A product older than 5 years then has a 5% probability of failure until the end of its functional life at 10 years. As discussed previously, the failures are distributed between a damaged state where the product remains repairable and a critical failure state, where the product is beyond repair. In this case, the majority of the transition matrix is sparse, as the only states that are accessible are those in the subsequent year. A sample of a non-sparse portion of the transition matrix is found in Figure 67.

		t = 3								
		SOH 1			SOH 2			SOH 3		
t = 2	age	3	2	1	3	2	1	3	2	1
SOH 1	2	.97	0	0	.02	0	0	.01	0	0
SOH 1	1	0	.97	0	0	.02	0	0	.01	0
SOH 2	2	0	0	0	.50	0	0	.50	0	0
SOH 2	1	0	0	0	0	.50	0	0	.50	0
SOH 3	2	0	0	0	0	0	0	1	0	0
SOH 3	1	0	0	0	0	0	0	0	1	0

Figure 67: Transition Matrix for Decision to 'Do Nothing' between t = 2 and t = 3

Figure 67 shows an example portion of the transition matrix for Action 1 – 'Do Nothing' i.e., leave the product installed and do not perform maintenance, and allow to run as normal transitioning between time periods 2 and 3. Each element of the matrix represents a specific state, and the value is the likelihood that the product would be in that state in the subsequent time step (here, year 3). If in Year 2, the product has not been replaced since original purchase and is in SOH 1 (i.e., in good condition) there is a 97% likelihood that in the subsequent time period the product would still be in SOH 1. If the agent is choosing to do nothing, then the product will age one year and be at age 3 in time period 3. There is a 2% probability that the product will have failed in a way that is repairable, and a 1% probability that the product will have failed catastrophically. The distribution of probabilities between SOH 2 and 3 from a data perspective is arbitrary. As data parsing between those two states was unable to be obtained an assumption was made by the researcher that there is a higher likelihood that failure modes are repairable and lower likelihood that failures are catastrophic. For the same time period transition (i.e., from time period 2 to time period 3) there are five other 2x2 matrices representing the transition probabilities given the other management decisions. As described, the probabilities used depend on the age of the product, the product SOH, the year, and the management decision.

The final element needed for the MDP model construction is the discount factor. The per time-step discount factor weights future rewards. Valid values are greater than 0 up to and including 1. Within this model a discount factor of 1 was used because of the relatively short time period of inspection, implying that costs incurred at year 10 are as important to customers as costs incurred at year 1.

The MDP was implemented in Python and solved numerically solved using the MDPToolbox [190], a free and open-source set of functions to solve stochastic dynamic programs and MDPs. The MDPToolbox provides functions to solve using algorithms for policy iteration, value iteration, as well as other mechanisms. Here, a backwards induction algorithm was employed for this finite horizon problem.

7.4 Assessment Results and Discussion

7.4.1 Optimal Technology Management Strategies

The MDP model enables analysis of what decisions are optimal at each time period, given costs, likelihood of failure, and the discounting of decisions over time. The major outputs of the MDP model are the optimal cost and environmental policies to follow over the 10-year time period. The optimal replacement strategy results for a product that begins in SOH 1, i.e., in good condition, are shown in Figure 68

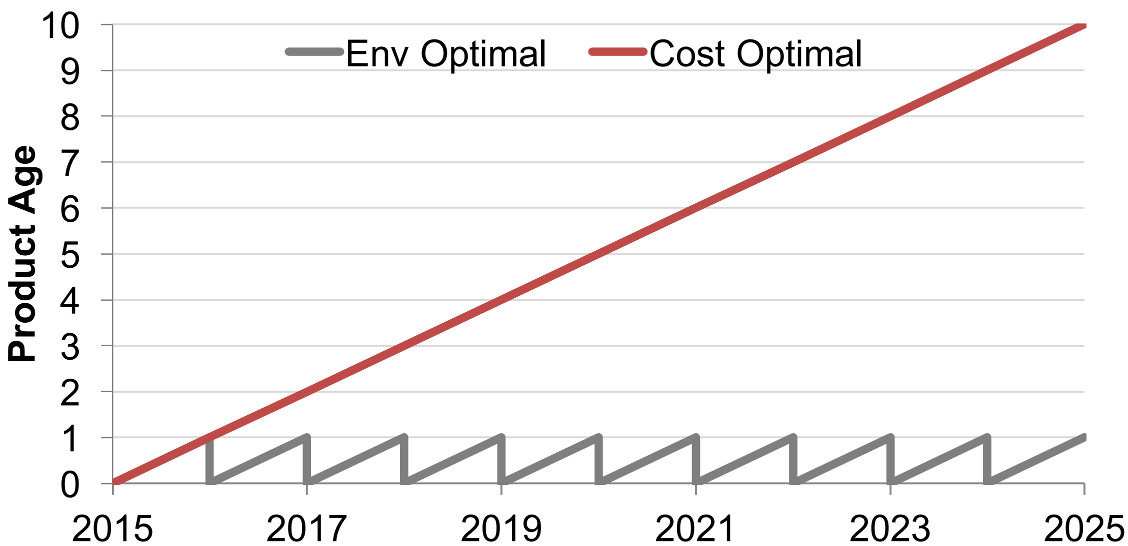


Figure 68: Environmental and Cost Optimal Replacement Policies from MDP Model

As shown in Figure 68, the best financial decision and the best environmental decision represent two drastically different policies. The strategy that leads to the lowest amount of carbon emissions according to the model is to replace the installed product every year and reuse the materials in their entirety. This could occur if the product is replaced to the latest efficiency and the one-year-old product is redistributed to a setting without the latest technology. From the financial perspective, the most cost efficient strategy is to keep the product through to the end of it's 10-year useful life and then recycle it at EOL. This is because the purchaser is then amortizing the capital cost of the product over a 10-year period. The findings here link back to prior observations about the potential benefits of 'lighting-as-a-service' business models. Having manufacturers retain product ownership of the physical assets while still providing users with the option to achieve the highest efficiency product may be one of the best options to help end users compromise between cost and environmental optimization.

