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Exploring Cost and Environmental Implications of Optimal Technology Management Strategies in the Street Lighting Industry

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A B S T R A C T

The market for solid-state lighting (SSL) systems has expanded 40-fold in installed lamps since 2001. At the same time, systems which preserve materials over time and promote material reuse are getting increasing attention in light of calls for reducing consumption of natural resources. As new lighting 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 (EOL) fate. Lighting-as-a-service (LaaS) business models have emerged as a potential strategy for preserving the materials embedded in lighting products. In this paper, we examine the cost and environmental implications of technology management decisions in the context of the street lighting industry, employing life-cycle assessment and a Markov Decision Process model. The goal of the research is to determine a policy that minimizes expected costs and emissions for the system over a fixed time horizon thus reducing uncertainty for managers. The model used in the paper evaluates the optimal replacement strategies for street lighting products and additionally connects the result to the optimal EOL product trajectory, taking both costs and carbon emissions into account. In doing so, we are able to more deeply understand the role that LaaS business models might play in enabling closed-loop systems within the street lighting industry.

1. Introduction

In the United States, lighting constitutes approximately 18% of total electricity consumption (Energy Information Agency, 2015) as well as 21% of commercial electricity consumption, which equals 350 TW h per year (Navigant Consulting, 2012a). As the number of initiatives to reduce carbon emission increases, implementation of new energy efficient technologies is regarded as a primary method to reduce environmental impacts (Geller et al., 2006; Morgan et al., 2009; Pacala, 2004; Rubin, 1992). As a result, the U.S. market for solid-state lighting (SSL) systems has expanded 40-fold in installed lamps since 2001 (Navigant Consulting, 2012a). 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, democratizing the availability of LEDs and expanding their potential to be incorporated into product systems (Haitz et al., 2000). As a result, development of LEDs has progressed rapidly especially during the last decade. Research and government initiatives have spurred improvements in lumen efficiency, lighting quality, and product life span (Navigant Consulting, 2012b).

In addition to these technological improvements, 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 (Haitz et al., 2000). Accompanying the decrease in production cost for LEDs, there has been a growth in the lumen output[1] per unit of energy consumption, or luminous efficacy (shown in Fig. 1) with new products on the market annually and an increasing product lifespan when compared to incumbent technologies (such as incandescent or compact fluorescent luminaires[2] in the residential sector and high pressure sodium or metal halide luminaires in the outdoor lighting sector) (Penning et al., 2016).

Overall, LED lamps consume approximately 3 TW h of electricity per year, which accounts for less than 0.5 percent of national lighting energy use (Navigant Consulting, 2012a). Nevertheless, LED lighting has penetrated into the commercial, residential, and outdoor lighting sectors significantly since 2010 and made 8 percent of the overall lighting inventory. In 2012, the EPA estimated that over 44 million street and roadway lights were in use throughout the United States. 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. However, over the past five years, the product portfolio used in the U.S. has begun to shift towards LED quickly. As a result of the long lifetime and high efficacy of LED products, the outdoor sector has seen the highest LED penetration, at 22 percent of

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[1] Lumen is SI unit of luminous flux, or the amount of light a source emits per unit of time.
[2] The luminaire is a complete lighting unit with hardware elements protecting light-emitting components

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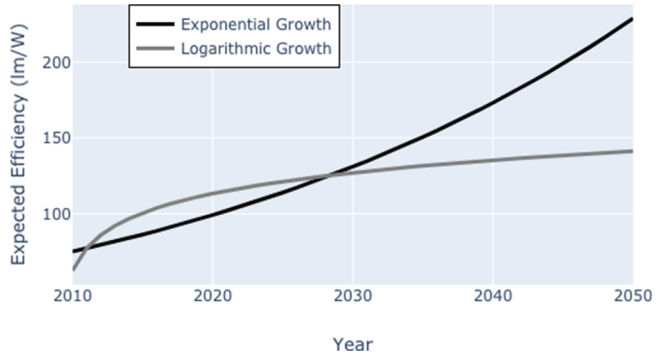

Fig. 1. Projected Efficacy Increases (lm/W) from U.S. DOE (Penning et al., 2016).

lighting inventory. The outdoor application which has seen the highest percentage LED penetration and the highest number of installed LED lamp is traffic signals, followed by parking and roadway applications (Navigant Consulting, 2012a).

