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Assessment of end-of-life design in solid-state lighting

Rachel Dzombak

Jack Padon

Josh Salisbury

Heather E. Dillon

University of Portland, dillon@up.edu

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LETTER

Assessment of end-of-life design in solid-state lighting

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Rachel Dzombak¹, Jack Padon², Josh Salsbury² and Heather Dillon^{2,3}

¹ Department of Civil and Environmental Engineering, University of California, Berkeley, CA, United States of America

² Department of Mechanical Engineering, University of Portland, OR, United States of America

³ Author to whom any correspondence should be addressed.

E-mail: dillon@up.edu

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Abstract

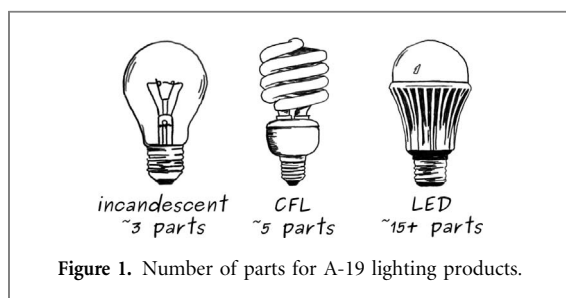
Consumers in the US market and across the globe are beginning to widely adopt light emitting diode (LED) lighting products while the technology continues to undergo significant changes. While LED products are evolving to consume less energy, they are also more complex than traditional lighting products 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.

1. Introduction

In the United States, approximately 18% of total electricity consumption is from lighting [1]; lighting constitutes 21% of commercial electricity usage, corresponding to 350 TWh annually [2]. As the global call for reduced carbon emissions grows louder, energy efficient technologies are seen as a prime mechanism to lower environmental impacts. For the lighting industry, this means that traditional incandescent lighting products are quickly being replaced by highly efficient LED (light emitting diode) lighting systems. As a result, the market for solid state lighting systems has seen a 40-fold increase in installed lamps since 2001 [2] and contributed to more than \$2.8 billion in energy savings since their debut in 2001 [3]. The DOE suggests that by 2025 LEDs will produce at least half of the electric light in the United States and even more globally [3]. 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. 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 1). 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 [4]. 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 an important time to analyze design trends and the impact of design decisions on environmental sustainability.

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 [5]. 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 [6]. 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 [7]. 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 [8, 9]. 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 authors will explore the latter 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, the authors analyzed A-19 products from multiple vendors and product years 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,

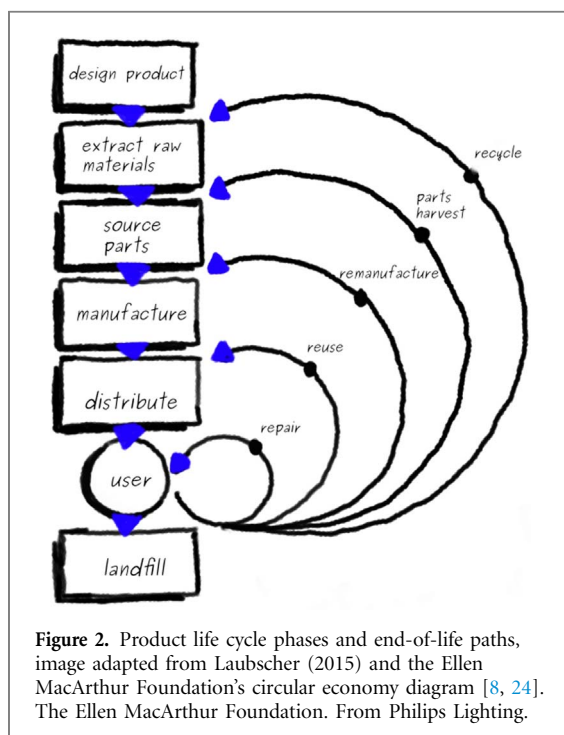
including landfilling, recycling and remanufacturing. Products were further compared to products studied in 2009 by Hendrickson *et al* [10]. Finally, the authors developed a set of design guidelines specifically for A-19 LED products that could be adopted by the industry.