Figure 69 provides a detailed examination of the costs and emissions incurred each year based on the optimal strategies. From the results, one can ascertain that there is a significant gap between the cost of the environmentally-optimal strategy and that of the cost-optimal strategy. In the current model, the purchaser does not reap the full reward of potential reuse of the product over time. They only get back a small fraction of their initial investment. If instead a service-based model was adopted, the customer could pay a flat rate to have access to the most updated technology if they so chose and the manufacturer could retain ownership of the resources and materials. This would help to ensure that materials are kept in circulation for as long as possible. The MDP results aligned with those of the simulations presented in Chapter 6. Originally, it was thought that because of the high use phase energy consumption, it would make sense to upgrade the product frequently from a cost perspective to capture efficiency savings. However, because the street lighting products considered are a relatively high-value product with high efficiency, the results instead show that the best decision is to keep the product throughout its entire useful life.

It is important to note that there may exist alternative motivations for upgrading and replacing products over time. Particularly in the street lighting context, LEDs and new products are seen as platforms with additional value propositions including options for security features, weather monitoring, and other technology applications. Thus, decision makers might choose to upgrade products despite both cost and/or environmental considerations in order to gain access to the benefits offered by connected lighting systems. Furthermore, the results may change as more locations transition to use of larger portions of renewable energy sources. As renewables become more integrated into the electricity grid, the level of carbon emissions associated with electricity consumption will significantly decrease. There would far less incentive to upgrade products for efficiency from a carbon perspective. This would shift decisions to instead focus on preserving the product throughout its usable lifespan.