A challenge in the lighting sector, and in any sector experiencing rapid technology change, is the decision of when to replace incumbent products for the latest and greatest technology. The quick evolution of lighting technology paired with an increasing importance of energy efficiency has led decision-makers to examine when they should upgrade to more efficient lighting technology as well as how long they should plan to keep the products installed. Given the high volume of products purchased by street lighting customers, including municipalities and utilities, small gains in energy efficiency can yield to significant potential energy savings and reduced operating costs. Operation of street lights can represent 60-80% of the electricity costs for municipalities, thus creating a strong incentive to adopt energy efficient products (Elejoste et al., 2013; Fiaschi et al., 2012). However, with technology replacement emerges a critical question for decision makers: How does one navigate the trade-off between: (1) replacing an installed light with a new product to gain a higher energy efficiency or (2) keeping a product installed through its usable life? The decision of product upgrade has both cost and environmental implications as one must consider the cost of new technology, the potential energy savings in terms of costs and emissions, as well as the environmental impact caused by the waste stream associated with the obsolete technology. Circular, or closed-loop systems eliminate waste from product cycles by redirecting materials to new applications at the end of a use phase (McDonough and Braungart, 2002). Reducing this waste stream is important, early estimates for waste from LED upgrades in the residential sector range have been estimated as 91,100+ million grams from 2002 to 2022 (Dzombak et al., 2019a). Constructing closed-loop systems through a circular economy can provide one way of navigating the described tradeoff between environmental impact and technology advances.

In this research, we adopt a circular economy framework to determine optimal technology management strategies for the street lighting industry, taking into account the entire life-cycle of street lighting technology products. Adopting a life-cycle perspective allows us to examine the potential of various end-of-life pathways and understand to what extent closed-loop systems are effective. The goal of this analysis is to determine a policy that minimizes expected costs and emissions for the system over a fixed time horizon thus reducing uncertainty for decision-makers. The Markov Decision Process model used in the paper evaluates 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. In doing so, we are able to more deeply understand how we might enable closed-loop systems within the street lighting industry.

2. Background

To understand the total impacts of a given technology management strategy, a holistic approach should be adopted (Hendrickson, 2012). Management of technology in the context of street lighting involves designing the product requirements, material sourcing, manufacturing, installation, use, maintenance and repair (Elejoste et al., 2013). 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. Uncertainty regarding end-of-life management of LED lights also results from the lack of robust guidelines and research around this emergent technology (Mizanur Rahman et al., 2017). In this paper, we examine the cost and environmental implications of technology management decisions in the context of the street lighting industry.

A key opportunity to rethink technology management 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 (Mayyas et al., 2012). Analyzing the environmental and economic dimensions of end-of-life strategies for particular products will be critical to such activities' expansion.

Prior work in the context of lighting technology assumed the end-of-life phase to comprise recycling and landfilling only and does not incorporate factors including projected energy efficiency gains and expected product degradation and failure. 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 street lighting industry.

2.1. A Circular Economy Framework

The current global economy follows a linear model of "take-make-dispose" (The Ellen MacArthur Foundation, 2013). 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 (Behrens et al., 2007; Mont and Heiskanen, 2015). 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 (Kirchherr et al., 2017). The circular economy aims to eliminate waste, increase the efficiency of resource use, and reduce energy consumption through recovery and reuse of materials (UNEP, 2011). 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 (The Ellen MacArthur Foundation, 2013).

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 (The Ellen MacArthur Foundation, 2013), 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 Fig. 2. Value in the form is maintained most effectively within the smallest loop as embodied

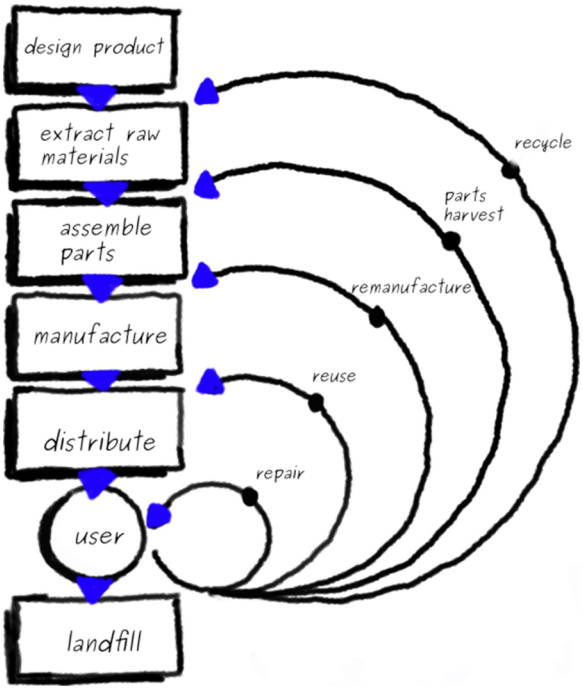

Fig. 2. Product End of Life Trajectories (Dzombak et al., 2017).

energy and materials within the product are preserved.

The circular economy framework is leveraged in this work as a tool to analyze the environmental and cost implications of technology management strategies. The cost and environmental implications of the various end-of-life pathways are incorporated into a broader Markov Decision Process model to identify the optimal technology management strategy over time. In order to bring the circular economy to fruition it is critical to understand the decisions that exist for governments, companies and consumers make throughout the product life cycle; here we analyze such decisions for the street lighting product life cycle.