2. Background

Solid-state lighting (SSL) has emerged as strong market force in lighting in the last 10 years [3]. 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 [11, 12]. The impacts are considerably less due to the higher energy efficiency of SSL products leading to lower use phase impacts [13]. 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 useful life is shorter than expected [14]. 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 [15, 16]. 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 [17].

In LED products the increase in metals compared to traditional lighting products has been driven by thermal management. LED performance is affected by the thermal environment, and many research groups have studied the issues of thermal performance that cause degradation of the light over time [18–20]. Other research groups are working to improve the thermal performance of LEDs for lighting applications [21], an effort that will reduce the mass of metals required in future LED products.

Decisions made in a product’s design phase can have important implications on the environmental impacts incurred throughout the life cycle (see figure 2) [22]. 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 [23]. Design influences what materials are used, how the product is manufactured, how energy efficient, 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 [10]. 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 [11]. Contribution to hazardous waste was the only area the LED product did not outperform existing compact fluorescent (CFL) technology [11].

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 [25]. 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 [25]. 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 [4]. The authors analyze six products from unknown vendors sold between 2011–2015. They note that vendors have begun to shrink (or in one case remove) the heat sink, made possible through the use of low power LEDs [4]. 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 [7]. 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 [26]. 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 [26]. One point that this article will pick up on is a guideline offered by Reuter and Van Schaik that states, 'Design clusters or sub-units in products that can be easily removed and which match with the final treatment recycling options' [26]. In this study we modified the methodology of Hendrickson *et al* [10] to consider how current A-19 products perform for end-of-life characteristics and compare to products from 2009 to 2016. 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. 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 1).

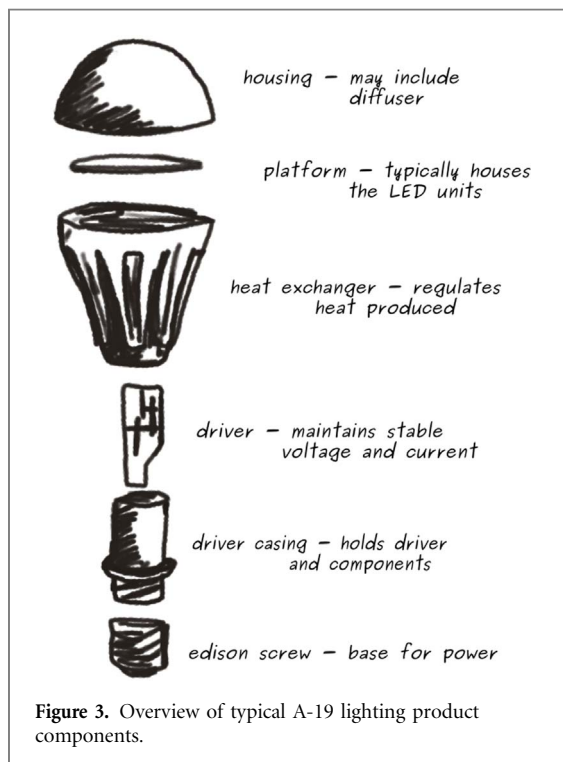
The common components of most A-19 lighting products are shown in figure 3. Information collected during the disassembly included tools required, time of disassembly, component materials, disassembly difficulty, matings between parts, etc. Tools required were categorized as simple (screwdriver and pliers) or complex (Dremel tool and drill). Each step of disassembly was recorded and photographed for later analysis.

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.

