A Study of Additive Manufacturing Applied to the Design and Production of LED Luminaires

Academic Supervisor:
Marinella Levi

Industrial advisor:
Valentina Folli

Graduating student:
Pedro Sanín Pérez
Matricola 797808

POLITECNICO
DI MILANO
Scuola del Design
MSc. in Design & Engineering
Anno Accademico 2013 / 2014

Contents

1. Background 01
  1.1. Introduction 01
  1.2. Project Background 01
  1.3. Justification 02
    1.3.1. Why Additive Manufacturing? 03
    1.3.2. Why LED? 04
    1.3.3. Why apply AM to the production of new LED luminaires? 06
  1.4. Personal Motivation 09
2. Objectives 11
  2.1. General Objective 11
  2.2. Specific Objectives 11
  2.3. Project scope 11
3. Methodology 12
  3.1. The Innovation Process 12
  3.2. The New Concept Development Model 13
  3.3. Creative Problem Solving 14
  3.4. The Mixed Model Methodology 16
4. Literature Review 18
  4.1. Additive Manufacturing 18
    4.1.1. Application Field 20
    4.1.2. AM Process Review 22
    4.1.3. Materials 31
    4.1.4. Design for AM 35
    4.1.5. Future Research 39
  4.2. LED Lighting 41
    4.2.1. Basics principles of Lighting 41
    4.2.2. LED Basics 48
    4.2.3. LED Luminaires 55
  4.3. AM applied to LED Lighting 69
    4.3.1. Case Study 1: Printed Optics 69
    4.3.2. Case Study 2: Advances in heat sink performance with DMLS . 72
    4.3.3. Case Study 3: Heat Transfer Enhancement 73
5. Analysis 75
  5.1. Applicability of AM technologies and materials 75
    5.1.1. Heat management 75
    5.1.2. Optical qualities 81
    5.1.3. Electrical Conductivity 82
  5.2. Analysis of lighting applications (benchmarking) 85
    5.2.1. Luminaires Created by Additive Manufacturing 85
    5.2.2. Recent Commercial LED Luminaires 92

6. Design Configuration 97
  6.1. Design Requirements 97
  6.2. Functional and Morphological Analysis 105
    6.2.1. Functional Analysis 105
    6.2.2. Morphological Analysis 107
    6.2.3. Product Architecture 111
7. Design 114
  7.1. Design concepts 115
    7.1.1. Conceptual references 116
    7.1.2. Design concept 1: Arista 120
    7.1.3. Design concept 2: Air on the G String 123
  7.2. Concepts selection and development 126
    7.2.1. Pendant, floor and wall variations 127
  7.3. Detailed Design 130
    7.3.1. Selection of internal components 130
    7.3.2. Detail design of the body 132
8. Validation and Results 137
  8.1. Design validation 137
    8.1.1. Printing Process 137
    8.1.2. Part assembly 142
    8.1.3. Copper plating 143
    8.1.4. Light generation 145
    8.1.5. Heat dissipation 147
  8.2. Design improvements 149
    8.2.1. Arista V2 149
    8.2.2. Printing and copper plating of Arista V2 152
    8.2.3. Arista Pendant 154
  8.3. Cost validation 155
9. Conclusions and Analysis 157
  9.1. Project Conclusions 157
  9.2. Future research 159
10. References 161
  10.1. Bibliography 161
  10.2. Websites 165
11. Acknowledgements 167

List of Figures

Chapter 1

Figure 01: Why AM?
Figure 02: Why LED?
Figure 03: Average lighting efficacy and cost per bulb projections
Figure 04: Why AM applied to LED?

Chapter 3

Figure 05: The Innovation Process (Bruce Archer, 1971)
Figure 06: The New Concept Development Model
Figure 07: Creative Problem Solving
Figure 08: The Mixed Model Methodology

Chapter 4

Figure 09: Overview of additive processing technologies
Figure 10: Procedure for fused deposition modeling
Figure 11: Staircase effect on curved parts
Figure 12: Classification of AM processes based on different mechanisms of laser-material interaction
Figure 13: Schematic cycle of the SLS process
Figure 14: Classification of metal AM processes
Figure 15: Visible Spectrum of light
Figure 16: Luminous flux generated by a light source
Figure 17: Iluminance
Figure 18: Luminous intensity
Figure 19: Luminance
Figure 20: Photometric curve of a light source
Figure 21: Light color range measured in °K
Figure 22: Warm white, white and cool white
Figure 23: structure of a LED package
Figure 24: Three basic levels of LED
Figure 25: LED panels, spot, strip and COB
Figure 26: Segmentation for cool and warm light binning
Figure 27: Optics produced by LED Engin
Figure 28: Halos generated from narrow, medium, wide and elliptical optics
Figure 29: LED Collimator
Figure 30: LED drivers by BAG electronics
Figure 31: Types of light distribution in luminaires
Figure 32: Light Fixture (Luminaire) Types
Figure 33: Example of LED thermal path
Figure 34: Examples of common heat sinks

Figure 35: Series of special lamps created using embedded components and internal illumination
Figure 36: Heat sinks manufactured by DMLS
Figure 37: Picture of milled copper and DMLS Aluminum alloy heat sinks
Chapter 5
Figure 38: Unterlinden pendant lamp, Herzog & De Meuron for Artemide (2014)
Figure 39: Florensis, Ross Lovegrove for Artemide (2013)
Figure 40: Printed and welded part made with Weld3D technology
Figure 41: Metallic printed part by MatterFab
Figure 42: Custom nylon and copper plated heat sink.
Figure 43: Repliform's electroplating process and results
Figure 44: Results of Luxcexcel's Printoptical in comparison to other AM technologies
Figure 45: Tizio, Richard Sapper for Artemide.
Figure 46: Diagram of curved layer deposition used to create continuous circuits
Figure 47: Searching the term "lamp" in Thingiverse produced 1116 results (15/03/2015)
Figure 48: 3D printed lamps designed by Nervous System
Figure 49: Hyphae lamp by Nervous System, comercialized through Shapeways
Figure 50: Bloom lamp, MGX by Materialise
Figure 51: Lilly lamp, MGX by Materialise
Figure 52: Aphillia and Rhizaria lamps by .exnovo
Figure 53: Knot lamp by Ingo Maurer (2013)
Figure 54: Chapo lamp, Phillipe Starck for FLOS
Figure 55: Aplomb, Studio Lucidi & Pevere for Foscarini
Figure 56: Clay printed parts by +Lab, Politecnico di Milano
Figure 57: One Chair, Konstantin Grcic for Magis
Figure 58: IN-EI, Issey Miyake for Artemide
Figure 59: Etch, Tom Dixon
Chapter 6
Figure 60: Symbols used to represent flows and functions throughout the system
Figure 61: Black Box analysis of a LED Luminaire
Figure 62: Functional Structure of a LED Luminaire
Figure 63: Volumetric representations of the elements that constitute the luminaire