2.2. Optimal Technology Management of Lighting

Many studies have shown that the application of LEDs results in higher cost savings and environmental benefits compared to incumbent lighting, looking from a life cycle perspective (Dillon et al., 2019; Navigant Consulting, 2012c; Tähkämö et al., 2016, 2012a; Tuenge et al., 2013). However, it is important for decision makers to consider the timing of technology replacement to ensure maximum cost and environmental benefits are achieved when replacing incumbent lighting with LEDs. Table 1 provides a summary of research conducted around the optimal technology management of lighting. Researchers have studied the question of when to optimally replace products due to changes in efficiency, technology availability, and expected component failure (Nguyen et al., 2014; Pan and Thomas, 2010; Wang et al., 2008), however few have studied in the context of the lighting industry.

In the context of the lighting industry, research exists on technology management from both the cost and environmental perspective as well as strategies to support decision makers as they navigate trade-offs. Optimal replacement has been studied from an economic perspective for both the residential (Balachandra and Shekar, 2001) and street lighting sectors (Ochs et al., 2014). Life cycle optimization has been used to examine the optimal replacement of residential lighting from an environmental perspective (Liu et al., 2017), but do not take end-of-life scenarios into consideration. Researchers have conducted cost-benefit analyses to support decision makers and guide technology management with respect to illuminance levels and electricity consumption (Beccali et al., 2015) as well as optimizing the timing of retrofit interventions to maximize energy benefits (Carli et al., 2018). Work also has been conducted on understanding the economic impact of implementing optimized energy policies (Carbonara and Pellegrino, 2018).

Prior work has also examined the potential of circular economy in the lighting sector. Several authors have conducted equipment dismantles of residential and street lighting products to understand the current state of products and their suitability for repair, reuse, remanufacturing and recycling (Dzombak et al., 2017; Hendrickson et al., 2010; Parajuly and Wenzel, 2017). Others have examined the waste impacts of lighting (Kumar et al., 2019) as well as management decisions regarding the tradeoff between longer product lifetimes and environmental impacts (Richter et al., 2019). The waste burden from rapid change in lighting technology has been shown to be significant (Dzombak et al., 2019a). The goal of this paper is to fill a gap in understanding how a circular economy framework might be integrated with optimal technology management strategies to guide replacement of street lighting infrastructure. The circular economy framework is needed to help industry weigh the tradeoffs between energy efficiency, cost, and waste generation. The complexity of this balance requires new tools and strategies that may be adopted by industry managers.

3. Methods

A Markov Decision Process (MDP) model was used in this work to analyze product replacement strategies for LED street lighting. Leveraging the circular economy framework, the model accounted for the cost and environmental impacts of different end-of-life (EOL) pathways such as landfilling, recycling, remanufacturing and reuse. Thus, the MDP model is particularly used to determine both the optimal replacement schedule as well as optimal EOL management strategy for obsolete technology. The data source for the costs and carbon emissions associated with each state of different EOL strategies are sourced from a life cycle assessment and life cycle cost assessment conducted by the authors. The MDP was implemented in Python and solved numerically solved using the MDPToolbox (Chadès et al., 2014), 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. A conceptual figure showing how the methodologies were used together is shown in Fig. 3. The full details of the Life Cycle Assessment can be found in the Supplementary Materials.

3.1. Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA)

Life cycle assessment (LCA), particularly when combined with life cycle cost assessment (LCCA) can model the realities and challenges associated with creating closed-loop material systems (Yong, 2007). 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. 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 (Finkbeiner et al., 2006). 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 (Norris, 2001).

In this study, attributional LCA is used to evaluate the cost and emissions associated with different technology management strategies (Supp. Materials – Eq 1 and 2). All of the process steps were assessed for inputs including labor, energy, and materials and outputs including costs in USD ($) as well as emissions (kg-CO2). Emission factors and Ecoinvent software were used to quantify the GHG footprint of the

Table 1
Summary of literature related to lighting technology and decision analysis.

Source	Analysis Goal	Analysis Type	Lighting Technology
Balachandra and Shekar (2001)	Lighting Technology Decisions	Cost benefit	CFLs
Hendrickson et al. (2010)	Circular Economy	Equipment dismantle	A-19 LED
Radulovic et al. (2011)	Lighting Technology Decisions	Spatial analysis	Street Lighting
Tähkämö et al. (2012b)	Lighting Technology Decisions	Cost LCC	Street Lighting
Ochs et al. (2014)	Lighting Decision making	Net Present Value	Street Lighting
Tähkämö and Halonen (2015)	Environmental and Energy Impact	LCA	Street Lighting
Beccali et al. (2015)	Energy and Economic Impact	Cost benefit	Street Lighting
Parajuly and Wenzel (2017)	Circular Economy	Equipment Dismantle	Household Waste Electrical and Electronic Equipment (WEEE)
Liu et al. (2017)	Lighting Technology Decisions	LCA and optimization	A-19 LED
Dzombak et al. (2017)	Circular Economy	Equipment Dismantle	A-19 LED
Carbonara and Pellegrino (2018)	Economic Impact	Net Present Value	Street Lighting
Carli et al. (2018)	Lighting Technology Decisions	Energy efficiency optimization	Street Lighting
Dillon et al. (2019)	Environmental and Energy Impact	LCA	A-19 LED, CFL, Incandescent
Richter et al. (2019)	Lighting Technology Decisions and Circular Economy	LCA	A-19 LED
Kumar et al. (2019)	Waste Management	Materials Inventory and toxicity characterizing	A-19 LED
Present Work	Lighting Technology Decisions and Circular Economy	LCA, LCC, and Markov Decision Process	Street Lighting

individual end-of-life strategies.