Table 1. 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 lifespan [hours]	Rated wattage [W]	Rated lumens [lumens]	Lamp efficacy [lm W^{-1}]	Product mass [g]
P01	2013	25 000	12.5	800	64	160.4
P02	2013	27 500	13.5	800	59	217.6
P03	2013	30 000	10	830	83	110.1
P04	2013	20 000	10.5	800	76	128.5
P05	2015	25 000	8	450	56	62.6
P06	2013	25 000	13	800	62	234.7
P07	2013	50 000	10	820	82	123.8
P08	2013	25 000	12	800	67	113.7
P09	2013	20 000	7.5	450	60	145.2
P10	2013	25 000	13.5	800	59	245.2
P11	2013	25 000	12	820	68	168.5
P12	2013	30 000	10	940	94	171.1
P13	2013	25 000	7	450	64	97.1
P14	2016	20 000	10.5	800	76	124.8
P15	2016	25 000	19	1680	88	229.2
P16	2016	25 000	11	800	73	108.3
P17	2016	50 000	10	810	81	110.0



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.

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.

Modularity Level: The ability of the product's components to be separated and recombined. Likert ranking, scale in appendix.

Material Complexity (H): Quantitative measure of disassembly efficiency. Likert ranking, scale in appendix.

Recovery Potential (R): Calculated mass % of product possibly able to be recycled, including both plastics and metals.

Likely Recovery (L): Calculated mass % of product likely to be recycled, including metals only.

Material complexity (H) is defined 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 [27]

$$H = \sum_{i=1}^n c_i \cdot \ln(c_i). \quad (1)$$

The recovery potential (R) is defined in terms of the total mass of the product (M_t) and the mass of the product that could be recycled including both plastic and metal components (M_r)

$$R = \frac{M_r}{M_t}. \quad (2)$$

The likely recovery (L) is defined in terms of the total mass of the product (M_t) and the mass of metal components which represent the components that are likely recycled (M_m)

$$L = \frac{M_m}{M_t}. \quad (3)$$

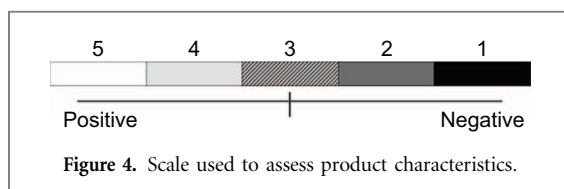


Figure 4. Scale used to assess product characteristics.

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 [26]. 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 [28].

The full rubric used to assess the products can be seen in the appendix. 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 4. 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 2.

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.

4. 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 5 shows the mass of components within each product analyzed as well as characteristic information about the product.

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 2 and the scaled results are shown in figure 6.

Once data was collected on every product, the quantitative results were converted to the same 1–5 scale as the qualitative criteria 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.

4.1. 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 time 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 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 7.

The ease of recycling metric examined the ability to manually separate plastic and metal product components. Most products scored poorly within