Chapter 7

Figure 64: Lithographic prints by Ernst Haeckel
Figure 65: Four examples of artwork by digital artist Andy Gilmore
Figure 66: Initial exploratory sketches
Figure 67: Arista ceiling fixture concept design
Figure 68: Arista ceiling fixture concept design (2)
Figure 69: Arista ceiling fixture characteristics and components
Figure 70: Air on the G String concept design
Figure 71: Air on the G String concept design (2)
Figure 72: Air on the G String components and characteristics
Figure 73: Arista 2 pendant and floor variations
Figure 74: Arista 2 wall and floor variations
Figure 75: Arista 3 variation shown as pendant lamp
Figure 76: CREE XLamp CXA 2530
Figure 77: Comparison of different COB lamps using CREE Inc.'s Product Characterization Tool
Figure 78: QLT Flat Box 700mA, 23W
Figure 79: LEDiL's Angelina reflector designed specifically for CREE COBs
Figure 80: Recommendations to improve the model done by +Lab Milano
Figure 81: Arista body with modifications
Figure 82: Section view showing the component assembly

Chapter 8

Figure 83: Printing a 1:5 scale model of Arista's body using Ultimaker 2 FDM printer at +Lab
Figure 84: Printing process and results with the DELTA 40-70 FDM printer
Figure 85: Removing the brim and the supports
Figure 86: Crown-shaped ring and base plate prints
Figure 87: Assembly of electronic components and printed parts
Figure 88: Problems with Crown-shaped ring and base plate
Figure 89: PLA copper plating tests at Politecnico di Milano
Figure 90: Arista body after copper plating
Figure 91: Detail of the assembly between the COB, the aluminum heat sink and copper body
Figure 92: Luminaire shown with half of the light beam covered by the diffuser sheet
Figure 93: Lamp lit
Figure 94: Room illuminated by Arista positioned in the ceiling
Figure 95: F13671_ANGE-RZ-LENS manufactured by LEDiL
Figure 96: Thermal images of the lamp
Figure 97: General view (render) of Arista V2 lit
Figure 98: Driver compartment
Figure 99: Exploded View of Arista's components

Figure 100: Minimum diffuser size to cover the light flux angle
Figure 101: Printing results of Arista V2
Figure 102: Sanding the edges of Arista V2
Figure 103: Arista V2 with copper plating assembled with aluminum disc and LED
Figure 104: Driver compartment printed in white PLA
Figure 105: Arista pendant version printed in white ABS

List of Tables

Chapter 1

Table 1: Comparison of selected additive processing technologies

Chapter 6

Table 2: Design Requirements evaluated for several commercial luminaires
Table 3: Design Requirements with metric, units and values
Table 4: Morphological Chart of a LED Luminaire

Chapter 8

Table 5: Costs of manufacturing 1 Arista luminaire

Abstract

Additive manufacturing allows manufacturing products with shorter lead times, lower ramp-up investment, more flexibility in form and design, and high personalization. Many of these qualities are required in the lighting industry, especially in small and medium enterprises. There are several cases of successful implementations of AM for the production of luminaires, but they have been driven by the AM industry rather than the lighting industry. The later has very specific requirements, especially in regards to the production of LED luminaires. The mechanical, thermic, optical and aesthetical characteristics of these luminaires require special attention, and large improvements can be made through a study of these requirements and the most appropriate design solutions that can be provided by AM. This project carried out this analysis, in order to identify possible design solutions. A luminaire was designed in order to demonstrate the results of this analysis. The result, named Arista, is a LED luminaire manufactured by FDM, which has a copper plating process that allows it to dissipate heat. It is a design solution that takes advantage of the full potential of both technologies, representing an innovation in functionality, aesthetics and in its market approach. This solution intends to demostrate to the lighting industry the high potential that exists in AM, and the infinite possibilities that can result from approaching these novel production technologies.

La manifattura additiva permette la fabbricazione di prodotti con tempi di consegna più brevi, investimenti iniziali più bassi, maggiore flessibilità nella forma e design, e l'alta personalizzazione. Molte di queste qualità sono necessarie nel settore dell'illuminazione, in particolare nelle piccole e medie imprese. Ci sono diversi casi di implementazioni di successo di AM per la produzione di apparecchi illuminotecnici, ma sono stati guidati dall'industria AM anziché del settore dell'illuminazione. Questo ultimo ha esigenze molto specifiche, in particolare per quanto riguarda la produzione di apparecchi d'illuminazione LED. Le caratteristiche meccaniche, termiche, ottiche ed estetiche di questi apparecchi richiedono particolare attenzione, e grandi miglioramenti possono essere fatti attraverso uno studio di tali requisiti e le più adeguate soluzioni progettuali che possono essere forniti da AM. Questo progetto ha condotto quest'analisi, per identificare possibili soluzioni progettuali. Un apparecchio è stato progettato per dimostrare i risultati di quest'analisi. Il risultato, denominato Arista, è un apparecchio a LED prodotto da FDM, che ha un processo di placcatura di rame che permette dissipare il calore. Si tratta di una soluzione di design che sfrutta tutte le potenzialità di entrambe le tecnologie, che rappresenta una novità in termini di funzionalità, estetica e nel suo approccio al mercato. Questa soluzione si propone per dimostrare al settore dell'illuminazione l'alto potenziale che esiste nell'AM, e le infinite possibilità che possono derivare da avvicinarsi a queste tecnologie di produzione innovative.

01.Background

1.1 Introduction

This report presents the results of a research and case study; the implementation of Additive Manufacturing technologies to the field of LED lighting. An initial phase of research was developed, where the 2 technologies where studied to evaluate the possible configurations, mutual benefits and potential improvements that could lead to a feasible product design. After this, a lamp design project was developed as a case study to validate the research results.

1.2 Project Background

Lighting leads a person instinctively through a space, and it controls what one sees or doesn't see. It can quickly and simply change the atmosphere of a space and how a person feels while in it. Additionally, the proper level of illumination allows the user to easily complete the tasks required.

The recent (less than 10 years) introduction of LED to the general lighting industry created a true revolution in lighting design, allowing designers to create products with shapes and features that were previously unthinkable. A LED is fundamentally different from all other light sources, in that it does not use a filament, a gas, or a fragile glass enclosure. It is a semiconductor device that emits visible light, and it comes in many different formats and shapes that in many cases have no resemblance whatsoever with a light bulb, nor do they have the same requirements in terms of shading, heat dissipation, etc. During decades the incandescent bulb was the standard by which all luminaires where made, but its forced extinction due to the introduction of more energy efficient light sources has led to a whole new breed of luminaire designs. Because of their unique anatomy compared to other light sources, many designers choose to develop fixtures around the geometry of a LED, instead of producing light bulbs to fit into the sockets of existing luminaires. This approach generally produces superior results, providing increased efficiency and longer life. Designers are tasked with identifying a suitable aesthetic language that benefits their physical characteristics and progressive qualities. The unfamiliar aesthetic, as well as new functional and luminous properties of these lighting technologies, offers a blank canvas for designers to exploit in highly personal ways.