The inventory, necessary to understand the cost and emissions associated with the product life cycle, was developed by conducting tear downs of street lighting products and using a variety of data sources. The complete bill of materials for the product is available in the supplementary materials (Supp. Materials –Table 1). 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 2 shows the key data sources used by the researchers to construct the inventory.

The functional unit of comparison here is a single LED lighting street lighting product, specifically the Leotek 87 W product with a lifespan of 60,000 h. Equations 1 and 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.

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

Eq. (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 $CO_{2\text{-eq}}$/$kg_{material}$]

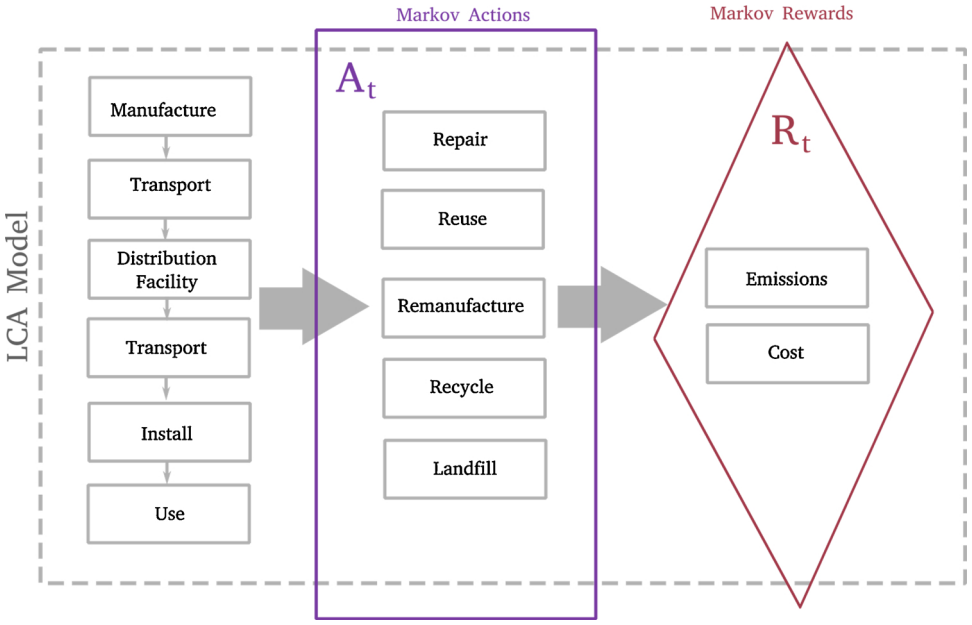

Fig. 3. Street Lighting Technology Management Model Overview.

Table 2
Key data sources used in inventory.

Inventory Component	Data Sources
Material Production Costs	Industry Specification Data Manufacturer Interviews and Earnings Statements: Philips (Philips, 2016) Cree (Cree et al., 2016)
Transport Distances	Municipality Interviews, Manufacturer Interviews
Transport Emissions	Ecoinvent V3.1 (Ecoinvent Database 3.1, 2014; Frischknecht et al., 2005; Moreno Ruiz et al., 2013) Municipality Interviews Taptich 2014 (Taptich and Horvath, 2014)
Labor Requirements and Costs	Manufacturer Interview, Municipality Interviews, National Labor Statistics (U.S. Bureau of Labor Statistics, 2017)
Material Production Emissions	Product Teardown, Ecoinvent V3.1 (Ecoinvent Database 3.1, 2014), Ciceri 2009 (Ciceri et al., 2010), Tahkamo 2015 (Tähkämö and Halonen, 2015)
Efficacy Projections	U.S DOE SSL Program (Penning et al., 2016)
Electricity Prices	U.S. EIA (U.S. Energy Information Administration (EIA), 2016)
Control Systems Penetration	PNNL (Brown et al., 2014)
Emissions Factor	U.S. EPA eGRID (US EPA, 2017)
Process Models	Stakeholder Interviews

- 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

$$C_{strat} = \frac{\sum_{i=1}^{P}\{\sum_{a=1}^{M} m_{a,i} \bullet c_{f_{a,i}}\} + \{\sum_{b=1}^{L} l_{b,i} \bullet c_{f_{b,i}}\} + \{\sum_{c=1}^{R} r_{c,i} \bullet c_{f_{c,i}}\}}{X} \quad (2)$$

Eq. (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

SimaPro software and the Ecoinvent database were used to understand the total environmental impacts associated. The authors decided to constrain analysis of the impacts to carbon emissions (kg $CO_{2\text{-eq}}$) and costs ($) in order to manage the scope of the assessment. Further details of the LCA, including the Process Flow Diagrams for each end-of-life strategy are in the supplementary materials (Supp. Materials – Section 3).