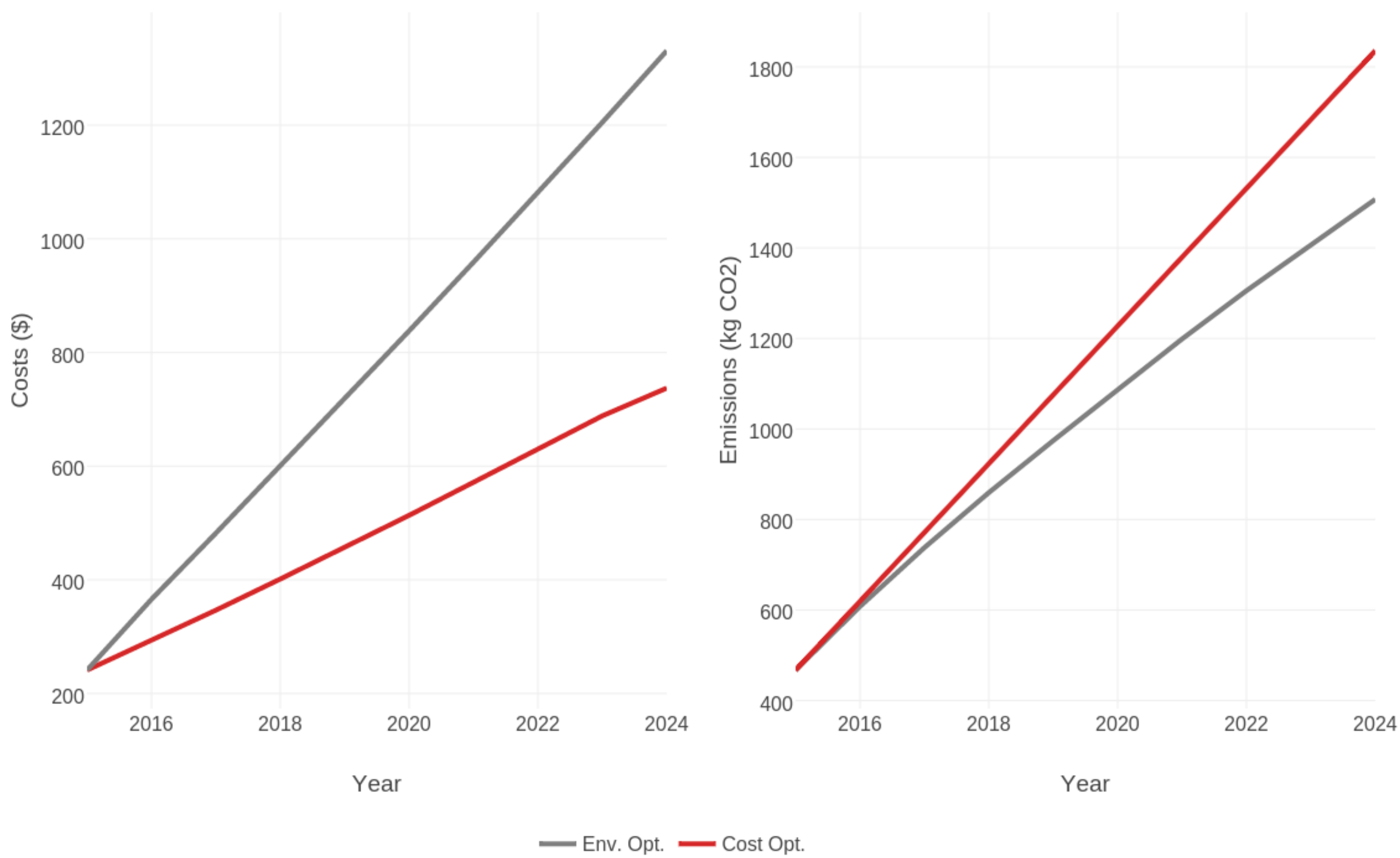


Figure 69: Total Costs and Emissions for Optimal Policies

7.4.2 Optimal Decisions for Each State

While the results in the previous section outline the optimal strategy given that the product starts in a particular state, it is feasible that the product could be in any of the possible 165 states throughout the 10-time period. Therefore, the MDP model was also used