Since the introduction of LEDs this technology has evolved at an incredibly fast pace, as new innovations arrive to the market every day. Without a foreseeable stabilization in the near future, it is expected that it will continue to develop at this pace, increasing in performance and reducing its costs until it will replace all other light sources. However, as LED is a new technology with new characteristics and requirements for product design and development, introducing LED lighting fixtures may be an initial burden for small traditional fixtures companies. Many companies find it hard to invest in new product developments; it's rather frustrating that during the product development cycle, continuously better LED components arrive on stage, so before the new luminaire is ready, it already needs an update. Therefore, it is risky for these companies to invest in time consuming, expensive molds and volumes of molded parts. Obsolescence is causing a huge waste, straining both environment as well as balance sheets, and companies are forced to use standard parts, making luminaires from different competitors look the same, and making it hard to customize products for specific projects or applications.

1.3 Justification

Taking in mind the panorama of the LED lighting industry exposed in the previous segment, Additive Manufacturing is proposed as a possibly appropriate production technology for new LED luminaires. To justify the formulation of this hypothesis, three questions must be answered:

1. Why Additive Manufacturing?
2. Why LED Lighting?
3. Why apply AM to the production of new LED luminaires?

1.3.1 Why Additive Manufacturing?

Additive Manufacturing is the name given to a series of technologies where three-dimensional parts are fabricated directly from CAD models and built in a layer-by-layer manner. These technologies will be presented in detail on Chapter 4.

Among the many benefits they have over other manufacturing technologies:

- There are few limitations in form, as undercuts become irrelevant in many cases. Some AM technologies allow even the production of precise, mathematically inspired textural surfaces, interlocking shapes or forms within forms.
- Design is less restricted, as virtually anything the designer can 3d model can be created with an AM machine.
- There is no need for stock, as products can be created on-demand, whenever/wherever.
- Material offer is large, with unique features and qualities.
- The rising offer of desktop 3d printers and online part collections allows imagining a future where everyone has a production facility “at home”.
- These technologies require a less experienced and skilled workforce, allowing for a cost reduction in this sense.
- Printed parts may be designed to avoid having assemblies.
- Designed parts may be uploaded and sold/shared through online services such as Thingiverse, GrabCAD, and others.
- Additive technologies have in general very little waste material resulting after production.
- Form variations over time are much easier than with other technologies, allowing customizing products, updating them, etc.

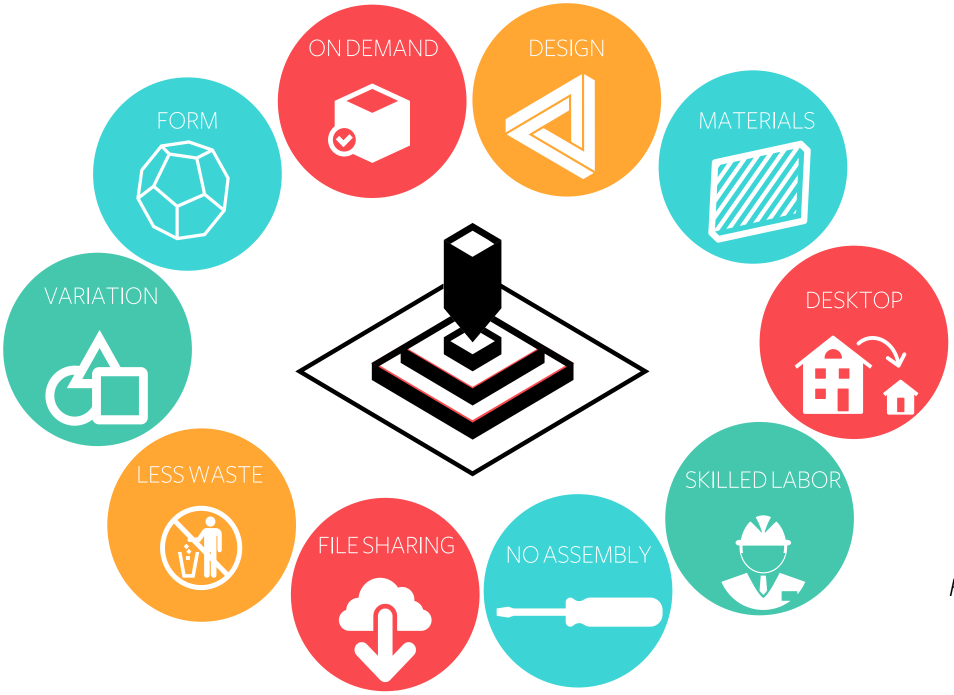


Figure 01: Why AM?

1.3.2 Why LED?

The market is on a clear transition path from traditional lighting technologies to LED. Regulation across the globe has become more stringent, fueling the penetration of more energy-efficient light sources, such as LEDs. For example, China has now passed legislation to ban incandescent light bulbs.

LED prices have eroded more aggressively, pulling forward the payback time of LED lighting. McKinsey's 2012 Global Lighting Market Model calculates the LED share in general lighting at 45 percent in 2016 and almost 70 percent in 2020. The green revolution in lighting is also continuing apace, with other energy-efficient lighting technologies being acknowledged as a bridge towards full LED penetration. In some countries, the price of LED lamps is expected to become competitive with CFLs (compact fluorescent lamps) as soon as 2015[1], which will further speed up the transition from CFLs to LEDs.

There are several reasons that explain this foreseeable LED

---

[1] McKinsey & Company. Lighting the way: Perspectives on the global lighting market. 2012

dominance:

- LED are more efficient (luminous performance) than any other light source. For example, as an incandescent lamp does 10-15lm/w, and a compact fluorescent lamp does 50-85lm/w, a LED Cree can do 74-139 lm/w, and is continually improving (the 300lm/w barrier has been recently exceeded).
- LEDs do not produce any UV or IR radiations.
- They have no toxic materials in their production, like mercury found in fluorescent lamps.
- The life of a LED is very long, usually over 50,000 hours (more than 15 years under a normal house use).
- Low maintenance costs.
- LEDs are resistant to vibrations.
- Lighting is immediate, with full intensity being reached in 1-2 seconds.
- Thanks to savings in energy, they contribute significantly to reducing CO2 emissions into the atmosphere.
- Economic savings directly linked to energy savings.

