Sparkle: Laterally Symmetric 3-D Printed Luminaire Ecosystem

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ABSTRACT

Luminaire manufacturers are traditionally referred to as "metal benders." The majority of luminaires for commercial lighting applications are either manufactured by extrusion, casting or bending of Aluminum or Steel. While perceived as recyclable and therefore sustainable, almost all luminaires go into the waste stream at end of life. We show the ability of 3D printed luminaires—starting with the design phase—to achieve circular economy goals. We also show features and manufacturing techniques available to 3D printing that would be prohibitive using traditional manufacturing techniques, but which facilitate design for disassembly and optimize circularity.

Keywords: Lateral Symmetry, Circularity, 3-D printed luminaires, Sparkle, Glare, Uniformity

1. INTRODUCTION

LEDs have disrupted the commercial lighting industry. Because of gains in device efficacy nearly every lighting application is now dominated by LED products. Even though LEDs have supplanted the lighting technologies from the last paradigm—specifically: fluorescent, incandescent and metal halide, manufacturers continue to design luminaires around these traditional technologies. This paper will limit its discussion to the most popular and specified luminaires in commercial lighting applications (office, education and healthcare:) the semi-indirect linear luminaire, which was populated by linear fluorescent lamps in the previous paradigm. In addition to designing LED semi-indirect luminaires around linear fluorescent lamps, many of the manufacturers adhere to traditional manufacturing and supply chain models, which limit features, which can provoke more circular design. We show how additive manufacturing can facilitate new feature systems, which would previously be prohibitively expensive and therefore impractical. These features allow for the use of less material, facilitate design for disassembly and enable recycling in a way that is currently not realized in commercial lighting. In addition, we'll show that by designing around the strengths of solid-state lighting technology instead of the previous technology, we can realize breakthroughs in spacing criteria and application efficiency, which translate into greatly reduced lighting power density. This results in the use of fewer luminaires and subsequently in the use of less material. Sparkle was undertaken as a thought experiment: to incorporate as many feature benefits of additive manufacturing, which currently are not represented via traditional manufacturing techniques, into a single product, while addressing systemic issues in commercial lighting applications.

Fluorescent Paradigm

In the past paradigm of semi-indirect linear fluorescent luminaires, there existed a strict dichotomy: lamps and "fixtures." Lamps—dominated by the Big Three (Philips, GE and Osram-Sylvania) were a commodity product. There were a limited number of skus which went to market through distribution. Fixtures (luminaire housings) had myriad skus and grades (utility, architectural and specification.) Fixtures were/are a high-commodity product sold predominantly through local agency networks. The two components—lamps and luminaires—met at the job site.

For decades, commercial fluorescent luminaires, which housed linear fluorescent lamps, were direct distribution only. Linear fluorescent lamps emit light omnidirectionally in the vertical axis (Figure 1.) When installed in direct-only luminaires, reflectors were used in the top of the luminaires to redirect indirect light down toward the work plane. Discomfort glare subsequently was an issue in the application. Luminaire designers used louvers to shield direct viewing. Light loss became a subsequent issue, however, with some fixture efficiencies as low as 50%[i]. With the advent of the semi-indirect linear luminaires, these issues were solved. By, in effect, removing the top of the luminaires, the upwards distribution that would normally be directed into reflectors was allowed to escape the luminaire unencumbered. Because of high reflectance common in commercial applications (80% for ceiling; 50% for walls; 20% for ground,) this indirect light was reflected down to the work plane—supplementing the direct light component.

This proved to be a highly efficient and effective solution. An average linear semi-indirect luminaire—using a linear fluorescent lamp with efficacy of 100 lumens/watt (LPW)—may have system efficacy of 70 LPW[ii]. With common hang heights of 1.5-2', these luminaires were closer to the work plane and produced less visual discomfort. This standard proved formidable enough to withstand the encroachment of LED technology for years after its initial deployment in commercial applications. Because of its successful deployment in the application, the semi-indirect linear fluorescent luminaire became the template for the most common LED luminaire today.

How LEDs changed the Game

With the introduction of solid-state luminaires in commercial lighting, the supply chain was disrupted. No longer could lamps meet luminaires at the job site. The LED—the solid-state equivalent to the lamp—became critical to the design of the product from inception. With the exception of TLEDs, which have shown limited success in the market due to electrical configuration complexities, LEDs were entombed within the luminaires. The LED became not only pivotal to the initial mechanical design but also the optical, electrical and thermal engineering of the luminaire. As a result, the number of skus luminaire manufacturers produced dropped precipitously while risk to the manufacturers subsequently increased.

It is not unusual for manufacturers to design new lighting technologies in the image of the past technology given existing market acceptance. In commercial lighting, unfortunately the attributes of LEDs do not make them appropriate replacements for linear fluorescent.

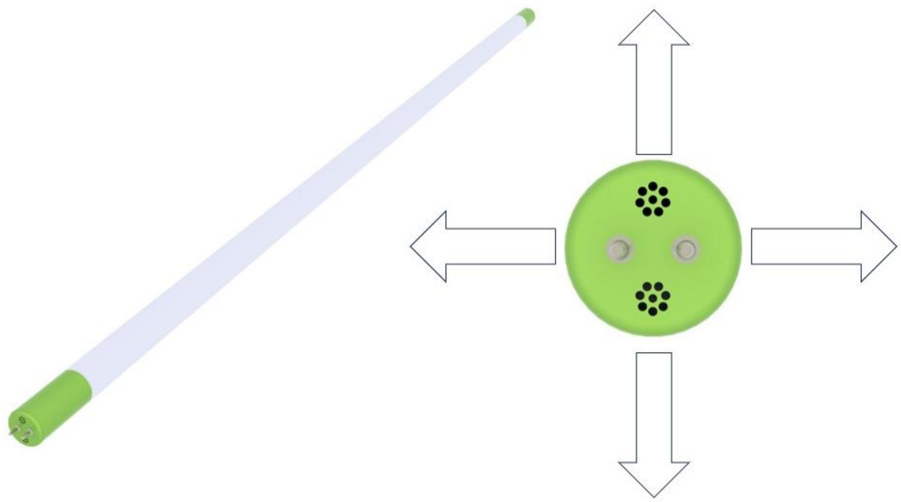

Figure 1: linear fluorescent lamp trimetric view and section view showing omni-directional distribution

For one thing, LEDs are not omnidirectional in the vertical axis. Their radiation pattern is limited to 170º-180º. In order to match the radiation pattern for a linear fluorescent tube in a semi-indirect luminaire, two sets of LEDs are necessary: one illuminating up, the other down. LEDs are oftentimes the most expensive element of the Bill of Materials (BOM,) so cost is increased. Additionally, given that LEDs are dynamic devices, doubling the number of LEDs increases the burden of balancing electrical loads among multiple strings of LEDs. Passive devices to mirror current among the strings becomes necessary, which increases costs. To borrow from modernism: less is more.

Then, we must consider horizontal illumination. One of the critical limitations with linear fluorescent technology is the bilateral symmetry that is a result of the endcaps blocking emissions. (Figure 2.)