to assess the optimal decision given the state the product is in. Figure 70 provides a guide to show the possible management decisions available. As stated, not all decisions are accessible at all times based on age of the product and the associated viability of the EOL strategy.

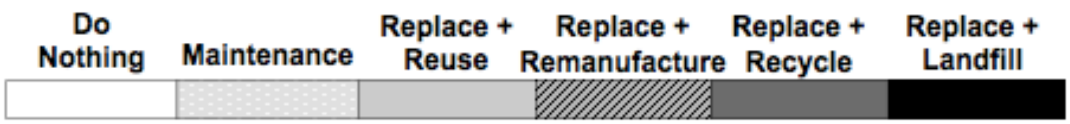
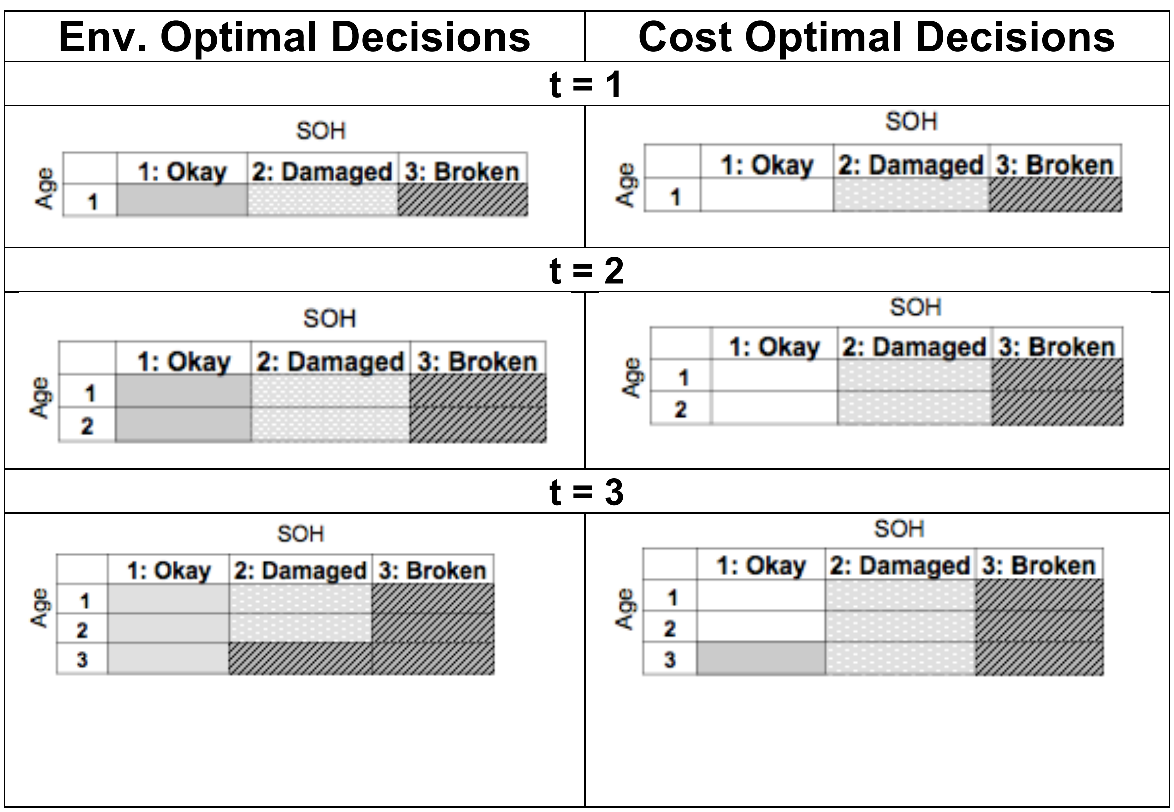
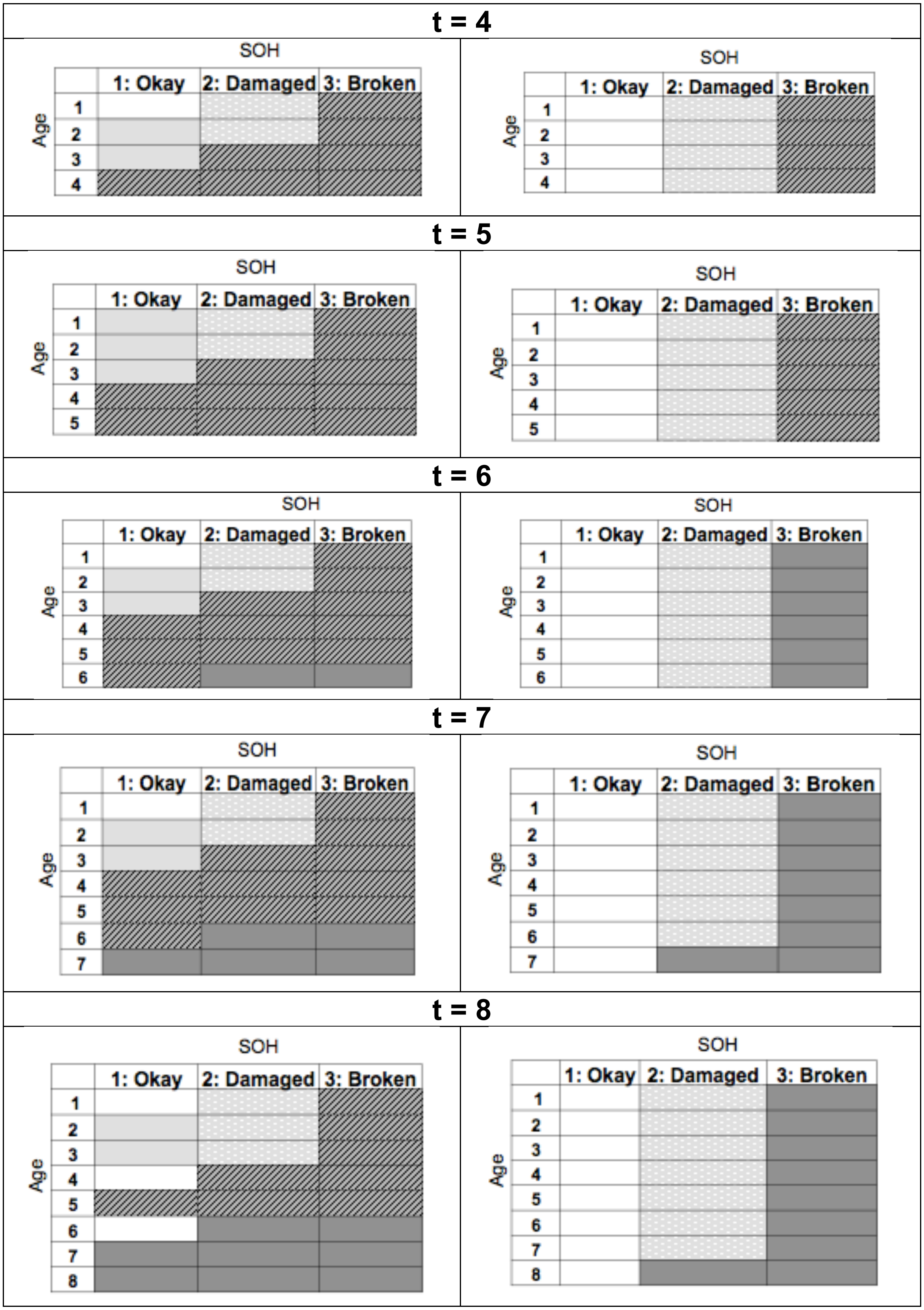