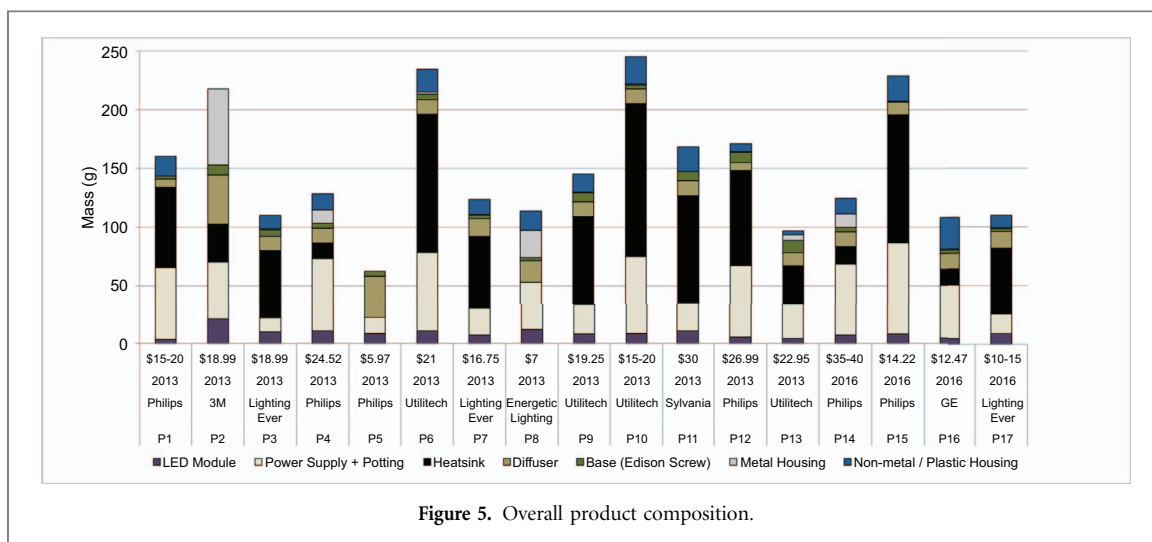


Table 2. Assessment of design and end-of-life suitability for A-19 products.

Product label	Number of parts	Time of disassembly [mins]	Ease of disassembly	Modularity level	Ease of recycling	R: Material recovery potential [%]	L: Likely material recovery [%]	Material complexity
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
Average	20	49.6	2.9	2.8	2.6	64.1	41.3	1.28

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 the liberating of recyclable components straightforward as shown in figure 8. 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.

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.

4.2. 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 programming language R [29]. The raw data from table 2 was used to calculate the correlation matrix. A correlation matrix indicates the relationship between the variables in the table with one another.