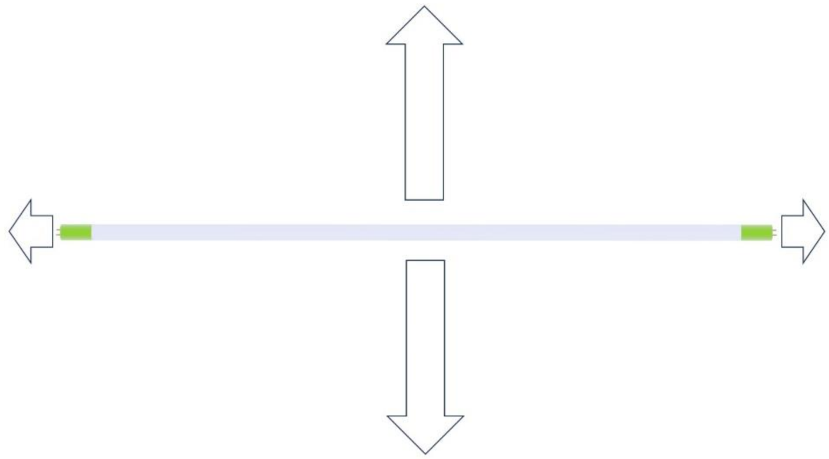

Figure 2: asymmetric horizontal intensity distribution of linear fluorescent lamps

This asymmetric radiation pattern manifests both in the corresponding luminaires and the application. In order to provide uniform illumination, irregular spacing became the standard. The basic building block of the linear fluorescent was nominally 4' in length. Standard spacing for this product would be 4' x 8'[iii] with the luminaires being installed end-to-end.

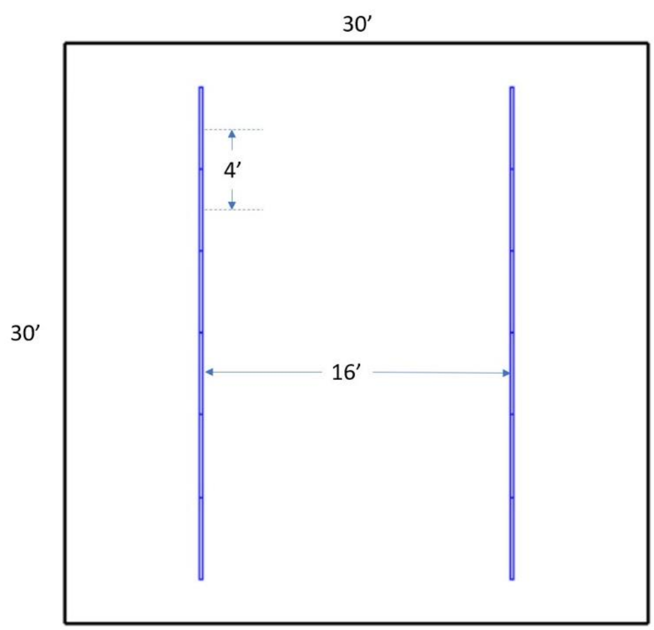

Figure 3: Plan View of Linear Fluorescent and LED luminaire layout in Classroom-sized Application

This artifact of linear fluorescent technology is not inherent in LEDs, which are, in fact, symmetric in the horizontal axis. Yet LED semi-indirect luminaires today—long after performance has surpassed linear fluorescent—are still installed in 4' x 8', end-to-end configuration (Figure 3.) This has resulted in an opportunity lost from the standpoint of reducing power density (W/ft^2) in commercial buildings—a sector where lighting is responsible for 17% of the electricity used[iv]. While other applications have translated rapid increases in device efficiency into power density drops, the application benefits in commercial lighting have lagged. Take commercial garage lighting as an example. The state-of-the-art LED garage lighting unit will yield average power densities well below 0.04 W/ft^2 approaching diminishing returns.

Design trends in garage lighting luminaires will reveal why this is the case. To the point of designing new technologies around older technologies, the MH sources LEDs were replacing in garage lighting were horizontally symmetric (i.e., symmetric spacing in the application.) It became the standard for designers of LED garage luminaires to create a similar beam shape. LEDs being small devices lend themselves to optical coupling. Using LEDs in conjunction with optics allowed for all manner of beam shapes. As a result, LED garage lighting quickly created wider spacing and cascade effects in application efficiency—specifically as the performance of LED increased. This could also be the case in commercial lighting applications as well.

Prior to discussing ways of improving the technology, it is helpful to see an application snapshot of not only the state-of-the-art linear semi-indirect LED luminaire but that of fluorescent as well.

2. METHODOLOGY

IES files based on independent laboratory testing characterize the intensity distribution of both LED and fluorescent linear products. These IES files were then used in Visual Lighting Software[v] to model the lighting in the application. A survey of competitive semi-indirect, LED luminaires was undertaken, and the best performer from the standpoint of uniformity both on the ceiling and work plane as well as power density was chosen. We used this leading company's LED semi-indirect luminaire[vi] as well as the application conditions (60'x60'x9') they used in their own collateral to show best-use cases. Reflectivity in the room was set to (80/50/30.) Illuminance readings were set to a grid of 2' x 2' on both the work surface and the ceiling. Light-loss factor for each luminaire was set to 0.9 with a ballast/driver factor of 1. Linear fluorescent performance based on independent lab testing[vii] in compliance with LM-79 protocol was also used for fair comparison. The results are tabulated below.

Table 1: performance of best-of-class LED linear vs. Fluorescent linear

	Workplane (FC)				Ceiling (FC)					
Product	Ave E	Max E	Min E	Ave:Min	Ave E	Max E	Min E	Ave:Min	# Fixtures	W/ft²
Fluorescent	77	164	23	3.4	64	246	15	4.4	39	1.2
LED	40	62	19	2.1	36	88	9	4.0	52	0.4

It becomes conspicuous upon viewing that while power density has dropped over the last decade, other performance metrics such as spacing are, in fact, worse than they were during the fluorescent paradigm. In this specific example pulled from the best-of-class collateral, the spacing between luminaires was 4' x 15' while spacing for the fluorescent was 4' x18' leading to an increase in the number of fixtures by 25%. In addition, ceiling uniformity appears to have not improved substantially over the last decade in the application. Based on this observation, we set out to design around the strengths of the LED technology in commercial applications with the goal to create near-perfect uniformity on the ceiling[viii]. The first step was finding the ideal distribution, and seeing if there were ways of achieving with existing components readily available.

The distribution, which we coined "rabbit ear distribution" that was achieved (Fig 4) through trial and error by creating multiple IES files and inputting into Visual light calculation software. A classroom-sized room (30'x30'x9') was used with average reflectance (80/50/30.) A single unit was suspended 1.5' below the ceiling. Illuminance readings on a 2'x2' grid on the ceiling plane were measured. The resulting distribution showed perfect 1:1 uniformity. We assigned a Lambertian distribution for the direct component of the lighting based on state-of-the-art downlight luminaires. While the nuances of the indirect distribution would be hard to achieve with off-the-shelf optics, we were able to approximate the core of the distribution. For the main beam shape, we were able to approximate the full width half max (FWHM) with an elliptical orthogonal optic with beam shape of (7ºx50º.) To approximate the peak candela, we matched the candela/lumen value of the optic[ix] with a LED that met the requirements of being small enough (<2mmx2mm) to allow for good flux coupling while being able to produce 300 lumens. The resulting 2400 peak candela was close to the ideal.