Figure 70: Possible Management Decisions at Each Time Period

Figure 71 shows the results for the cost- and environmentally-optimal decisions at each time period for each state that is accessible. Not all management strategies will follow the exact optimal path, as a product may fail spontaneously or be replaced after a non-optimal period of time.




t = 4
SOH
1: Okay
2: Damaged
3: Broken
Age
1
2
3
4
t = 5
SOH
1: Okay
2: Damaged
3: Broken
Age
1
2
3
4
5
t = 6
SOH
1: Okay
2: Damaged
3: Broken
Age
1
2
3
4
5
6
t = 7
SOH
1: Okay
2: Damaged
3: Broken
Age
1
2
3
4
5
6
7
t = 8
SOH
1: Okay
2: Damaged
3: Broken
Age
1
2
3
4
5
6
7
8

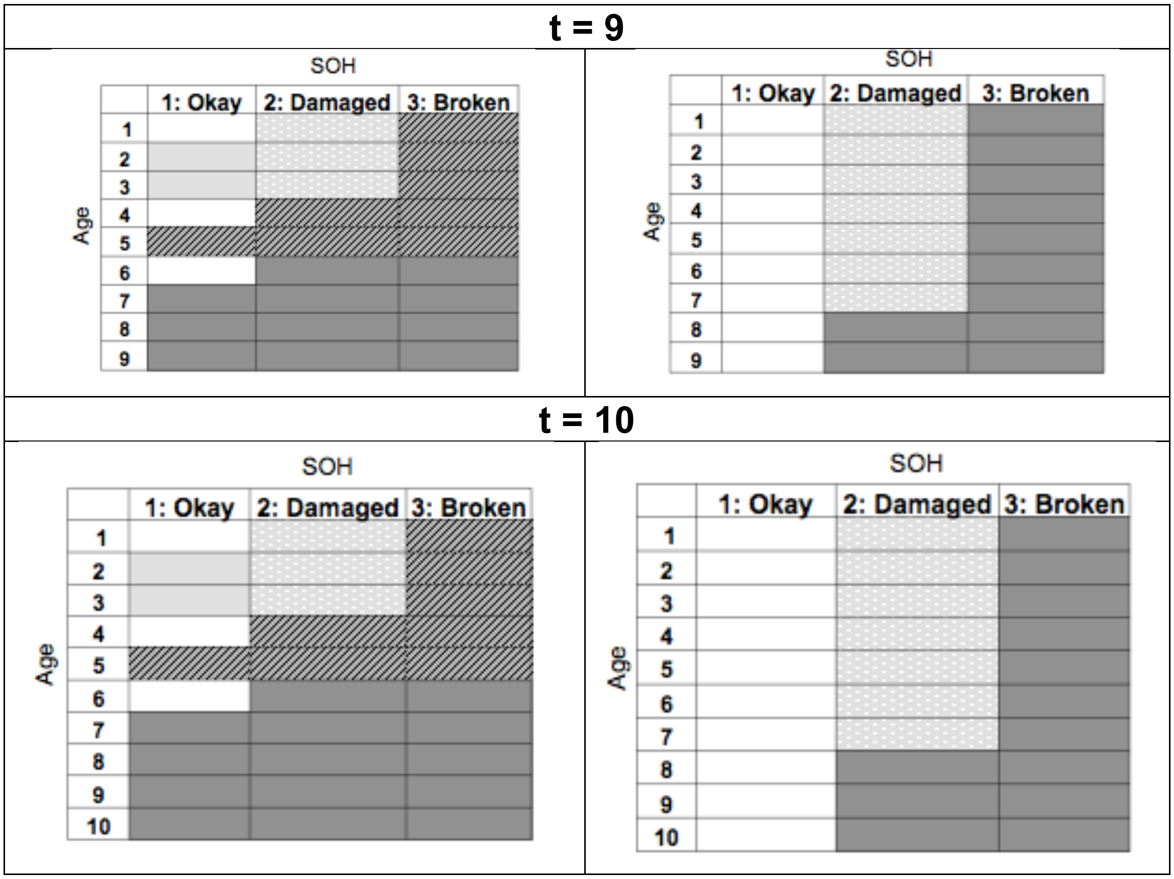


Figure 71: Optimal Decision Given Product State

For the environmentally-optimal decisions, the results still favor frequent replacement in order to capture energy efficiency gains in new products. However, the available EOL processing strategy changes depending on the age of the product. For products that are in good condition, the results indicate that the action of Do Nothing should be chosen if the product has reached the age of 4 or 6. This could be due to the fact that by that point the potential energy efficiency gain of the subsequent year product has reduced, making it advantageous to adopt a strategy of replacing every two years. After the product has aged past 6 years, the optimal decision is to replace and recycle at EOL. This could also be influenced by the fact that once a product has aged the probability of spontaneous failure increases as well. If a product is damaged and yet repairable, the results indicate that it should be repaired and not wholly replaced if less than 3 years old. Subsequently, the product should be replaced utilizing the EOL strategy that best preserves material properties, i.e., reuse then remanufacturing then recycling.

The cost-optimal decisions at each time point closely resemble those described in Section 7.4.1 for the 10-year time period. If the product is in SOH 1, then the optimal decision from a financial standpoint is to do nothing. Unlike the environmental-decisions, if the product is in SOH 2, the recommended decision is to perform maintenance until the product is 7 years in age and then replace it with recycling in all subsequent years. A second difference is that upon a product reaching SOH 3, or to where the product is broken, the optimal decision is to recycle. This is likely because the shipping costs associated with remanufacturing are higher than the cost to recycle, and the returned value for each strategy is relatively low.

An additional finding from this analysis is that the landfilling is never the cost-optimal decision. Even though the potential value returned from recycling is low, it is sufficient to make landfill a less cost-effective decision. This finding is significant to note as from the interviews it was revealed that several municipalities are continuing to landfill street lighting products at EOL because they do not see the financial benefit of recycling. More outreach is needed in those geographic locations to both ensure that recycling credits are being distributed properly and that individuals in technology management positions understand the potential cost benefits of EOL options that are also environmentally preferable.

7.5 Chapter Summary and Need for Future Work

The goal of this chapter was to describe the construction and execution of a Markov Decision Process model that yielded insight as to optimal technology management decisions. The MDP was used as a framework to discover methods to decrease the life cycle costs and emissions of street lights. First, the optimal cost and environmental strategies were presented for the case when a street lighting product started out in working condition. The results showed that from an environmental-perspective it is advantageous to upgrade frequently to the latest technology in order to capture efficiency gains. This strategy however is highly dependent on the availability of a reuse market. A major area of future work is to incorporate into the model the limits on reuse and remanufacturing from an economic perspective. Frequent replacement does however reinforce the need for product design to be increasingly oriented for end-of-life processing. As technology will continue to evolve rapidly, manufacturers must place emphasis on designing products with the intent of reuse of the embedded materials and resources over time. The incentive for doing so will increase as business models shift towards services and OEMs retain ownership of the product and then also retain responsibility for the product's EOL fate. For manufacturers, selling light as a service may offer an incentive to optimizing design for reuse that would not otherwise exist.