3.2. Markov Decision Process

Determination of an optimal technology management policy can be found through the use of a 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-

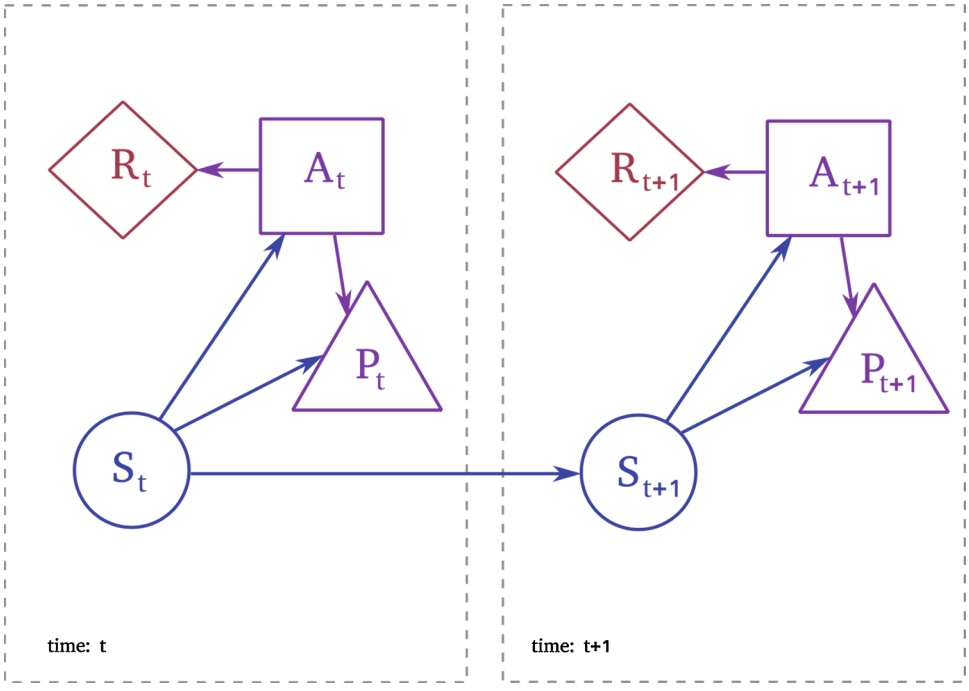

Fig. 4. Model Markov Decision Process, Adapted from (Memarzadeh et al., 2015).

making, particularly when uncertainty plays a role within the decision (Puterman, 1994). Within the lighting industry, MDP has not been previously used to model replacement strategy in connection to EOL pathways.

An example MDP model is shown in Fig. 1 and a full description of the model can be found from Sutton and Barto (Sutton and Barto, 1998).

As shown in Fig. 4, the model is comprised of five primary components (S, A, P, R, g).

- S: a finite number of system states (in Fig. 4 as circles)
- 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 (in Fig. 4 as squares)
- P: a transition probability matrix that is both action and state dependent. (in Fig. 4. as triangle)
- 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 (in Fig. 4 as diamond)
- 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.
- t : The time step increment (outside box).

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 3. 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 Equation 4.

Eq. 3: Bellman Equation

$$V_k(s) = \max_{a \in A} \left[R_k(s, a) + \gamma \sum_{s' \in S} P(s, a, s') V_k(s') \right] \quad \text{for} \quad \text{k= 0, 1, ...N} \tag{3}$$

Eq. 4: Value Function at Final Time Step

$$V_N\,(\text{s}) = R_N\,(\text{s}) \tag{4}$$

3.2.1. MDP Model Development

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 *Pk*. Catastrophic failure could occur if the light were struck by lightning 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 3. Each decision is associated with both cost and environmental rewards (with data from the life cycle assessment) 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 (CO2) incurred, and A are the emissions avoided upon material recovery.

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

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

The transition matrix was parameterized using the results of a survey conducted by the DOE with manufacturers on expected failure rates of new products [48] and confirmed through empirical 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 Fig. 5.

Fig. 5 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 2 × 2 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 0.99 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.

4. Results

4.1. Optimal Technology Management Strategies

The MDP model enables analysis of what decisions are optimal at

Table 3
Decisions Available and Associated Cost and Environmental Rewards.