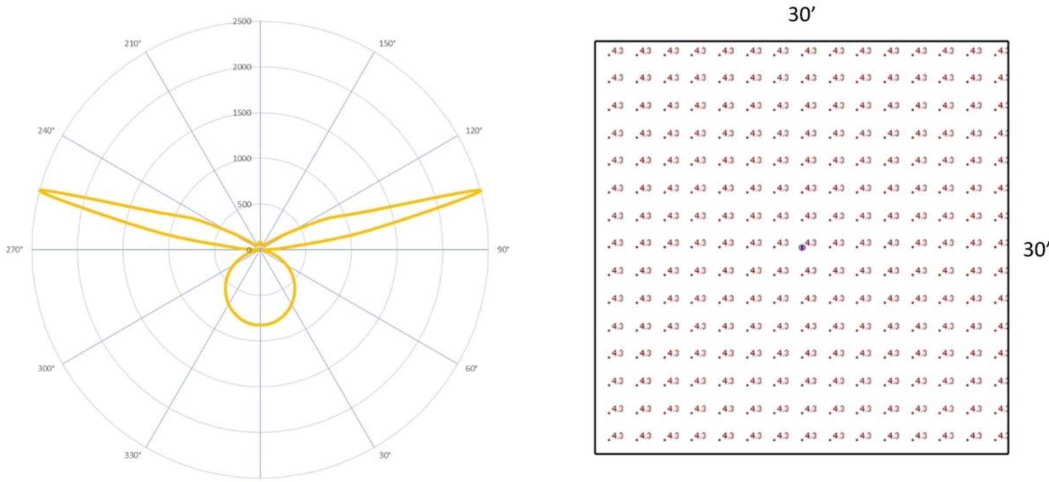

Figure 4: Ideal “Rabbit Ear” Distribution and Corresponding Ceiling Illuminance for Indirect component alone

The resulting IES file was dropped into the previous room layout from table 1 and the results are tabulated below in Table 2. Given the room size, the hero, Sparkle, luminaire was spaced out on 15’ x 15’ centers in order to meet the minimum illumination standards of 20FC. It was suspended, as the other linear luminaires at 1.5’ hang height below the ceiling.

Table 2. Ideal Distribution vs. Best-of-class linear LED and Fluorescent Linear

	Workplane (FC)				Ceiling (FC)					
Product	Ave E	Max E	Min E	Ave:Min	Ave E	Max E	Min E	Ave:Min	# Fixtures	W/ft^2
Fluorescent	77	164	23	3.4	64	246	15	4.4	39	1.2
LED	40	62	19	2.1	36	88	9	4.0	52	0.4
Sparkle	24	58	11	2.2	17	23	6	2.7	16	0.16

As can be seen, the hero distribution created noticeably better ceiling uniformity. Most importantly, however is the number of luminaires that were used. 16 luminaires represent a 69% reduction in the number of luminaires needed saving not only on cost of luminaires for the project but installation as well. In addition, a great deal of materials for luminaires and packaging was saved. Finally, the power density (W/ft^2) was reduced by 60%. By designing around the strengths of the technology, we have been able to see breakthroughs in the application efficiency, performance and light quality.

Arrangement of these individual optics is critical to achieving horizontal symmetry and ceiling uniformity. With each LED/optic tilted to the ideal peak candle angle (104^{o},) we could arrange 8 of the optics in a circle and with a small overlap for each (50^{o}) beam provide 360^{o} coverage in the application. Instead of bilateral symmetry, poor uniformity on the ceiling and end-to-end arrangement of the luminaires, this breakthrough allowed for much wider and symmetric spacing. It has been said[x] that the most profound technologies disappear, and it's worth noting that an over-arching request from designers to luminaire manufacturers over the years is to blend in, don't demand attention and, in effect, disappear. Depopulation is the best strategy for achieving this goal.

3. DISCUSSION

The Role of Additive Manufacturing in the development of the Uplight/Heatsink

The indirect engine, LED and optic assembly, require heat sinking. To house these uplight optics, we considered the benefit of using additive manufacturing in the form of a single-piece heat sink and housing. Material uniformity—being one of the tenants of circular design—is a critical requirement in this thought experiment. With traditional manufacturing methods, a separate heat sink would be produced by cast metal; the product designer would need to reconcile any differences in appearance of the heat sink and the remainder of the product. They would also need to mechanically join the heat sink with the other elements of the product. Invariably that would require 2[nd] operations on both the heat sink and the body of the luminaire to produce screw holes, and the two elements would be mechanically attached to one another using screws in order to achieve as seamless of a barrier between the two elements as possible. From an operations standpoint and that of disassembly, this is a non-optimal solution. One of the requirements for Sparkle was that it would be a completely toolless design. This allows not only for ease of assembly in the manufacturing cell but ease of disassembly in the field—a basic tenant of circular design philosophy. Moreover, we were able to create a housing and heat sink as a single monolithic component using the same material as the remainder of the luminaire.

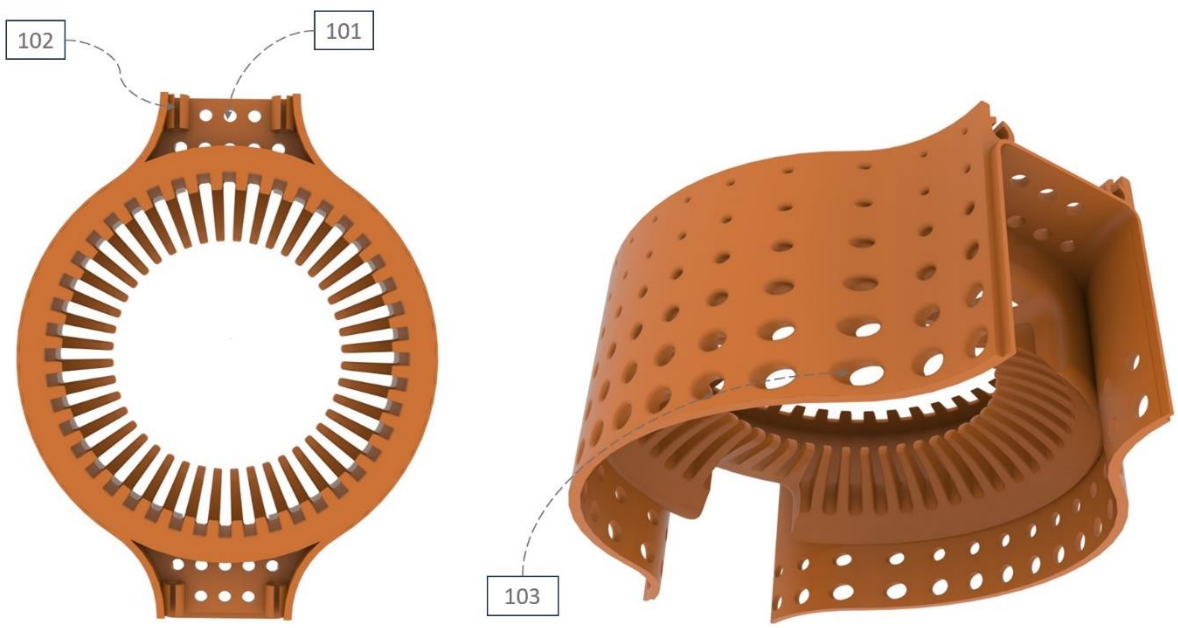

Figure 5. Plan and Isometric View of Uplight/Heatsink component and different hole conditions

Working with the Lighting Research Center, an initial design for a 3D-printed heatsink was proposed and tested for its ability to mitigate heat buildup. Modifications were made to facilitate the incorporation of direct lighting elements as well as novel attachment mechanisms. The results are shown in Figure 5. Even though second operations to create the myriad features would render this component prohibitively expensive to produce, this particular component—as is—would be impossible to create with traditional metal manufacturing techniques. The body shape itself when looked at in plan view would require a mold to produce. The top holes in the x plane (101) could be achieved through machining, but the embossed through holes (102) for toolless attachment of the luminaire to other luminaire components is on a separate y-axis. In addition, the filet features (103) in the cut-outs—some through holes some counter-sunk—would need to be CNC machined. The slope of this third z-axis changes across the length of the fixture. How the component would be captured, so that it could be machined, may be the biggest issue. The slots and filet features for the heat sink fins would also prove impossible to reproduce with state-of-the-art metal machining. While impractical, expensive and impossible to produce via metal fabrication techniques, the only limitations to the level of features and sophistication to the part through additive manufacturing was the imagination of the designer. The final uplight holder/heat sink component is shown in Figure 6 with LED starboard and individual off-the-shelf optic in an array. Worth mentioning is the fact that additive manufacturing facilitated the use of high-risk design strategies. For example, the uplight optic array are held in place via a friction fit with very slight tolerances (<0.1mm.) The ability to prototoype this feature allowed the designer to not only bracket different cavity dimensions in order to find the best fit, but the prototyping allowed them to accurately anticipate the material behavior and flow for subsequent, high-volume additive manufacturing. While 3D printing is an often-used tool in the embryonic stages of metal luminaire design, there is a disconnect between these early prototypes and final parts as a function of not only the variability between metal and plastics but also tolerance variations in metal components for certain manufacturing techniques (such as extrusion.)