The results presented in this chapter further showed that from the cost perspective, the optimal strategy is to use the product for as long as possible in order to amortize the upfront capital costs over a longer period of time. Because the cost of electricity is relatively low, there exists less incentive to replace and capture efficiency gains. However, the analysis was run only for a single product. The cost dynamics for street lighting may change significantly when viewed at the scale of implementation, on the order of 100,000 lighting products. A final finding from the MDP is that landfilling is neither the cost nor environmentally optimal strategy regardless of product state. However, from the interviews conducted it is known that some municipalities within the United States are continuing to landfill products at EOL.

The model used here is meant to be a starting point for a larger examination of technology management decisions in the lighting context. From a higher level of abstraction, the results presented demonstrate that economics are not aligned with the environmental benefits. Further research is needed from the academic community to understand how stakeholders should navigate tradeoffs in the context of technology management. Those wishing to study how suitable a particular product is for EOL processing can also utilize this model. If a product is highly modular, then the processing steps at EOL may become significantly easier, and thus the benefit of remanufacturing would increase even more. The hope is that this model will be employed to inform future street lighting product design. Future work extending from this dissertation could also include improved modeling of the impacts of economies of scale in order to achieve a higher level of detail around the financial impacts of decisions.

8 Dissertation Summary and Contributions

This dissertation combined several fields in order to adopt a systems approach when analyzing environmentally benign product design and management decisions. Fields utilized include: (1) Mechanical Engineering – when considering how product design and technology characteristics enable end-of-life processing (2) Industrial Engineering – when examining end-of-life strategy logistics and finally (3) Civil and Environmental Engineering – when determining the environmental impacts of end-of-life strategies. Waste management systems are complex; the analysis would be incomplete if only viewed through the perspective of a single discipline. By combining research methods from ME, IE, and CEE, researchers are able to better understand the trade-offs that existing when making technology management decisions. LEDs currently represent a small percentage of the lighting waste stream, though the rate of LED disposal is poised to change rapidly in the next decade. Previous research on LEDs has focused on technology development and use phase energy savings. This research sought to examine the optimal design, use, and end-of-life strategy for LED lighting products. The end goal of the research was to provide a methodology for assessing the economic and environmental implications of design, ownership, and end-of-life strategies. Multiple dimensions of technology management were examined including:

- The role of product design in influencing the viability of end-of-life strategies include repair, reuse, remanufacturing, and recycling.
- The contextual factors that must be considered when designing products for use in developing countries.
- The socio-technical influencers that drive a product's end-of-life fate in the U.S. street lighting industry, as understood by diverse stakeholders throughout the product's lifecycle.
- The current methods to determine a replacement schedule for lighting technology and how they vary depending on owner perceptions and context characteristics.
- The economic and environmental implications of end-of-life strategies including the reverse logistics.
- The levers that exist for shifting the system dynamics to encourage more environmentally optimal end-of-life strategies.

Chapter 3 presented a new approach of assessing a product's suitability for end-of-life processing and provided guidelines for the lighting industry. The research identified what design characteristics should be altered to minimize environmental impacts at end-of-life. Within this chapter, 17 product designs were characterized to understand the extent to which the lighting industry is incorporating best practices from the design for environment and sustainability literature. The disassembly and characterization also helped the researchers to identify industry trends. A main contribution of this work is the development a novel method of product assessment that was applied to a set of lighting products. A further contribution is the recognition that a disconnect exists between suggested approaches to design and industry realization. It is well established that decisions made in the design and production phases have significant influence on a product's lifespan, use patterns, and trajectory upon obsolescence or failure. However, a company's desire to sell a high volume of products to consumers continues to be at odds with strategies to make products with features that enable a long life span. If a circular economy is to be achieved on a global scale, methods to overcome such disconnects, including moving to service-based business models, must be adopted by industry. How the complete transition to a closed-loop economy occurs still remains a massive research question.

As developing countries are on the verge of experiencing significant growth in middle class consumers, there is a need to examine how products designed for use in such contexts must shift to incorporate sustainability concerns. Chapter 4 examined the challenges associated with designing products for use in developing countries and the need for global sustainable development. A taxonomy of considerations was developed that can serve as a reference both for those wishing to research design within low-resource setting as well as OEMs looking to offer products in these emerging markets. The other contribution from this chapter is an examination of the manufacturing phase and how manufacturing influences a product's sustainability. Finally, the chapter assesses currently available products from the solar powered lantern market to understand where industry stands on incorporating principles of sustainable design.

Chapter 5 provides an examination of the complex factors influencing technology management strategies within a specific industry, LED street lighting. While economic and environmental impacts were a key focal area of this dissertation, technology management decisions for lighting are also influenced by local and federal policy, stakeholder opinion, public perception of change, financial mechanisms, and availability of end-of-life processing options. Interviews conducted with stakeholders throughout the decision-making chain yielded insight into the factors that are constraining implementation of optimal management decisions. This work yielded insight into the true problem context of lighting technology management and can serve future research by showing the diverse array of factors contributing to the complexity of decision-making.