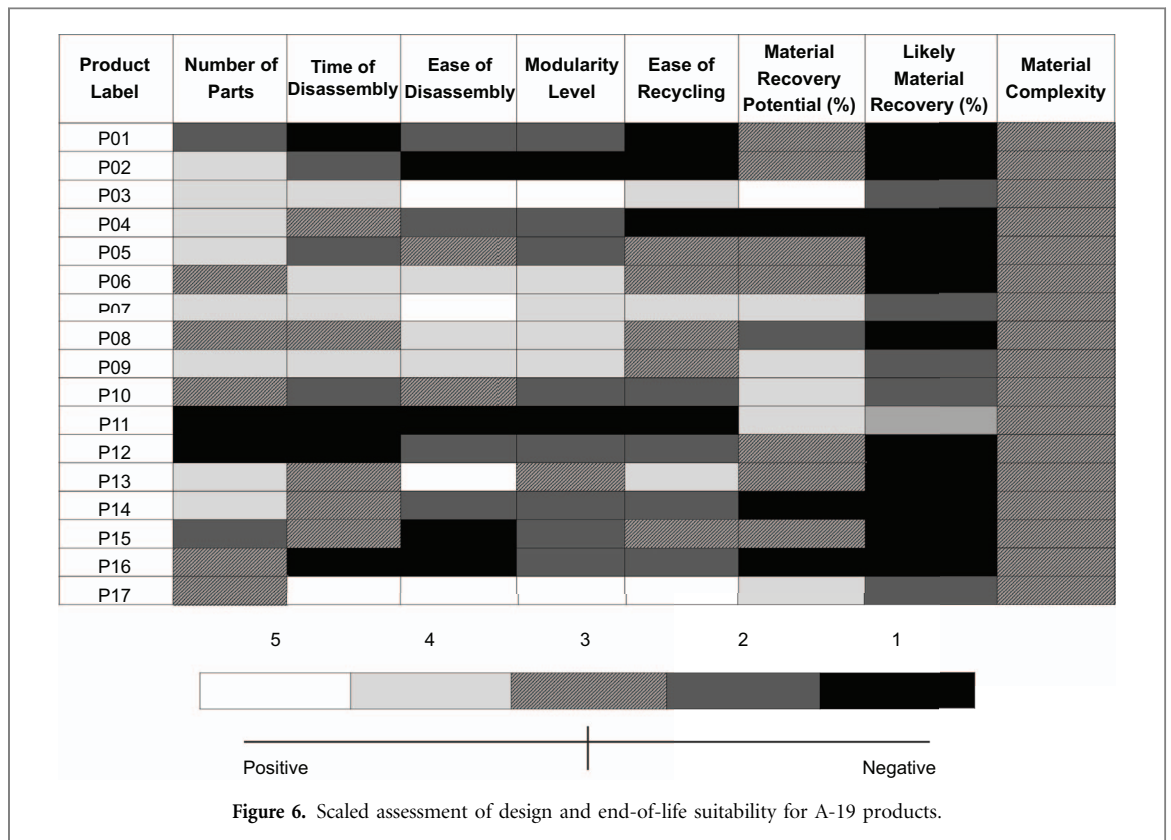


Figure 6. Scaled assessment of design and end-of-life suitability for A-19 products.

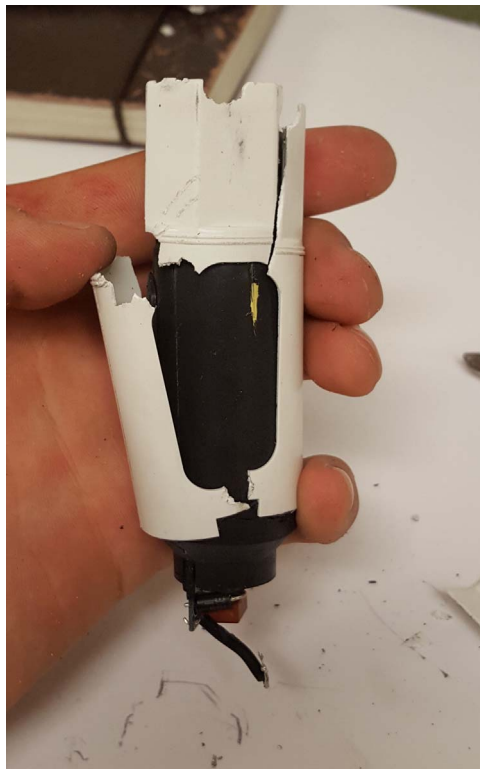


Figure 7. P15 challenging access to driver.

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 9.

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 ($P = 0.67$).

4.3. 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 to 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



Figure 8. P17 design with high ease of recycling.

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 [19]. Although the fin design (shape of the exchanger) was various in nature, a metal exchanger was commonly present, and it was ubiquitously made from aluminum. From a sustainability standpoint, metal exchangers still have room for improvement. Although 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 [11].

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 in figure 10. Furthermore, the LED chip could not be removed from the heat exchanger.

P11 also required significant effort for disassembly. The design incorporated a complex plastic casing for the driver. The plastic casing lacked practicality and impeded driver access. The plastic casing was destroyed to release the driver as shown in figure 11. Though the casing did provide for an attractive aesthetic, the plastic form inhibited the ability to recover component materials upon disassembly.

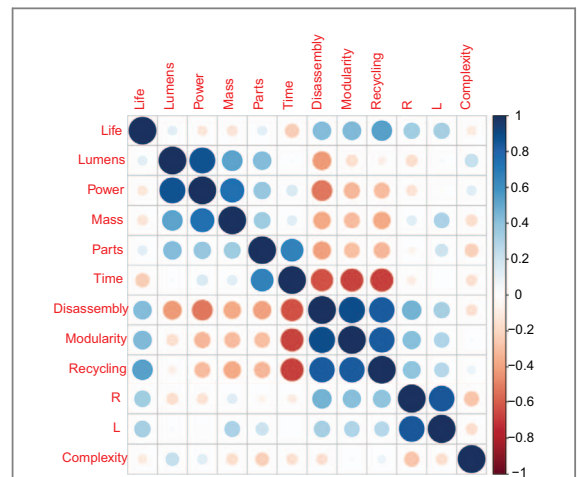


Figure 9. Correlation matrix for LED end of life parameters measured. The size of each circle is proportional to the correlation coefficient calculated.



Figure 10. P02 product disassembly with heat exchanger in two parts. The sections required a dremel tool for separation.