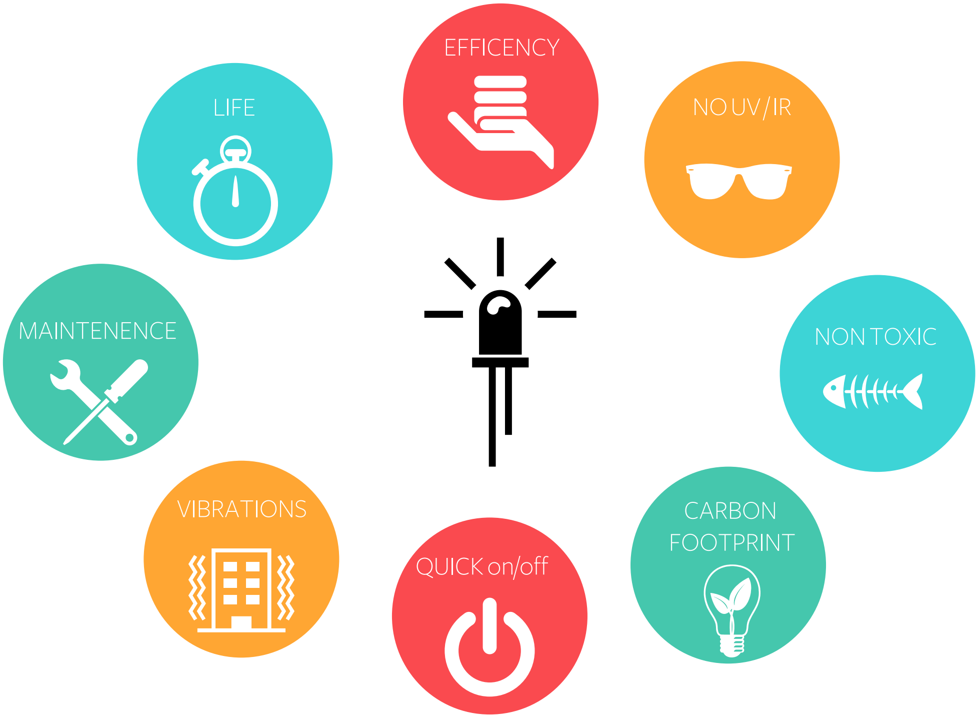


Figure 02: Why LED?

1.3.3 Why apply AM to the production of new LED luminaires?

Until now each technology has been presented individually and the benefits of each one are clear. However, beyond the benefits it is important analyzing how these two technologies combine… will their benefits multiply? Will their individual flaws be improved by the combination? These are the questions this research and design project sets out to resolve.

There are some initial promising areas where the use of AM technologies to the design and production of LED luminaires seems to provide potential benefits and improvements:

Form: Form is a definitive factor in lighting design. Luminaires, during the day, are mostly decorative objects, and their aspect impacts enormously the overall look of a space. When lit, the form is also enhanced, and whatever textures or materials existent are rendered visible. New formal languages are needed, new icons that have the look and feel of the 21st Century and have a suitable aesthetic for new LED developments. Traditional manufacturing technologies have many limitations, not only regards to form, but specially regards to repetition, as molds and manufacturing fixtures require thousands of identical units to be produced in order to offer any economical feasibility. Repetition is a paradigm of the industrial revolution, not of the 21st Century. In a time of individuality, customization acquires importance; exclusivity, expression, one-of-a-kindness. Additive Manufacturing allows creating these shapes of the future, where creativity is the only limit, where ongoing evolution of digital design allows visualizing, sharing and producing products in ways that were unthinkable a few years ago. With the freedom to visualize and realize almost any shape, the ongoing challenge for lighting designers is to identify appropriate uses for these techniques that result in a necessary synergy between light, form, material and process.

Variation: As exposed before, the fast development of LED technologies makes it hard for companies to mass produce lamps because these need constant updates. For a company like IKEA that can sell millions of units in a year it's not a big deal to create new molds, but small and medium enterprises can't be making these economical efforts each year so their products end up being outdated regards to those of their competition. Updating a product must not be a means of planned obsolescence; the idea is not to continually create "new" products that will make the previous look "old", but to keep a product feasible for a company over time. As LED supplies reduce their prices and increase performance luminaires must reflect these changes, otherwise they will lose market appeal (Figure 03). LEDs have a life span of 50,000+ hours, so a person that buys a product should have it for many years and not feel the environmentally harmful urge to replace it before it reaches its end of its service life. There are two ways to do this; creating a product that can be updated over time, or creating a timeless piece that still feels "new" despite the pass of time. Having a person update his/her lamp over time is a difficult enterprise and it will still generate waste. The second method instead has two approaches; the case of lamps such as Artemide's Tolomeo that is such an icon that it becomes as attractive now as it was in 1986 when it first appeared; or a lamp that is so customized and so personal that it becomes an exclusive, something that won't be comparable to successive products because of its unique nature. In both cases additive manufacturing becomes an attractive possibility. Not many companies have the possibility of creating Tolomeos, but if a company did create a lamp that becomes an instant icon it should continue to exist for many years in the market despite technological changes. Digital fabrication allows for easy internal housing changes to accommodate different electrical supplies, to update the "inside" of a lamp without affecting its exterior. Additive manufacturing also allows customizing products much easier, so products become an individual's personal treasure instead of a fashion item subject to trends.

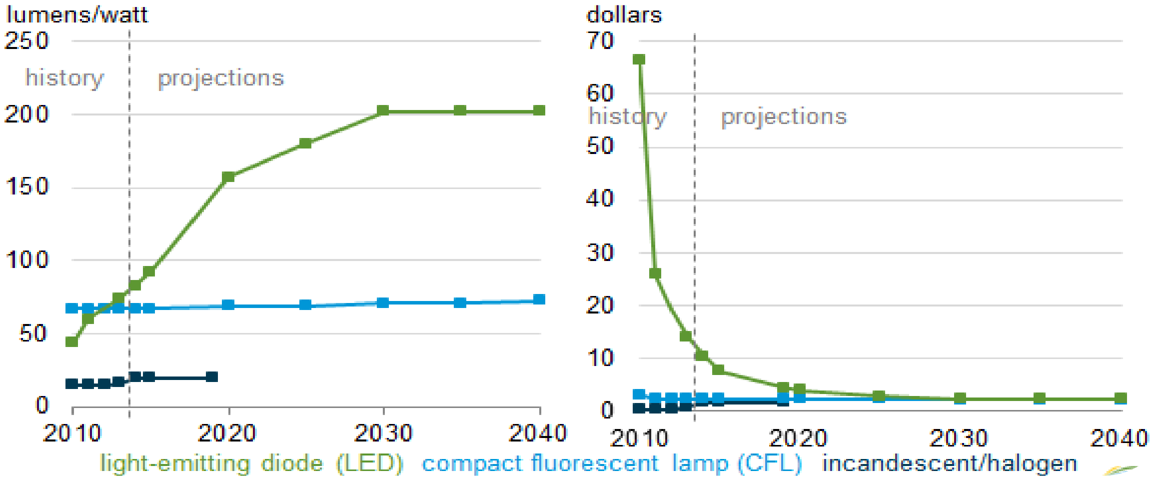


Figure 03: Average lighting efficacy and cost per bulb projections 2

Lead-times: There is a common practice in the lighting industry of showcasing new product developments at design fairs to test the public's reception and decide to continue the development into a full product or not. Usually these luminaires are showcased while still at a very initial phase of their development, so prototypes must be manufactured manually or through Numeric Control machines or Additive Manufacturing tools. However, in case the product is successful it must still have a long development before it reaches the market, the design must be finished, the internal components must be chosen and negotiated, molds must be produced, technical tests performed, packaging designed, etc. This process may last anywhere from 6 months to several years. In this long gap between the product's initial "unveiling" and the actual launch the product can easily lose market appeal, buyers might become inpatient and lose interest, the product may change due to production restrictions, etc. Additive Manufacturing may help avoid this because lead times are reduced drastically, as no molds are required and setting up production is very quick. If the amount of units to be sold is expected to exceed what is economically feasible with Additive Manufacturing, an initial production lot may be manufactured by this method to be sold before the final molded parts are

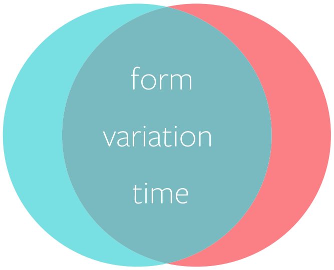


Figure 04: Why AM applied to LED?