Life-cycle assessment was employed to determine the economic and environmental impacts associated with end-of-life strategies for street lighting products. Chapter 6 contains the results of this characterization, using the material inventory developed within the prior chapter. This characterization is a significant contribution to the literature because prior LCA work in the lighting industry only considered the options of recycling and landfilling, and the end-of-life phase typically was assumed to be a percentage of the manufacturing process impacts. The work completed in this chapter shows the processes undertaken for each end-of-life strategy and their associated impacts. A key finding here is that for the case of street lighting products, the assessment results support what is typically qualitatively described within the circular economy literature. Thus, this work provides insight into the differential that must be overcome if the lighting industry is to move toward fully closed-loop product systems.

Chapter 7 describes the development of a Markov decision process model to assess optimal technology management with respect to environmental and economic impacts.

The model included consideration of future energy efficiency improvements as well as product degradation and failure projections. The main contribution of this chapter was identifying that the cost-optimal strategy is frequently not aligned with the environmentally-optimal management strategy. This is an important finding as it highlights the need to find strategies that can help consumers avoid tradeoffs between cost savings and environmental impacts incurred from increased levels of material waste. Many of the findings in this body of work support 'light as a service' business models to encourage manufacturers to proactively optimize the entire product chain rather than relying on end-users to make decisions based on complex cost and environmental systems. This is an area that should be explored more fully in the future both in the lighting context but also for other technology industries.

Research on end-of-life strategy can lead to lower life-cycle costs and environmental impacts as well as higher rates of material recovery and preservation. Furthermore, understanding the current challenges associated with disposal of a new technology can help to influence design and manufacturing processes for future product generations. As technology products continue to rapidly change and improve, continued examination of end-of-life is needed to ensure long-term sustainability.

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Appendix 1: Rubric for Product Evaluation

	# of Parts	Time of Disassem	Ease of Disassembly	Modularity	Material Complexity	Material Recovery Potential	Likely Material Recovery	Ease of Recycling
1	29+	>60 min	Less than half of parts disassembled, used complex tools	No parts able to be reconnected	2<=x	<50%	<50%	Less than half of metal and plastic parts isolated, high amounts of epoxy to scrape / remove
2	23-28	45-60 min	Most parts disassembled, used complex tools	Few parts able to be reconnected	1.5< x= <2	50 - 60 %	50 - 60 %	Most metal and plastic parts easy to isolate, high amounts of epoxy to scrape / remove
3	17-22	30-45 min	Most parts disassembled, no complex tools needed	Most parts fit together well, connections not epoxied or glued	1<x=<1.5	60 - 70%	60 - 70%	Most metal and plastic parts easy to isolate, some epoxy to scrape/remove

4	11-16	15-30 min	Able to be disassembled entirely, some complex tools needed	Most parts fit together well	.5<x=<1	70 - 80 %	70 - 80 %	Most metal and plastic parts easy to isolate, no epoxy to scrape/remove
5	10 or less	<15 min	Able to be disassembled entirely, no complex tools needed	All parts fit together easily, with easy connections	x=<.5	>80 %	>80 %	All metal and plastic parts easy to isolate, no epoxy to scrape/remove

Appendix 2: Interview Instrument

Organization type:

1. What kinds of lighting applications does your organization manage?
2. Does your organization own lamps? If so, approximately how many?
   a. If you lease or rent lamps what influence do you have on specification?
   b. Besides energy efficiency, are there other sustainability criteria you build-in to your program?
3. Have you converted your lamps to LEDs? If so, what percentage? How many products is this? When?
   a. What challenges have you encountered during the installation and maintenance of the LEDs? How have you adapted to address these concerns?
   b. Have you seen any failures earlier than expected?
   c. How do you handle such failures?
4. When making decisions to convert to LEDs..
   a. What are your key priorities or requirements?
   b. What are the most critical barriers to overcome..
      i. in making the decision?
      ii. in specifying?
      iii. in installation?
5. Describe for me how your maintenance processes work or how lamp maintenance is carried out.
6. Have you explored the opportunity where customers can upgrade their lamps to the latest features every few years?
7. What do you do with retired or failed lamps? How do you help to ensure sustainable product end-of-life decisions are made?
   a. Is this different for LED luminaires vs. more traditional lighting products?
8. Would you consider sending products, where there are warranty/ performance issues with LED luminaire, to be re-manufactured and brought back to full OEM spec?
9. How does you manage lighting products removed as part of the retrofits you incentivize?
10. What changes to the products themselves could lead to better end-of-life management in your opinion?
11. What do you think is the role of OEMs in managing products at end-of-life, if any?
12. What key features would make your management of lighting assets easier and more cost effective? Would you consider lower warranties, if the cost was lower?

Appendix 3: IRB Protocol Approval

UNIVERSITY OF CALIFORNIA AT BERKELEY

BERKELEY • DAVIS • IRVINE • LOS ANGELES • MERCED • RIVERSIDE • SAN DIEGO

SAN FRANCISCO • SANTA BARBARA • SANTA CRUZ

COMMITTEE FOR PROTECTION OF HUMAN SUBJECTS
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Website: http://cphs.berkeley.edu
FWA#00006252

NOTICE OF APPROVAL FOR HUMAN RESEARCH

DATE:	*November 28, 2016*
TO:	*Sara BECKMAN, Haas Sch of Bus*
	Rachel Dzombak, Civ Engr/CEE
CPHS PROTOCOL NUMBER:	*2016-09-9195*
CPHS PROTOCOL TITLE:	*Decision-Making Tools for Environmental Sustainability*
FUNDING SOURCE(S):	*Funding Type# Graduate Fellowship, Funding Type# Graduate Fellowship*

A(n) *new* application was submitted for the above-referenced protocol. Your submission has been reviewed by the Office for Protection of Human Subjects (OPHS) and granted exemption, as it satisfies the Committee's requirements under category *2* of the federal regulations.