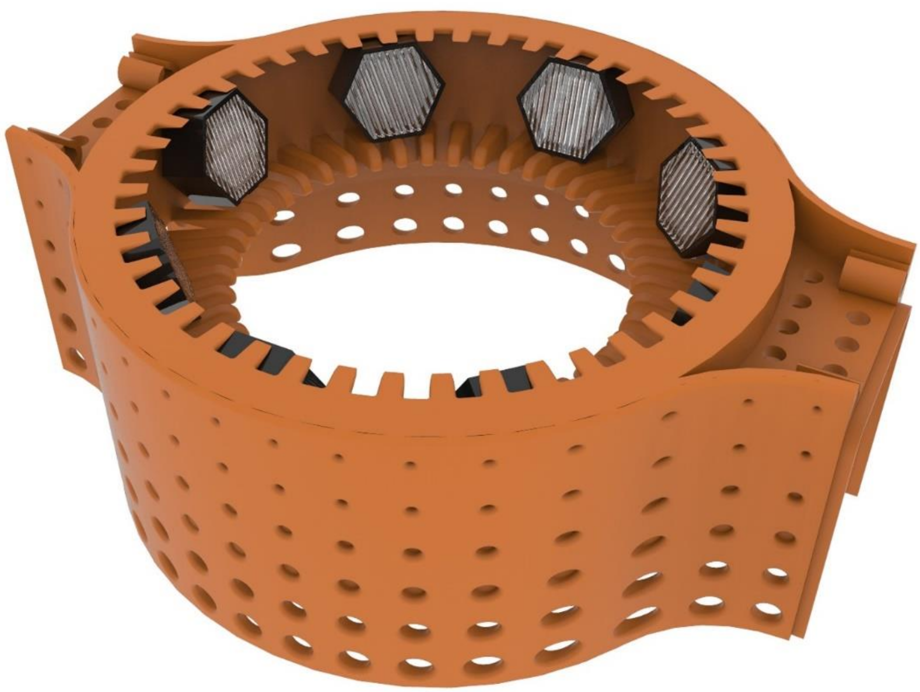

Figure 6. Trimetric View of Heatsink/Uplight Module including individual off-the-shelf optics

Sparkle Louver

Louvers are common in commercial lighting luminaires. They are used to mitigate discomfort glare. The initial idea of the Sparkle louver came from a frustration with the light loss and poor fixture efficiencies for state-of-the-art louvered luminaires. One of the benefits of metal louvers used in traditional fluorescent luminaires was that they were made of sheet metal. They were thin walled (<1mm thick,) and, being metal, they could have some level of specularity. The amount of light scattered back into the luminaire was minimized. The current trend in LED lighting, however, is to have louvers made of plastic. These louvers—as a requirement of the manufacturing techniques and the molds being used—are much thicker than their fluorescent predecessors. Wall thicknesses of 3mm are not uncommon. This results in highly compromised fixture efficiencies. The first requirement for the sparkle louver was thin walls, and additive manufacturing was an ideal method for achieving that outcome. Indeed, the wall thickness of the sparkle louver is < 1mm. We also realized in the design that additional holes could be added to the fins of the louver to allow more light to escape (Figure 7.) Like the heat sink/uplight component, this component is only able to be made through additive manufacturing. Molds would be unable to create all the features, and second operations couldn't be performed on the part without damage. Upon prototyping, we also noticed some unexpected effects.

First, the thin walls of the louver worked in mitigating direct viewing of the light source. Being thin, however and plastic, they allowed a slight transmission of light. The glow from the louver fin itself was aesthetically pleasing and beneficial for subsequent illumination. We also noticed that while viewing the louver from below, tiny pieces of the light source were able to be seen. This had a similar biophilic effect to that of dappled light seen while looking up into a dense canopy of trees in the forest. Previous research on the use of Sparkle in applications came to mind.[xi] Sparkle—described as a narrow band between merely bright and glare—was shown to increase the perception of brightness in commercial lighting applications. This allowed for reduced illumination levels and energy use. The sparkle louver, we hope, may produce the same effect.

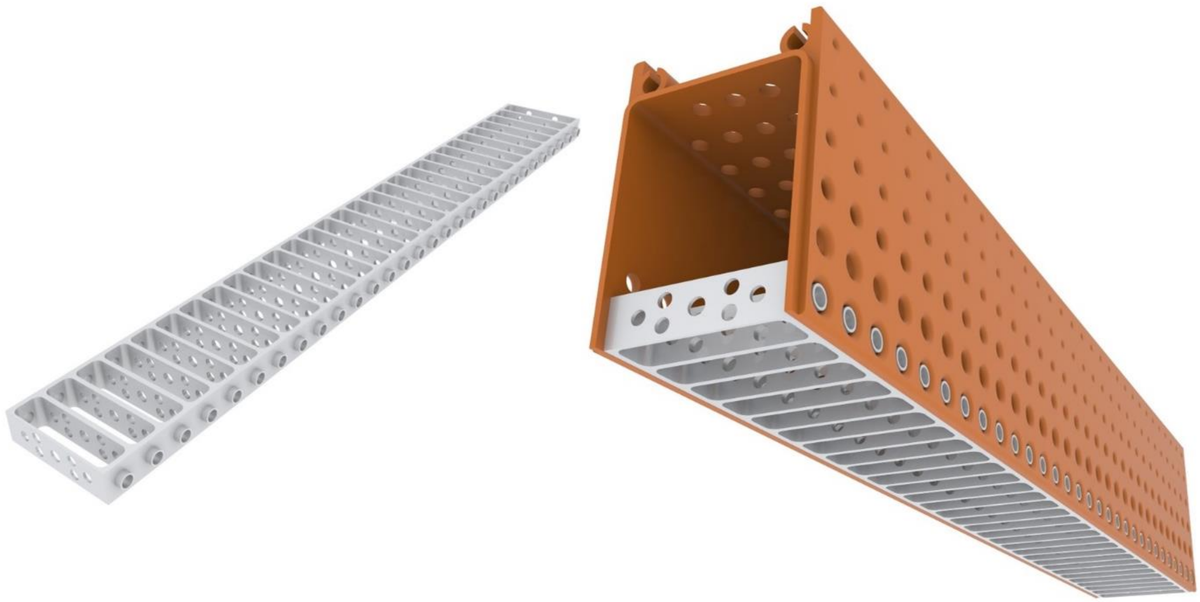

Figure 7. Sparkle Louver and corresponding frame section showing attachment mechanism

The sparkle louver is affixed to the louver by the side protrusions nesting into corresponding holes in the body. Given that the use of plastics provides a slight elasticity. While keeping memory of the original shape, the sides of the body can be pulled out and the louver removed easily with no tools needed for both access to the LEDs and ease of disassembly.