---

2 http://theenergycollective.com/todayinenergy/356546/led-bulb-efficiency-expected-continue-improving-cost-declines

produced. This is known as Bridge Manufacturing because it bridges the gap between product design and production. In order to have this method be successful the product must be designed to be produced by both technologies (the temporary AM and the definitive mass production technology) with minimal changes in appearance and performance.

1.4 Personal motivation

I did my MSc Design & Engineering's internship at NEMO Lighting, a company that produces and sells beautifully designed luminaires with the "made in Italy" identity and a strong strive for innovation. I enjoyed this internship very much and found it inspiring in many ways. I would like for companies such as NEMO, where design is a fundamental asset of the company, to have success and continue to exist, despite the fierce competition of mass production and market giants. To do so, they must continue to be innovative and be always one step ahead of mass-produced, low-cost luminaires. Furthermore, they must concentrate their efforts in areas where they can be strong, such as design, marketing and sales, and less on production. For small companies production is often a weak area that slows down creativity in many cases and generates excessive lead times and costs. Thinking on ways to improve this, Additive Manufacturing came to mind, and the idea grew in my mind as I started to research what was being done and thinking of the potential these manufacturing technologies could have for companies such as NEMO. As I approached the end of my internship and discussed it with experts on both fields, lighting and AM, I found other interesting possibilities of following this research, and found it to be at the precise point where research must be done, where it's getting warm but before it boils.

The road to innovative product design is not always straight forward. It is difficult to justify why some ideas come to reality, who would invest on then, who took the risk. There are few opportunities in life where the economic success of a product's design is not the designer's top prerogative, where he/she gets the chance to follow a desire, a 'hunch', an idea, without the urge to find a lucrative remuneration at the end. Where he can take the chance to research and follow this idea despite the risk of finding it unfeasible at the end of the road. This thesis is, most probably, one of the few chances I'll have to do this in my life, taking in mind that after my graduation I will have to live off my work. As Enzo Mari said[3] , *"guardo all'università come a un miraggio, il luogo felice in cui la società riconosce a un giovane il diritto di pensare, riflettere, potenziare la propria capacità di acquisire conoscenza senza obbligarlo a vendere immediatamente I frutti del proprio impegno".*

I started this project with what I thought was an interesting idea, but most importantly, with curiosity of what was up to that point an unknown outcome, a big "what if": What if Additive Manufacturing was used to produce innovative LED lamps, not only gadgets with a neat and complex shape, but really feasible, functional, and out of the box? My motivation was to find out, to solve this curiosity, to prove or disprove this possibility.

---

[3] Mari, E. 25 Modi per piantare un Chiodo. Mondadori, Milano. 2011 p.23

2. Objectives

2.1 General Objective

The general objective of this project is to:

“Research how Additive Manufacturing can be used to improve the design and production of LED luminaires and validate the research results with a new luminaire design.”

2.2 Specific Objectives

The general objective can be divided into the following specific objectives:

- Research and identify key technical, economical and aesthetical aspects of LED luminaires that are susceptible of being improved by Additive Manufacturing.
- Research and identify Additive Manufacturing processes, materials and machines that could provide potentially beneficial solutions to the design and production of LED luminaires.
- Research and document the State of the Art of Additive Manufacturing applied to lighting design.
- Design, fabricate and test a LED luminaire to demonstrate and validate research findings.

2.3 Scope

This project will be developed in the lapse of 11 months running from May 2014 to March 2015. The project has an academic purpose of a Graduation Thesis within the framework of the Design and Engineering Master of Science program at Politecnico di Milano. The research results and product designs generated are strictly of academic nature, with further study and development required in case of any economic interest derived thereof.

3. Methodology

The methodology proposed for the development of this thesis project is a mix of three different methodologies for new product development, innovation and problem solving.

3.1 The Innovation Process

One of the most influential Design theorists in history was Bruce Archer from the UK. He was professor at the Royal College of Art in London when, in 1971, he published a six-stage model of the product innovation process, and inside the stages he placed different steps. He did not start with a product idea or an ideation stage, but was one of the first scholars to introduce the idea that product design has to fit within the corporate strategy of a company. He also merged the ideas from the engineering worlds with the ideas from the commercial worlds: his model is one of the first integrated product innovation models. The model is shown in Figure 5.

This model is important for the overall development of the product innovation process that was used in this project. It has all the main phases, and has all the stages necessary for research, design and development. However, the only “flaw” that was found is its linear nature, which is often not representative of the reality of research and design. Specially on the initial stages, when a design concept is not clear, it is very common to jump from one phase to another and backwards as new paths are continually emerging as result of new ideas, findings, opportunities, etc.

1	**POLICY FORMULATION**	Establish strategic objectives. Lay down outline timetables, overall budgets and guide lines.
2	**PRELIMINARY RESEARCH**	Select an invention, discovery, scientific pple, product idea or technological base. Identify an area, marketing opening, consumer appetite, product deficiency or value base. Establish the existing state of the art (library and market research). Prepare outline performance specification. Identify probable critical problem areas.
3	**FEASIBILITY STUDY**	Establish technical feasibility (basic calculations). Establish financial viability (economic analysis). Resolve critical problems in principle (inventions). Propose outline overall solutions (sketch designs). Estimate work content of phases 4 and 5 and probability of success.
4	**DESIGN DEVELOPMENT**	Expand and quantify performance specification. Develop detailed design. Predict technical performance and product costs. Prepare design documentation. Design technical evaluation experiments and user trials.
5	**PROTOTYPE DEVELOPMENT**	Construct prototypes, mock-ups. Conduct bench experiments with prototypes. Evaluate technical performance. Conduct user trials with prototypes. Evaluate performance in use.
6	**TRADING STUDY**	Re-appraise market potential in light of trials. Re-appraise costing. Appraise marketing/production problem. Revise performance specification.