Decision	Action (A)	Reward (R)	
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]

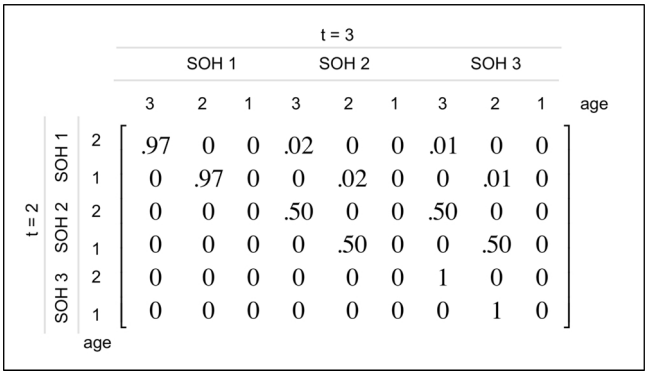

Fig. 5. Transition Matrix for Decision to 'Do Nothing' between t = 2 and t = 3.

Fig. 6. Environmental and Cost Optimal Replacement Policies from MDP Model.

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 Fig. 6.

As shown in Fig. 6, 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 its 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.

Fig. 7 provides a detailed examination of the costs and emissions incurred each year based on the optimal strategies resulting from the model. The model used a discount factor of 0.99, though the results of varying the discount factor are also shown in Fig. 7. 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 choose 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. From an emissions perspective, the cost-optimal and environmentally-optimal strategies are not as far apart and when the cost-optimal scenario is modeled with a discount factor of 0.9 it results in lower cumulative emissions than the environmentally-optimal strategy modeled with a discount factor of 0.99.

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 (from a cost perspective) is to keep the product throughout its entire useful life. In the service-based model, the service provider is responsible of upgrading, replacing and maintaining the product through the product's lifecycle. Thus, an increase in useful lifetime would create the service provider more opportunity to capture most of the lighting-related energy savings by finding alternative end-of-life strategies to its customer instead of the customers dispose all the lights before their failure. Furthermore, as the customer avoids paying a substantial setup cost due to frequent replacement of all the products, service providers would be able to attract more customers who have adopted a cost perspective.

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. Additionally, the results show the decisions when optimizing for two particular variables: cost and emissions. However, there are many other factors that decision-makers must navigate when considering management of street lighting technology. When street lighting is managed by local governments, managers are beholden to the interests of the public and community stakeholders. When technology is managed by private utilities, managers are beholden to shareholders.

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

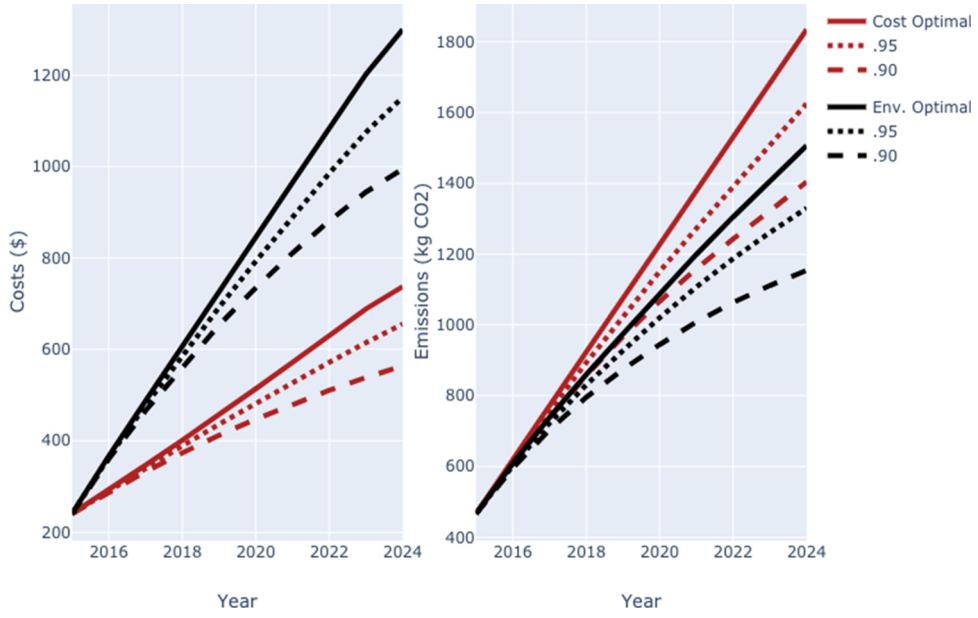

Fig. 7. Cumulative Costs and Emissions for Optimal Policies.

Fig. 8. Possible Management Decisions at Each Time Period.

associated with electricity consumption will significantly decrease. There would be 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.

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. Fig. 8 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.

Fig. 9 shows the results for the cost- and environmentally-optimal decisions at each time period for each state that is accessible. The model was run with a discount factor of 0.99. 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.

5. Discussion

For environmentally-optimal technology management decisions, the results 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 re-paired 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.

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.