Effective Date: *November 28, 2016*

Amendments/Modifications: Any change in the design, conduct, or key personnel of this research must be approved by the OPHS ***prior*** to implementation. For more information, see Amend/Modify an Approved Protocol.

Please note that although your research has been deemed exempt from full committee and subcommittee review, you still have a responsibility to protect your subjects, and the research should be conducted in accordance with the principles of the Belmont Report. Download the Belmont Report at this link: www.hhs.gov/ohrp/humansubjects/guidance/belmont.html.

This approval is issued under University of California, Berkeley Federalwide Assurance #00006252.

If you have any questions about this matter, please contact the OPHS staff at 642-7461 or email ophs@berkeley.edu .

Sincerely,

Rebecca ARMSTRONG
Committee for Protection of Human Subjects

Appendix 4: Material Inventory LED Street Light

LED Module		
Material / Process	**Amount**	**Unit**
Aluminum removed by drilling, conventional	38	g
Synthetic rubber	20	g
Aluminum removed by milling, average	164	g
Light emitting diode	5	g
Polycarbonate	16.6	g
Steel, chromium steel 18/8	10	g
Chromium steel product manufacturing, average metal working	139	g
Aluminum removed by turning, average, computer numerical controlled	75	g
Metal working, average for chromium steel product manufacturing	4	g
Metal working, average for chromium steel product manufacturing	20	g
Metal working, average for aluminum product manufacturing	1826	g
Electricity, medium voltage	189	kWh
Heat, central or small-scale, natural gas,	208	kWh
Heat, light fuel oil, at industrial furnace	52	kWh

Non-metal Housing		
Material / Process	**Amount**	**Unit**
Acrylonitrile-butadiene-styrene copolymer	35	g
Injection moulding	35	g

Packaging		
Material / Process	**Amount**	**Unit**
Packaging film, low density polyethylene	30	g
Corrugated board box	1168	g

Power Supply		
Material / Process	**Amount**	**Unit**
Copper	102	g
Aluminum removed by drilling, computer numerical controlled	11	g
Polybutadiene	6	g
Nylon 6-6	27	g
Acrylonitrile-butadiene-styrene copolymer	50	g
Aluminum, cast alloy	21	g
Chromium steel 18/8, at plant	6	g
Electronic component, active, unspecified	68	g
Steel, chromium steel 18/8	16	g
Acrylonitrile-butadiene-styrene copolymer	184	g
Capacitor, film type, for through-hole mounting	8.27	g
Cable, unspecified	1.82	g
Capacitor, electrolyte type, < 2cm height	1.13	g
Capacitor, electrolyte type, > 2cm height	13.7	g
Diode, glass-, for through-hole mounting	0.553	g
Resistor, metal film type, through-hole mounting	1.17	g
Transformer, low voltage use	6.78	g
Electronic component, passive, unspecified	0.976	g
Resistor, auxiliaries and energy use	1.51	g
Resistor, surface-mounted	0.404	g
Diode, glass-, for surface-mounting	0.171	g
Integrated circuit, logic type	0.129	g
Capacitor, for surface-mounting	0.518	g
Electronic component, active, unspecified	0.0257	g
Transistor, surface-mounted	0.426	g
Electronic component, active, unspecified	0.0171	g

Diode, auxiliaries and energy use	0.133	g
Nylon 6-6, glass-filled	193	g
Steel, chromium steel 18/8	7.41	g
Copper	7.05	g
Tin	0.261	g
Copper	42.5	g
Printed wiring board, for surface mounting, Pb free surface	0.00647	m2
Printed wiring board, for surface mounting, Pb free surface	0.00647	m2
Wire drawing, copper	102	g
Injection moulding	6	g
Injection moulding	27	g
Injection moulding	50	g
Aluminum product manufacturing, average metal working	21	g
Chromium steel product manufacturing, average metal working	6	g
Aluminum removed by drilling, conventional	11	g
Metal working, average for steel product manufacturing	16	g
Injection moulding {GLO}| market for	184	g
Metal working, average for chromium steel product manufacturing	7.41	g
Wire drawing, copper	42.5	kg
Mounting, through-hole technology, Pb-free solder	0.00129	m2
Mounting, surface mount technology, Pb-free solder	0.00129	m2

* power supply modeled using tear-down, manufacturer information and Takhamo 2015

Photocell		
Material / Process	**Amount**	**Unit**
Polycarbonate	23	g
Acrylonitrile-butadiene-styrene copolymer	1	g
Printed wiring board, surface mounted, unspecified, Pb free	54	g
Plug, inlet and outlet, for network cable	1	piece
Synthetic rubber	2	g
Injection moulding	23	g
Injection moulding	1	g

Thermal Management		
Material / Process	**Amount**	**Unit**
Aluminum removed by milling, large parts	120	g
Aluminum, primary, ingot	1936	g
Steel, chromium steel 18/8	42	g
Aluminum removed by milling, large parts	120	g
Metal working, average for aluminum product manufacturing	1936	g
Metal working, average for steel product manufacturing	42	g