Figure 05: The Innovation Process (Bruce Archer, 1971)

3.2 The New Concept Development Model (NCD)

This model was created by a group of fourteen innovation practitioners from eight multinational companies who rejected the notion of a logical sequence in the innovation processes. They compared the Fuzzy Front End (FFE) of innovation with the new product and process development (NPPD) and concluded that the NPPD process is a logical, structured, disciplined and goal-directed activity with a project plan, in contrast to the FFE, which is experimental, chaotic, difficult to plan and unpredictable[1]. Therefore they collectively determined the best practices of the Fuzzy Front End (FFE) of innovation. The model consists of three key parts: five front end elements, the engine that powers the elements, and external influencing factors[2].

The main contribution of this process to the methodology

---

[1] Buijs, Jan. "Modelling product innovation processes, from linear logic to circular chaos." Creativity and innovation management 12.2 (2003): 76-93.

[2] Koen, Peter, et al. "Providing Clarity and a Common Language to the "Fuzzy Front End" Research-Technology Management 44.2 (2001): 46-55.

is its cyclic nature. It is very interesting to find a model that reflects what was said previously, that during new concept development it is hard to have a lineal sequence, because of the chaotic and unpredictable nature of innovation. The stages described, similar to the initial stages of Archer's methodology, work as a cycle where there are inputs and outputs but the process is continually spinning, driven by what the author's call 'the engine'; a force that represents the leadership and culture of the organization.

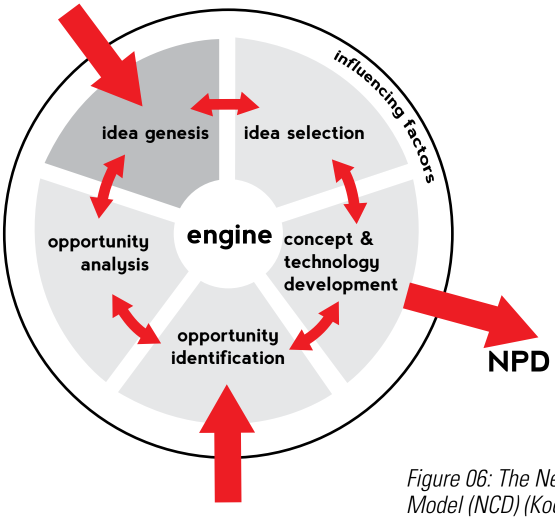


Figure 06: The New Concept Development Model (NCD) (Koen et.al, 2001)

3.3 Creative Problem Solving

Creative Problem Solving (CPS) is the trademarked name for the Osborn-Parnes process of how to solve problems creatively. Alex Osborn, the "O" in the advertising firm BBD&O and is credited with being the Father of Brainstorming, and Sidney Parnes, PhD, a psychologist who worked with Alex Osborn and designed methods for teaching CPS[3].

Creative Problem Solving is a proven method for approaching a problem or a challenge in an imaginative and innovative way. It's a tool that helps people re-define the problems they face, come up with breakthrough ideas and then take action on these new ideas. Alex Osborn and Sidney Parnes conducted extensive research on the steps that are involved when people solve problems, the result of which is the following 6 steps that are broken down into 3 stages:

---

[3] http://en.wikipedia.org/wiki/Creative_problem-solving

Figure 07: Creative Problem Solving (Alex Osborn and Sidney Parnes)

The following is the description of the 6 steps in the author's words[4]:

(OF) Objective Finding - Identify Goal, Wish or Challenge
This could be a wish or a goal. It might be the initial dissatisfaction or a desire that opens the door to using the CPS process.

(FF) Fact Finding - Gather Data
Assess and review all the data that pertains to the situation at hand. Who's involved, what's involved, when, where, and why it's important. Make a list of the facts and information, as well as the more visceral hunches, feelings, perceptions, assumptions and gossip around the situation. In this step, all the data is taken into consideration to review the objective and begin to innovate.

(PF) Problem Finding - Clarify the Problem
In this step, explore the facts and data to find all the problems and challenges inherent in the situation, and all the opportunities they represent. This is about making sure you're focusing on the right problem. It is possible to come up with the right answer to the wrong problem. Re-define what you want or what's stopping you.

---

[4] http://www.creativeeducationfoundation.org/our-process/what-is-cps

(IF) Idea Finding - Generate Ideas
Generating ideas is much more than brainstorming. During this step, be vigilant about deferring judgment and coming up with wild, outrageous, out-of-the-box ideas. This is where you explore ideas that are possible solutions and have the most fun. It's also where you need to stretch to make connections, take risks, and try new combinations to find potentially innovative solutions.

(SF) Solution Finding - Select and Strengthen Solutions
First, try to strengthen and improve the best ideas generated. Next, generate the criteria that needs to be considered to evaluate the ideas for success. Apply that criteria to the top ideas and decide which are most likely to solve the redefined problem. The best idea needs to meet criteria that makes it actionable before it becomes the solution. A creative idea is not really useful if it won't be implemented.

(AF) Acceptance Finding - Plan for Action
In this step, look at who's responsible, what has to be done by when, and what resources are available in order to realize this idea as a full-fledged, activated solution.

This process is very generic; it is not directed at product development or design but at general problem solving. However, the phases presented are the daily bread of a designer, and this simple, straight forward terminology is more useful and representative of real life design practice than many academic models. For this reason they were adopted on the final model, because although Archer's phases continue to be the 'backbone' of the methodology the 6 phases of this model become an effective way of expressing the mental process that the designer is going through.

3.4 The Mixed Model Methodology

The final model, as stated previously, is a combination of the 3 models exposed. Two levels are present throughout the model; a procedural level and a mental level. Procedures are best described by Archer's 6 phases, although the first 3 are developed in a cyclic engine, taken from the NCD model. The mental level describes the mental process that occurs while these procedures are being executed, and this is done best by taking the 6 steps in The Creative Problem Solving model. The first 5 of these steps replace the 5 steps inside the NCD model, and the last step (acceptance finding) is a linear process that includes Archer's last 3 phases.

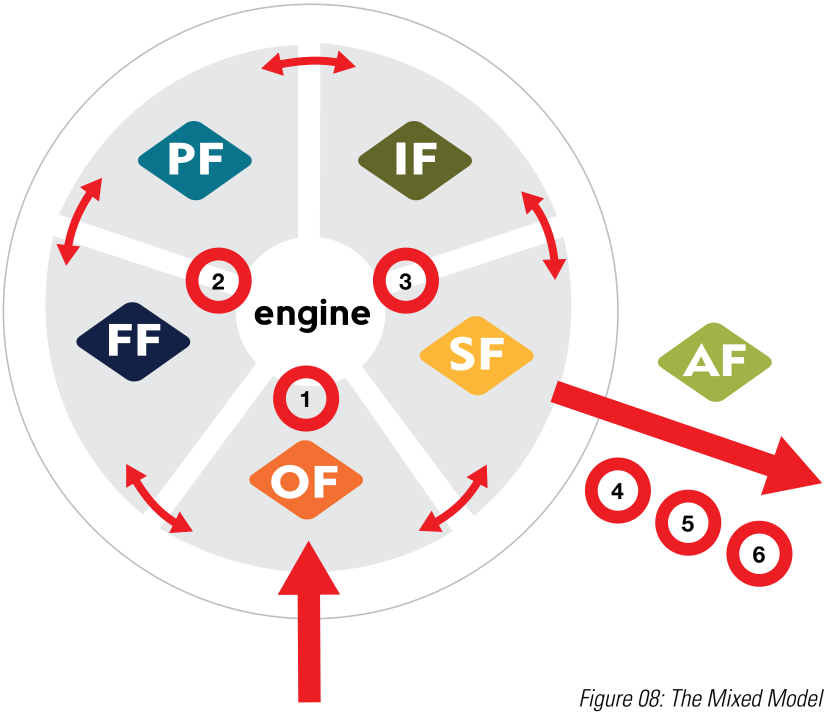


Figure 08: The Mixed Model Methodology (Own elaboration)