Frame

The main chassis of the frame serves multiple purposes. Many of the features are made possible through the process of additive manufacturing and would not be possible in traditional metal fabrication or machining techniques. Two rows of holes at the bottom of the frame allows for light extraction and sparkle effect. Additionally, the holes serve the potential purpose of sound dampening/absorption in the environment[xii]. In addition to the side holes and perforations, the top of the luminaires has a series of holes (Figure 8.) These holes serve the purpose of accessory attachment both from below and above. Wire routing, hanging hardware and light engine accessories can be friction fit into the holes allowing for ease of disassembly while also being able to pass a UL shake test. There is no need for adhesives or secondary hardware components such as screws. The use of holes across the entire frame allows for the use of less materials in construction, which helps meet our circular economy goals.

Another capability that we have at our disposal that is unique to additive manufacturing is the ability to have printed text on the frame itself. Figure 8 shows an example of disassembly instructions that are printed onto the upper cavity of the frame. In this situation, the information is hidden from direct viewing in the space but is available for any contract workers interfacing with the luminaire in the field. This ability to call out different features and instructions specific to the luminaire can be an important maintenance feature.

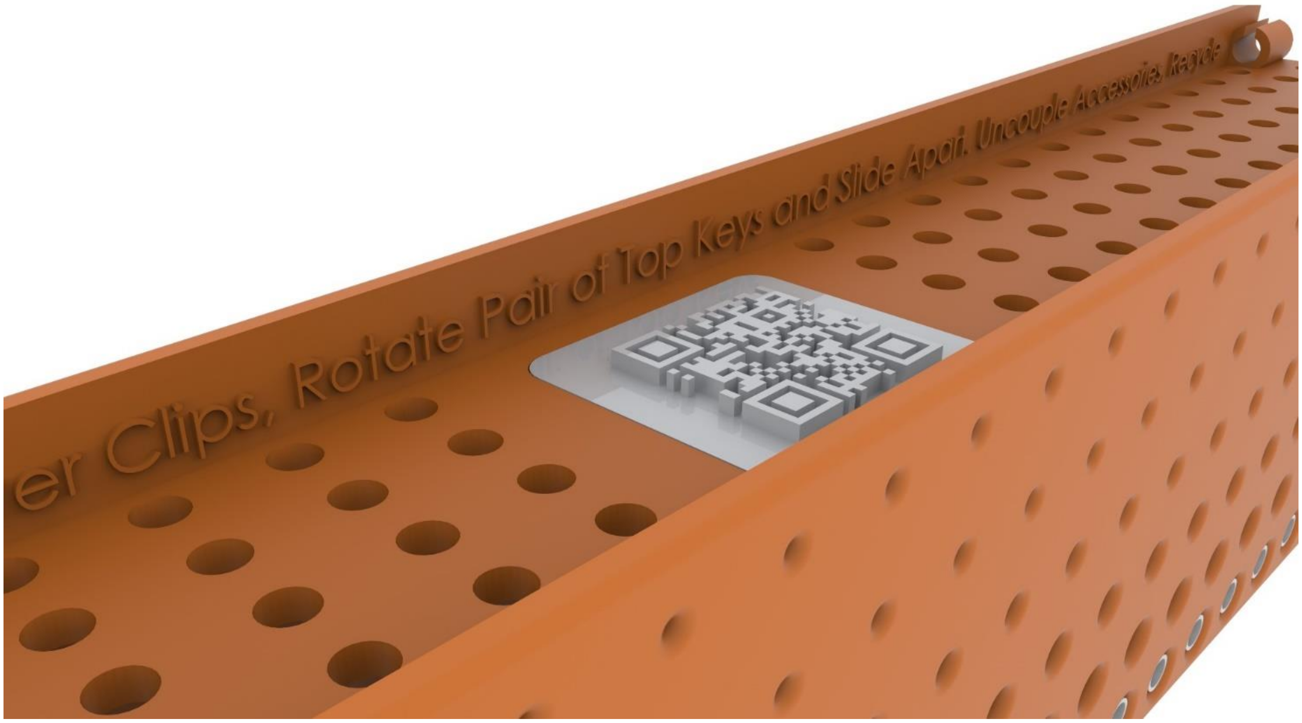

Figure 8. Top of the Body of Sparkle Luminaire showing extruded disassembly instructions and removable medallion

Finally, the use of a removable medallion is unique to this design and easily executed using additive manufacturing. The concept for a removable medallion is based on the expected lifetime of LED systems. Given normal duty cycles in commercial applications, it is expected that LED luminaires can provide functional illumination for several decades. Given the durability of this product type, we cannot be certain of the changing requirements vis-à-vis code and company information. For example, the current model has a QR code that can be scanned by a smart phone. The code will send the user to the Smash the Bulb website where they are directed to installation and disassembly instructions as well as information about materials and application conditions. The QR format may be obsolete within a decade, replaced by something else. Smart phones as well may no longer be prevalent, and the environmental conditions would warrant a newer system. Removability of the medallion allows this information—instead of being permanently affixed to the luminaire via sticker, for example, to be replaced by a newer medallion with updated information. In addition to the ability to update, it is assumed that multiple units are installed in commercial lighting applications, so there is an opportunity to provide different types of medallions with different information. Figure 9 shows medallions with material recycling information and different regulatory designations depending on location.

One notable strategy for achieving circular economy goals in lighting[xiii] is extending product lifetimes vis-à-vis improved maintenance scenarios. The ability to house spare LED engines on the luminaire is critical in this strategy. The LED can be swapped for a *similar* LED if unforeseen issues arise. Luminaires currently have very limited capabilities for servicing—especially without the need for tools. The issue with servicing of LEDs in the field is a result of the LEDs coming from a particular bin, phosphor blend and changes that may occur to these devices in situ over time. For example, LEDs are binned in three separate modes currently: output (in lumens,) color coordinates and forward voltage. AT0 LED module may be prioritized for output, and in the event the luminaire needs to be serviced, it is difficult to match the existing LED in color properties. Having a LED from the same batch not only reduces the time needed to service the product, but the user can also be assured that the LED will match.

Figure 9. 3D-Printed, Removable Medallions: QR code, Recycling Code, Spare LED and Regulatory Medallion

A New Type of Engine

The current trend in LED industry is to use small-format devices (30-60 lumens.) Because of improvements in phosphor technology, LEDs have enjoyed rapid gains in device efficiency and color quality while prices have dropped precipitously. Two of the common low-format building blocks for commercial luminaires is the 3030 (3mm x 3mm) and the 2630 (2.6mm x 3mm) LED packages. Given that the price is so low, it becomes a low-risk strategy for LED luminaire designers to "attack with numbers." The opportunity cost of adding an additional 30% of LEDs, for example, is low given the fact that you can lower the drive current and subsequently improve device efficiency while extending lifetime by lowering current density and temperature. While this makes sense from the standpoint of cost, we have created a scenario where the cost of the LED is less than the FR4 substrate that it is mounted on. Indeed, in a common "level 2" solution that incorporates strings of LEDs (Figure 10,) the LED comprises less than 5% of the surface area of PCB.

Figure 10. Standard Zhaga LED board with LED array vs. Single Starboard with CSP

One of the end-of-life (EOL) strategies for lighting is the reuse and recycling of components. Current trends in LED technology have done away with some of the traditional components of the low-format LED—specifically its packaging. Older LEDs (2630 and 3030) were housed inside of packaging that was sometimes an ablative material such as ceramic, but in most cases was made of plastic. While inexpensive, there was a danger with temperatures and melting of the package. As a result, there are strict limitations on the drive current for low-power devices. Therefore, lumen ranges for the luminaire system are limited on the high end of output. With the advent of Chip Scale Packaging (CSP) type LEDs we not only eliminate a major component of the LED, the package itself, we a free from the constraints of over-driving. As a result, there are available today, many CSP LED packages that emit over 300 lumens—in a much smaller footprint for better flux coupling. In addition, they have a much wider drive current range, which allows for a wide range of product types as a function of lumen output. The sparkle louver employs a novel LED package that can produce 250 lumens (Figure 11.)