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 connected the driver and LED platform as shown in figure 12. If a two-pin connector had been utilized instead of soldering, this product could be easily serviced in case of LED failure, the second-most common product failure mechanism [30].

P02 (already noted for poor access to the LED platform) exhibited a small PCB connector (see figure 13) 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 [30].

The design of P03 provided an example of driver accessibility. The design used effective, removable



Figure 11. P11 product casing made of complex plastic.

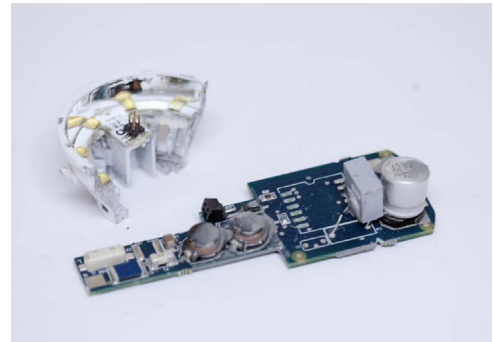


Figure 13. P02 product chip connector. This connector replaces metal wiring and creates higher modularity for the bulb.



Figure 12. P10 product as example of modularity.

fasteners (screws) and avoided thermal epoxy and adhesives as shown in figure 14. These qualities allowed quick deconstruction with a screwdriver and prying tool. Without scraping thermal epoxy, separation of materials was simplified.

5. Conclusions and recommendations

Throughout this paper, we critically examine the recent market for A-19 lighting products and explore products' suitability for end-of-life processing as a result of design characteristics. The work done builds on work completed in 2009 by Hendrickson *et al*. In the analysis done by Hendrickson, the authors proposed that manufacturers should (1) create products that can be easily disassembled, (2) incorporate with replaceable parts, and (3) reduce the number of materials used [10]. After seven 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



Figure 14. P03 product with removable fasteners and limited adhesives.

disassemble. Most products still included elements or materials that were difficult to isolate.

The market for LED lighting products is on the verge of a dramatic scaling; reports from the US Department of Energy suggest that by 2025, LEDs will produce at least half of the electric light in the US and even more globally. Before consumer uptake increases any more, 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* [4], the potential for end-of-life material recovery may decline if the suggested design principles are not followed by manufacturers.

Table 3. Rubric used to analyze A-19 LED products.

Rating	Number of parts	Time of disassembly [mins]	Ease of disassembly	Modularity level	Ease of recycling	R: material recovery potential [%]	L: likely material recovery [%]	Material complexity
1	29+	> 60 min	Product unable to be disassembled, used complex tools	No parts able to be reconnected	Less than half of metal and plastic parts isolated, high amounts of epoxy to scrape / remove	< 50%	< 50%	> 2
2	23–28	45–60 min	Less than half of parts disassembled, used complex tools	Few parts able to be reconnected	Most metal and plastic parts easy to isolate, high amounts of epoxy to scrape / remove	50%–60%	50%–60%	1.5–2
3	17–22	30–45 min	Most parts disassembled and/or some complex tools needed	Most parts fit together well, connections not epoxied or glued	Most metal and plastic parts easy to isolate, some epoxy to scrape/remove	60%–70%	60%–70%	1–1.5
4	11–16	15–30 min	Able to be disassembled entirely, some complex tools needed	Most parts fit together well	Most metal and plastic parts easy to isolate, no epoxy to scrape/remove	70%–80%	70%–80%	0.5–1
5	10 or less	< 15 min	Able to be disassembled entirely, no complex tools needed	All parts fit together easily, with easy connections	All metal and plastic parts easy to isolate, no epoxy to scrape/ remove	> 80%	> 80%	< 0:5

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 their green properties by 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.

- i. 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.
- ii. 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.
- iii. 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.
- iv. 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 an end-of-life strategies such as reuse or remanufacturing are deemed to be infeasible, products should be designed to optimize for recycling.

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ORCID iDS

Heather Dillon  <https://orcid.org/0000-0002-4467-2306>

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