This methodology has what is considered the best of the three methodologies, and fits perfectly with the projects objectives. The "engine" part of the model represents a research phase of the thesis, a part where new hypothesis will be continually formulated, opportunities will arise, ideas will be explored, and facts will be studied. The output of this engine must be a path, a concept, the beginning of a more sequential and rational design project. This project will be the Case Study that will prove or disprove the research results.

4. Literature Review

4.1 Additive Manufacturing

Additive Manufacturing is the name given to a series of technologies where three-dimensional parts are fabricated directly from CAD models and built by adding layers one at a time. These technologies, with over 20 years of history, are also known as 3D Printing, additive fabrication, additive processes, direct digital manufacturing, rapid prototyping, rapid manufacturing, layer manufacturing and solid freeform fabrication[1]. In its early years AM was mostly applied for the fabrication of conceptual and functional prototypes, also known as Rapid Prototyping (RP). RP remains the dominant application of polymer AM processes and is well established in the market. However, throughout the years, and thanks to the development of new materials and processes, the industry has made AM techniques move from prototype fabrication to rapid tooling and rapid manufacturing.

The concept of Rapid Manufacturing (RM) –"the production of end-use parts from additive manufacturing systems"[2] – is still emerging today; though its economic impact remains modest[3]. There are few-large scale applications of RM, many of which are for producing personalized products in the medical field[4]

As Barry Berman explains, in contrast to injection molding

---

[1] Pham D T, Dimov S S. Rapid prototyping and rapid tooling – the key enablers for rapid manufacturing. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2003, 217(1): 1–23

[2] Hague, R., Mansour, S., Saleh, N., 2004. Material and design considerations for rapid manufacturing. International Journal of Production Research 42 (22), 4691–4708.

[3] Levy, G.N., Schindel, R., Kruth, J.P., 2003. Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state-of-the-art and future perspectives,. CIRP Annals – Manufacturing Technology 52 (2), 589–609.

[4] Strategic Directions, 2008. The next frontier: New technologies will enable cost-effective customization. Strategic Directions 24 (8)

processes that require costly molds, AM entails relatively low fixed costs. Since AM does not require expensive tooling, forms, or punches, it is particularly cost effective for very small production runs. This enables firms to profitably use AM to economically fill custom orders and serve niche markets. 3-D technologies are also able to produce initial products much more quickly than injection molding and cutting-based operations since no set-up time is required. Further, considerable time savings are incurred when producing revised designs[5].

Holmström et al.[6] suggest the unique characteristics of AM production lead to the following benefits:

- No tooling is needed, significantly reducing production ramp-up time and expense.
- Small production batches are feasible and economical.
- Possibility to quickly change design.
- Allows product to be optimized for function (for example optimized cooling channels).
- Allows economical custom products (batch of one).
- Possibility to reduce waste.
- Potential for simpler supply chains; shorter lead times, lower inventories.
- Design customization.

3-D printing has been compared to such disruptive technologies as digital books and music downloads that enable consumers to order their selections on-line, allow firms to profitably serve small market segments, and enable companies to operate with little or no unsold finished goods inventory. “In the near future, we will have a desktop 3-D printer in our homes that can produce parts for our cars, computer widgets, and toaster knobs. We’ll all have factories in our homes”[7]. For this stage to be reached, though,

the purchase price of 3-D printers will have to lower significantly[8].

---

5 Berman, B. 3-D printing: The new Industrial revolution. Business Horizons (2012) 55, 155—162

6 Holmström, J., Partanen, J., Tuomi, J., Walter, M. Rapid manufacturing in the spare parts supply chain: alternative approaches to capacity deployment.

7 Klaft, L. Open-source 3-D printers head to a desktop near you; instantly make a part to replace what’s broken. (2010, October 17). Worcester Telegram and Gazette, B5.

8 Berman, B. 3-D printing: The new Industrial revolution. Business Horizons (2012) 55,

Although AM techniques have progressed greatly, many challenges remain to be addressed. These challenges include the limited materials that can be used in AM processes, relatively poor part accuracy caused by the "stair-stepping" effect [9], poor repeatability and consistency of the produced parts, and lack of standards for AM processes. Furthermore, the availability of CAD design software descriptions on the Web has significant implications for intellectual property security.

4.1.1 Application Field

Current applications of 3-D printing typically involve small-quantity production runs of small, complex items. These include mass-customized products, prototypes and mockups, replacement parts, medical and dental applications, and bridge manufacturing[10]. The products that obtain the most benefit from AM are:

- Products with a degree of customization.
- Products with increased functionality through design optimization.

Whether or not a specific 3-D application is technically possible or economically feasible largely depends on its production volume, part size, complexity, and material cost. 3-D printing is most widely used in applications with low production volumes, small part sizes, and having complex designs. AM is particularly suitable for producing low volumes of products, especially for parts with complex geometries. According to one source, 3-D printing is cost effective with plastic injection molding on production runs of 50 to 5,000 units[11] . Another source states that 3-D printing is competitive with plastic injection molding of runs around 1,000 items[12].

155—162

[9] Onuh S O, Yusuf Y Y. Rapid prototyping technology: applications and benefits for rapid product development. Journal of Intelligent Manufacturing, 1999, 10(3/4): 301–311

[10] Berman, B. 3-D printing: The new Industrial revolution. Business Horizons (2012)

[11] Sedacca, B. (2011). Hand built by lasers. Engineering and Technology, 6(1), 58—60.

[12] Print me a Stradivarius: How a new manufacturing technology will change the world. (2011, February 17). The Economist, p. 7.

3-D printing is also used in bridge manufacturing, ‘bridging’ the time span from when a part design is complete and when the part is ready for mass production. Bridge manufacturing using 3-D printing is commonly employed when tooling operations are complex, costly, and time consuming. It is also necessary if a firm needs to secure several thousand parts prior to molds being generated[13].

The current development focus of AM is to produce complex shaped functional metallic components, including metals, alloys and metal matrix composites (MMCs), to meet demanding requirements from aerospace, defense, automotive and biomedical industries[14].