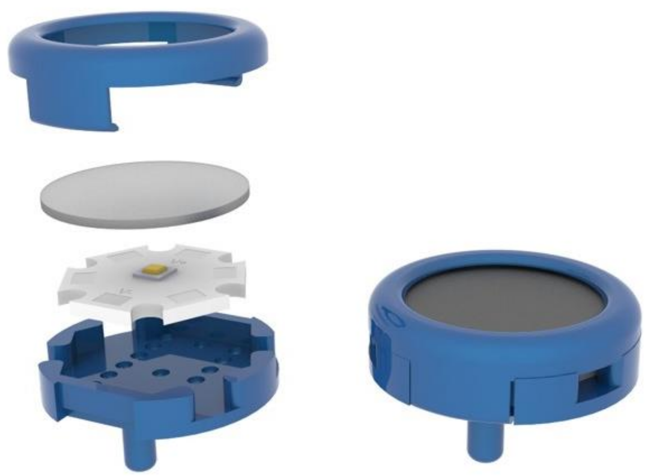

Figure 11. Sparkle Downlight LED module with toolless snap fit housing and removable starboard

Given that a standard metric for specification of linear LED lighting systems today is 1,000 lumens/nominal foot, we can see a scenario where 4 starboards (Figure 12) with CSPs are used to replace the 27 low-power devices that would be on a standard LED board—reducing the number of LEDs in a standard 4' semi-indirect luminaire (uplight and downlight boards) by 92% (in the case of Sparkle) and reducing the amount of PCB material by 84%.

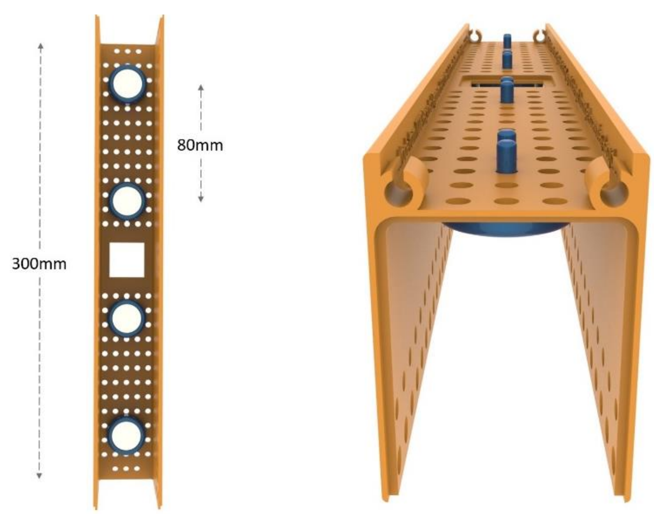

Figure 12. Individual LED modules in frame showing pitch and toolless friction-fit frame interface

Sparkle louver allows for spacing of the LED packages that are not conspicuous. Normal processes use a diffuser (virgin plastic) below each downlight LED array. Uniformity is a must-have, so LEDs are spaced close together (10mm pitch,) the diffuser is placed a certain distance away and reflectors are often used in conjunction. Sparkle louver allows for the use of individual CSP packages and much wider spacing (80mm pitch) with only local diffusers. This creates a circular strategy for luminaire design where the same effect can be created while using much less material.

To the point of re-use, however, it is important to understand the difference in the electrical configuration of the “standard” level 2 boards. Because so many LEDs are used, LEDs (typically 3V nominally) are broken into strings with a number of LEDs arranged in series with multiple strings in parallel. Number of LEDs per board can vary dramatically. In the case of the board in Figure 10, we have 3 strings of 9 LEDs. Even among LED vendors, there is a wide variation in the number of LEDs in a string and the number of strings on a board. Given that the electrical vias are created specifically for this board, the ability to use afterwards is severely limited. A starboard, on the other hand, has a single channel in and a single channel out. The ability to refurbish and reuse not only for lighting applications but for other applications is optimized. This is why the strategy for Sparkle not only reduces the materials used but also anticipates reuse at EOL with this novel engine strategy.

4. MATERIALS AND DESIGN FOR DISASSEMBLY

The burden of metal fabrication is significant on our environment. The number one reason a power plant is built today is for the refining of metal. Copious amounts of water are used in the processing and recycling of metals. Mining of the raw materials of metals creates issues with noxious dust that compromises local air and water quality. The process of recycling also uses a tremendous amount of natural resources, and one of the byproducts of recycling, dross, is considered highly hazardous and needs to be stored in special containers. While the perception of utilizing metal in luminaire manufacturing is associated with the ability to recycle consumer drink containers, the fact remains that only a small percentage of commercial luminaires are recycled at EOL. Most go directly into the waste stream.

One reason for this issue is the inability to easily separate luminaires into individual components, the lack of common material for these components and the use of paints, adhesives that cannot be removed. Sparkle was designed with a key requirement being uniformity of material. Each of the components with the exception of the wiring, the LED and hanging hardware is made of the same materials and can be recycled in the same waste stream. For example, one Sparkle configuration is made from reground plastic. This plastic at EOL again can be reground and reused for luminaires or other types of products. This closed loop system helps reduce the introduction of virgin materials, reduces emissions and exponentially reduces the carbon footprint. One of the main aesthetic advantages of additive manufacturing are the range of colors at the designer’s disposal. Painting and anodization not only compromise the ability to recycle metal luminaires at the EOL, most manufacturers don’t paint luminaires themselves. They are sent out, which creates an additional burden of carbon used in shipping and additional operational steps for quality assurance not to mention waste in the form of rejects. With additive manufacturing, recycled material in the color choice and finish (matte, glossy) can be achieved in the printing process.

Design for disassembly was not only a critical requirement for Sparkle, in the interest of maximizing the circularity, there was a mandate that the luminaire be completely toolless. No screws or fasteners were used. Instead, we employed a series of 3D-printed keys and louver connectors. The key had the effect of pulling the different body parts together (Figure 13.) In addition, the designers used a lip that extruded beyond the frame and a corresponding cavity for accommodating the lip on the opposite side (Figure 14.) This is a detail that would have required extra parts, fasteners and different manufacturing techniques. Take the straight middle section body as an example. This is a part that might be extruded normally. Granted there would be secondary CNC machining that would need to make the holes and filets around the holes, it theoretically would be possible to make this part. The lip and corresponding cavity would require a mold, which would cost tens of thousands of dollars. Because of additive manufacturing, we were able to add these features with no impact on costs. The other connector that we used was a louver clip (Figure 15) that pulls the two adjoining louvers together and allowed for seamless transition due to matching hole patterns. The shape of this clip is easily achieved as a metal part, but the secondary holes on such a small and fragile part would prove to be very difficult to manufacturer without damaging the part and taking too much time to set up given the need to make this component for pennies.