Finding a cost- and environmentally-optimal technology management strategy in street lighting industry is not currently feasible due to the complexity of the system which is influenced by many actors and external factors. Also, based on the findings, there is currently no overlap between cost- and environmentally-optimal strategies, which presents a significant challenge for decision-makers. In addition, 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.

However, new business models are emerging that allow for the harmonization of the cost- and environmentally-optimal management strategies. If a single entity retained product ownership of the physical assets with the intent of reuse and remanufacturing, the functional life of the materials could be extended and the upgrading of the product and reverse logistics at EOL or even before EOL could be easier and more cost-effective. While service-based business models have long been a fixture in other industries such as appliances and office equipment (Intlekofer et al., 2010), they are relatively new to the lighting

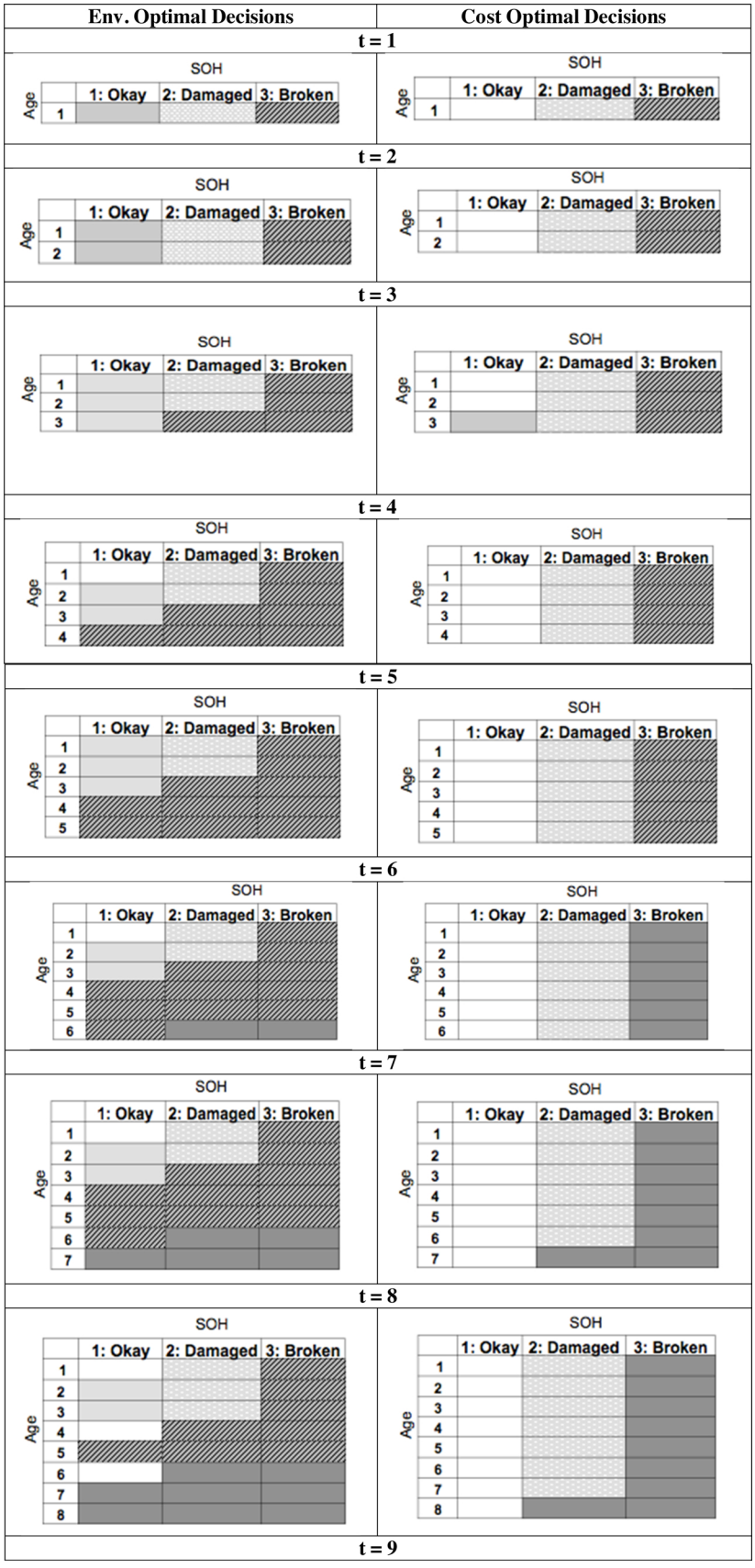

Fig. 9. Optimal Decision Given Product State.