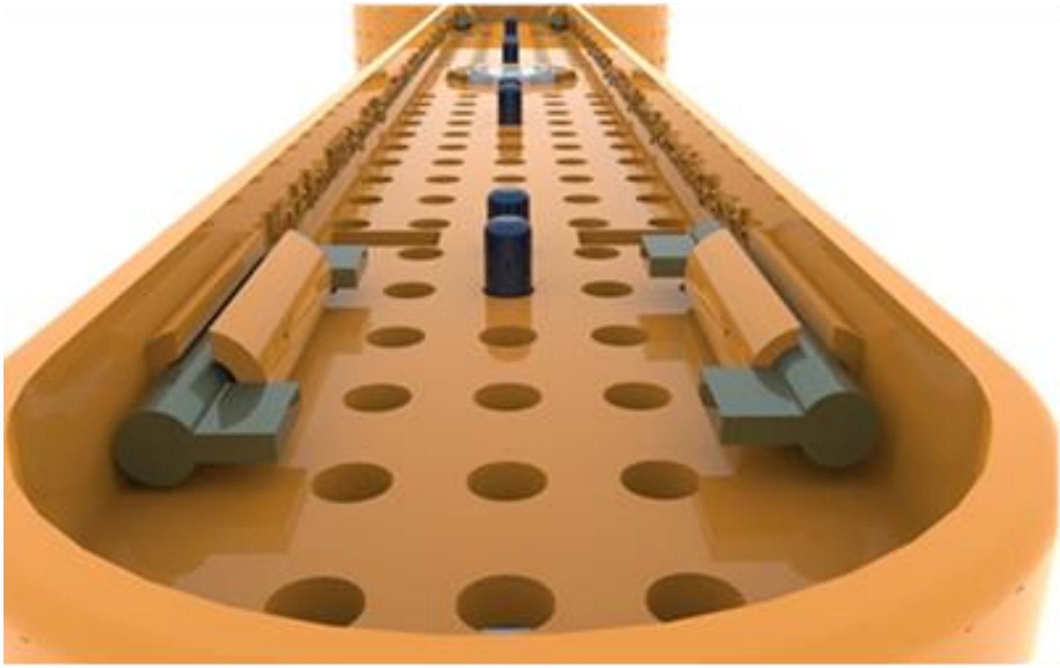

Figure 13. Key locks (in Green) shown in locked position connecting end cap to main body

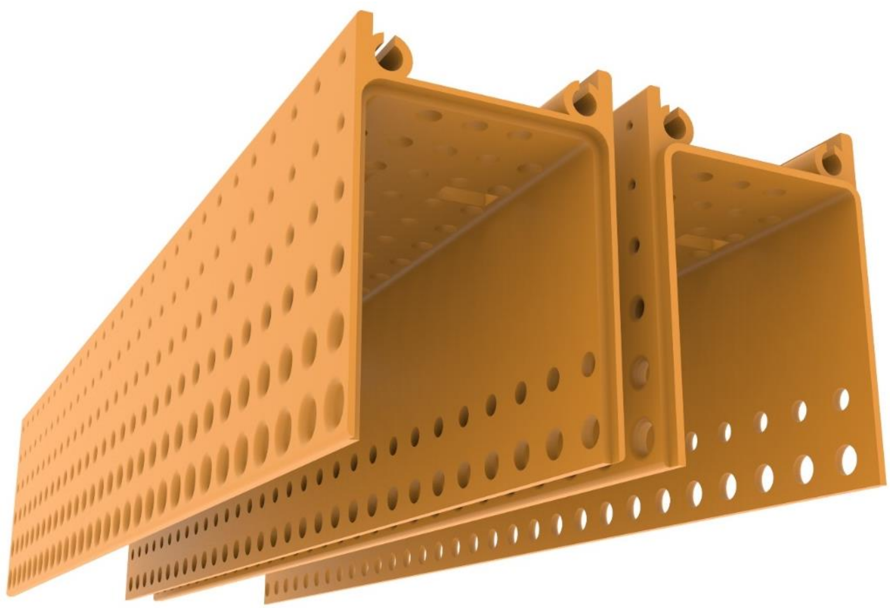

Figure 14. Two middle section pieces showing with opposite sides facing displaying nesting mechanism

Modularity is another strategy for circular design, which we employed in the design of Sparkle. With the use of universal joining components and the lip/cavity technique, there are myriad ways that a Sparkle luminaire may be assembled (Figure 16.) Different radii corners as well as different length body pieces allow for ease of assembly, in-situ servicing and EOL disassembly.

Figure 15. Bottom of Sparkle luminaire with detached louver clip below louver sections to join

Figure 16. Showing Sparkle Eco-System (wood finish) and one example of how modularity can create custom designs

5. DIVERSITY, EQUITY AND INCLUSION

DEI goals were an important requirement—especially as it pertains to equal access to commercial lighting products. Traditional North American sales runs through local agency networks. For small businesses or individual users, the ability to order commercial products is limited. Small orders tend to get de-emphasized. In addition, current practices of overages can make the price to the end-user disproportionally expensive relative to the costs. It is for this reason that we offer these products for free. STL files for the various components (Figure 17) can be downloaded from the Smash the Bulb website. There is a simple TLED version that can accept a standard 4' linear lamp.

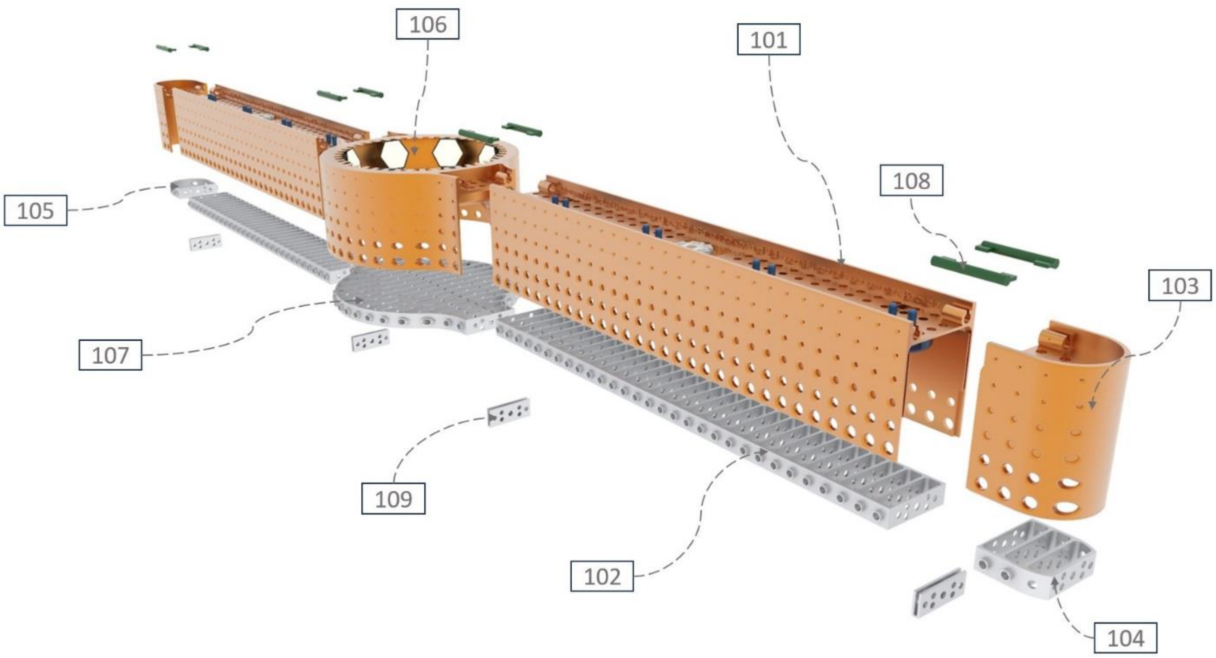

Figure 17. Exploded View of standard, stand-alone Sparkle luminaire with numbered components

Basic cost breakdowns along with amount of material used are shown in Table 3. We used a basic slicing software[xiv] to ascertain material amounts as well as the expected costs for the material used. While the total weight of the print came to 417g and the cost $12.52, it is worth noting that a standard spool of 3D printed filament with 1,000 grams of filament can be purchased for $25. Premiums are charged at this date for recycled filament, but the price does not exceed $40/kg. A standard line voltage TLED, tombstone connectors and hanging hardware would keep total costs for a 4'linear semi-indirect luminaire, well below $40. At roughly $10/linear foot, this represents a great savings over the state-of-the-art commercial luminaires, which could easily fetch 5-10 times that price.

Table 3. Costs and weight of Sparkle luminaire if 3D-printed using readily available SLR printing methods/materials

Component	Part (Fig. 17)	Weight (g)	#	Cost/Unit ($US)	Sub-total ($)
Middle Piece Body	101	81.3	2	2.44	4.88
Middle Piece Louver	102	37.1	2	1.11	2.22
End cap	103	15.9	2	0.48	0.96
Enc cap Louver (no sensor)	104	3.5	1	0.11	0.11
End cap Louver (sensor)	105	2.6	1	0.08	0.08
Uplight Body	106	96.6	1	2.90	2.90
Uplight Body Louver	107	33.6	1	1.01	1.01
Connector Key	108	0.7	8	0.02	0.16
Louver connector	109	1.7	4	0.05	0.20
Totals		**417.3**			**$12.52**

By achieving an inexpensive lighting unit, uncoupling it from the usual sales channels, we provide an opportunity for anyone with access to a desktop 3D printer, which have become ubiquitous in local schools, libraries and some businesses, to benefit from the design.

6. CONCLUSIONS

Sparkle was undertaken as a thought experiment to display the unique benefits of additive manufacturing over traditional manufacturing techniques such as they exist in the luminaire manufacturing industry. The design of sparkle allowed us to achieve many goals. Each of these goals either directly benefited from the capabilities of additive manufacturing or, in some cases, were unique to 3D-Printing. As previously noted, many of the features displayed in Sparkle would not only be prohibitively expensive with traditional manufacturing techniques but would be impossible to produce in scale. For this reason, we consider the design a success.

Achieving performance breakthroughs in the application was an important requirement—specifically breaking the habit of designing around previous paradigm technologies and supply chains and instead designing around the strengths of solid-state lighting. This was facilitated by additive manufacturing in the creation of fewer parts (separate heat sink) with no need for fasteners or adhesives. It also reduces the need for sub-assemblies and off-site, secondary modifications such as painting.

The perception that additive manufacturing is not ready to address the challenges of the commercial lighting industry is resonant of a time early in the adoption of LED technology. At the time (2007-2010,) thought leaders in the lighting industry suspected that LEDs may be suitable for niche applications such as undercabinet lighting, but that there would always be a place for the technologies it was being poised to replace (Metal Halide, Fluorescent and Incandescent.) Today, we see that this is not the case, and that there isn't a commercial lighting application where LEDs haven't or will not dominate in the future (such as UV lighting.) Much the same can be said about additive manufacturing. Given the abilities to customize, lower carbon footprint for products, reduce operational steps/complexities and, most importantly, achieve results other technologies cannot, additive manufacturing is a viable solution to replace metal-based luminaire manufacturing soon.

Circularity is arguably the biggest trend in commercial lighting. Sparkle has shown that features that enhance circularity—from material uniformity, material efficiencies, extended product lifetimes, ease of disassembly, easy reuse/recycling of components and materials and toolless/fastener-free assemblies—can not only be easily realized, they would be prohibitive to do with traditional manufacturing techniques. A visit to a job site where commercial lighting is being installed can show another major benefit of the technology over traditional methods. Not only do most metal-based luminaires travel long-distances to reach their destination (producing tremendous amounts of carbon and utilizing resources in the process,) the waste of luminaire packaging on a typical jobsite can be overwhelming. One of the keenest benefits of additive manufacturing that have not yet been realized is the possibility of mobile 3D printing plants that are on or near the job site—such as in a shipping container with mobile-racking capabilities (Figure 18.) Using a standard size shipping container, we were able to utilize the mobile-racking system to house 132 medium-sized SLA printers. The ability to produce locally saves resources, saves time and prevents unnecessary waste in the process.

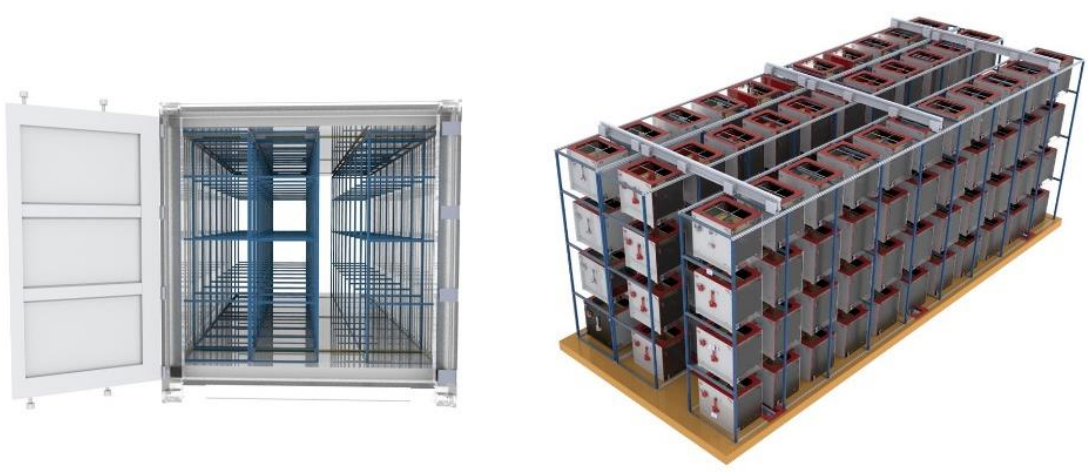

Figure 18. Shipping Container with Mobile-Racking System (left) and containing 132-SLR Printers

Other elements of additive manufacturing that have yet to be fully explored may provide even more efficiencies. Semi-translucent luminaire frames, for example, that increase fixture efficiencies, 3D-Printed optics and circuit boards can help us create a bill of materials that approach 100% additive manufactured parts greatly simplifying the supply chain, while reducing costs and addressing application inefficiencies. Simplifying, producing locally with the option of customization by utilizing additive manufacturing can help create a future paradigm of commercial lighting—the benefits of which will lead to more salubrious applications of light in the commercial environment.

Disclaimer: The Design and Concept of Sparkle discussed in this paper are filed with the USPTO and is designated as Patent Pending

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[2] Akashi, Y., "Effect of sparkling luminous elements on the overall brightness impression," Lighting Research and Technology. (2000) 32(1): 19-26

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[i] DOE Caliper Benchmark Report: Performance of T8 and T12 Fluorescent Lamps

[ii] After 20% fixture losses and 10% power supply losses

[iii] Sometime 4' x 9'

[iv] CBECS 2012: Trends in Lighting in Commercial Buildings

[v] https://www.acuitybrands.com/resources/technical-resources/visual-lighting-software

[vi] https://fluxwerx.com/products/aperture/performance/

[vii] ITL62319, Independent Testing Laboratories, Inc.

[viii] This would address systemic application issues such as cave effect and hot spots with dark surrounds

[ix] 8 candela/lumen

[x] Weiser M. "Ubiquitous Computing"

[xi] Akashi, Y. "Effect of sparkling luminous element on the overall brightness impression," Lighting Research and Technology (2000) 32(1):19-26

[xii] Currently, no sound testing has been performed on the sample/prototype and cannot be verified.

[xiii] Hickox, K and Smith, A. "Strategies for achieving circular economy goals in the lighting industry through design for disassembly-based methodologies," Light-Symp-2022. IOP Conf. Series: Earth and Environmental Science 1099 (2022) 012004

[xiv] Idea maker version 4.2.1