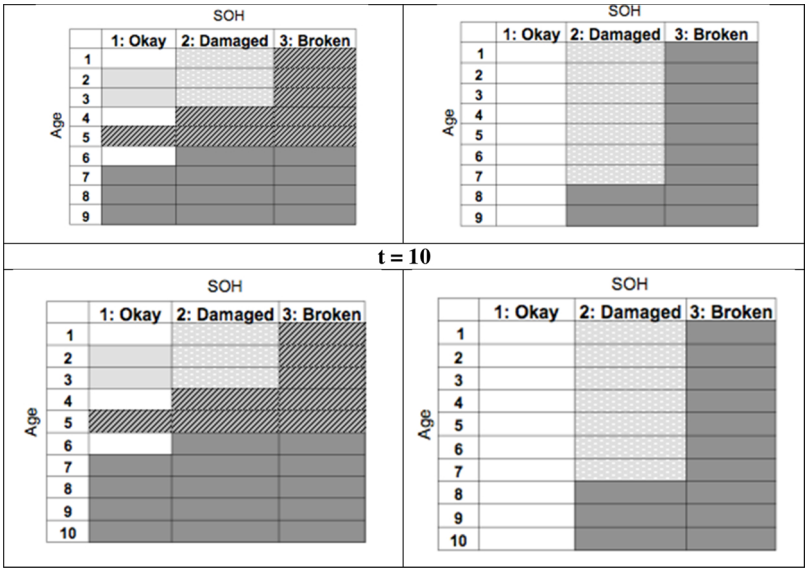

Fig. 9. (*continued*)

industry (Labrador and Ferrante, 2017). However, several businesses have begun to scale operations selling light-as-a-service (LaaS). Philips (Netherlands, US), Aura Light (Sweden), and other major OEMs have begun to pilot offering LaaS, guaranteeing a lux level (light per unit area) over a defined period of time (Fleming and Zils, 2014; França et al., 2017). Under a LaaS model, service providers consult with customers to develop a lighting system to meet their customers' performance requirements and over the time of the contract they can replace the incumbent system equipment as lighting technology changes enable more cost-effective solutions to meet the customers' performance demands. The control that service providers have over the lighting system equipment and operations enables them to optimize lumen performance and lighting-related cost savings (Calhoun et al., 2017). For customers, the cost of the service remains comparable to traditional product purchase business models, however the benefits come from alleviated maintenance costs, energy savings, and the utility of enhanced lighting quality (Calhoun et al., 2017).

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 (Calhoun et al., 2017)." Lighting Europe also conducted research to understand how LaaS models might be implemented within the European lighting market and found that a key step in enabling LaaS business models is serviceable LEDs (Lighting Europe, 2017). At present, most LEDs are not suited for repair or remanufacturing (Dzombak et al., 2017). Selling LaaS would incentize the development of serviceable LEDs as the business model enables upgrading, reuse, and remanufacturing of products over time as the customer pays the service provider for the performance but the service provider maintains and retains ownership over the equipment (Fleming and Zils, 2014). The service provider then is incentivized to keep core technologies in use for as long as possible to derive further value from capital-intensive resources (Fleming and Zils, 2014).

Under LaaS, the control the manufacturer has over the equipment would enable them to track the life of the product and so optimize lumen performance and related cost savings by maintaining and replacing the products at the right time. As a result, users would have the option to achieve the highest efficiency product by paying a flat rate. Thus, LaaS may be one of the best options to help end users compromise between cost and environmental optimization. However, research on environmental benefits of service-based business models has noted that the role of product design is non-trivial (Gutowski et al., 2011). The maximum value is gained from reuse and remanufacturing when products are intentionally designed for end-of-life processing (Bakker et al., 2014). More could be done to create lighting products that are suitable for material reuse (Dzombak et al., 2017).

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. However, several municipalities still landfill street lighting products at EOL, overlooking the financial advantage of recycling (Dzombak et al., 2019b). Thus, in these regions more outreach is needed 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.

6. Conclusion

The goal of this study was to examine optimal technology management decisions in the street lighting industry and also analyze the viability of circular economy models when managers choose to optimize both cost and environmental implications of their decisions. The authors analyzed this through the construction and execution of a MDP model leveraging industry and life-cycle assessment data. The model included consideration of future energy efficiency improvements as well as product degradation and failure projections. 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.

The main contribution of this work 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 management strategies that can decision-makers 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 as a mechanism for resolving the trade-off between economically- and environmentally-optimal decisions. This is an area that should be explored more fully in the future both in the lighting context but also for other technology industries.

An additional area of future work is to incorporate into the model the limits on reuse and remanufacturing from an economic perspective. At present, the reuse market is not well defined for the street lighting industry. Companies, such as Philips, however are already capitalizing on product reuse (Philips, 2019) and secondary lighting markets are poised to grow in light of increased regulation of product manufacturing and end-of life (Halpert, 2018). Frequent replacement does

reinforce the need for product design to be increasingly oriented for reuse and remanufacturing. 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 study 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. 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. Future work extending from this study 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.

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 (Dzombak et al., 2017). The hope is that this model will be employed to inform future street lighting management decision.

Declaration of Competing Interest

The authors have no conflicts of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.rcrx.2019.100022.

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