Technological and organizational factors

In order for the adopting organization to gain competitive advantage from the implementation of AM its ability to link the technology benefits to the business strategy has been emphasized. There is also an inherent RP legacy with AM system which may result in a psychological barrier to adoption, as management only see the technology-class as being suitable for RP applications. It is proposed for successful implementation of AM technologies the decision to adopt will be accompanied by a change in jobs and tasks, and thus a change in work practices and structure. Using AM processes as a manufacturing technology requires designers and engineers to re-think design for manufacturing (DFM). It also requires users to match product with process and to understand new technology process capabilities[15].

---

[13] Berman, B. 3-D printing: The new Industrial revolution. Business Horizons (2012) 55, 155—162

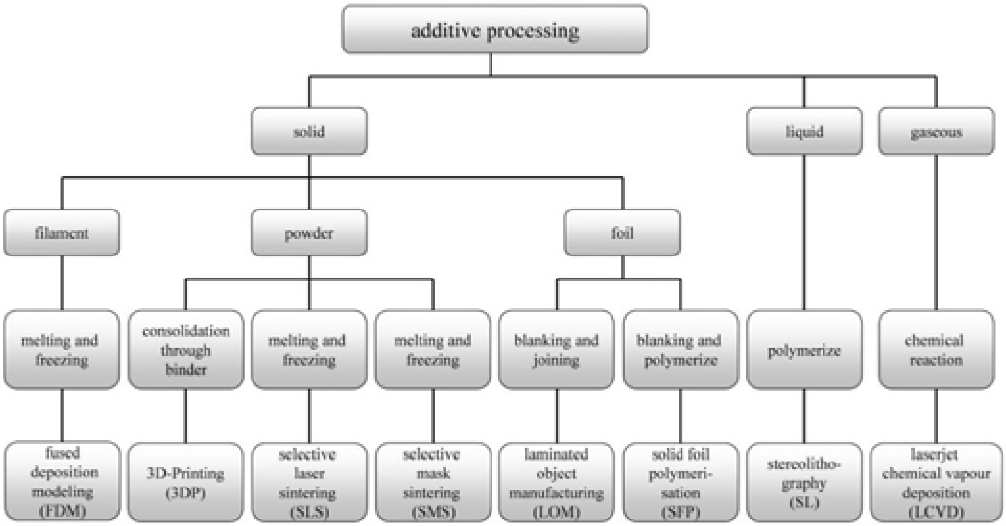
[14] Gu D. D. Meiners W., Wissenbach K. and Poprawe R. Laser additive manufacturing of metallic components: materials, processes and mechanisms. International Materials Reviews 2012

[15] Mellor S, Hao L, Zhang D. Additive manufacturing: A framework for implementation. Int. J. Production Economics 149 (2014) p. 194–201

4.1.2 AM Process Review

There is abundant literature available on the different types of AM technologies, in the form or review papers as well as in other thesis projects. In this chapter, therefore, the different technologies will only be shortly described and mentioned, leaving the reader the possibility to further complement this information on the cited bibliography.

There are many different types of AM technologies, with the only common factor that the part is built layer by layer. The method by which each layer is deposited, fixed, and finished changes in each technology, as does the materials used by different machines. In this chapter a differentiation is made by grouping technologies under the state in which the input material comes in; liquid, solid filament or paste, powder, and sheet.



[16]

Figure 09: Overview of additive processing technologies

---

[16] Wendel B, Rietzel D, Kühnlein F, Feulner R, Hülder G, Schmachtenberg E. Additive Processing of Polymers. Macromolecular Materials and Engineering. 2008

	SLA	SLS	LOM	FDM	SMS	3DP
Materials	photopolymers (acrylic- and epoxy-resins)	metals, sand, thermoplstics (PA12, PC, PS)	foils (paper, polymers, metals, ceramics)	thermoplastics (ABS, PC, ABS-PC -blend, PPSU)	thermoplastics (PA12)	thermoplastics, cement, cast-sand
Part size (mm)	600 x 600 x 500	700 x 380 x 550	550 x 800 x 500	600 x 500 x 600	210 x 297 x 600	508 x 610 x 406
Accuracy	< 0.05 mm	0.05 -0.1 mm	0.15 mm	0.1 mm	0.05-0.12 mm	0.1/600 x 540 dpi
Cooling-off time/ curing time	no cooling-off or curing time up to 30 min	depending on geometry and bulk	depending on geometry	no cooling-off or curing time	depending on geometry and bulk	no cooling-off or curing time
Commercially available since	1987	1991	1990	1991	2005	1998
Costs (T s)	from 130	from 150	from 150	from so	from 150	from 25
Relative sample costs	medium	medium-high	low-medium	low-medium	medium-high	low

Table 1: Comparison of selected additive processing technologies[17]

From Liquid

Stereolithography (SLA) is a process in which a liquid photosensitive resin, deposited in a bath, is scanned and solidified by a laser. The laser scans the specific area and cures the monomer in a defined penetration depth. The platform is subsequently lowered, new resin is applied by a wiper blade and the next layer is simultaneously generated and bonded to the previous layer.

Commercial SLA machine vendors include 3D Systems (USA), EOS (Germany), and CMET (Japan).

Variants of the SLA process have been developed to fabricate ceramic and metal parts by using suspensions of ceramic or metal particles in a photo-curable monomer vat.

Although one of the oldest and most known technologies, SLA remains to be relatively expensive. In recent years some low-cost machines have been developed by companies such as FormLabs, Full Spectrum Laser, DWS Systems, amongst others. They are still relatively small companies though, with a limited

---

17 Wendel B, Rietzel D, Kühnlein F, Feulner R, Hülder G, Schmachtenberg E. Additive Processing of Polymers. Macromolecular Materials and Engineering. 2008

customer service and distribution. These machines prices start at approx. 2,000 euros, making them competitive in comparison to top-of-the line low-cost FDM machines, such as the Ultimaker 2 or MakerBot. However, print times are longer, the print area is usually smaller (13x13 cm VS 22x22cm) and materials employed (consumable resin) cost twice as much per pound compared to the filament used in FDM. However, parts produced by STL have a much better surface resolution, achieving results similar to those of professional grade milling, and translucent shapes can be obtained with a much higher transparency than that obtained by FDM using transparent filament.

Multi-Jet Modeling (MJM)[18] is an AM process using a technique akin to ink-jet printing but using multiple nozzles. Usually at least two nozzles are needed, one to inject a photosensitive polymer resin and another to inject a wax used as support material (that can be melted after) or used to produce patterns for direct investment casting. The printer head will often have a high power UV lamp to cure the layers as they are deposited. Parts with excellent surface quality and detail can be obtained by this process.

The advantages of the MJM process include cost-effectiveness, shorter build time and office-friendliness. The commercial manufacturer of the MJM equipment is 3D Systems.

Rapid Freeze Prototyping (RFP), is an interesting but not yet commercialized AM process that builds ice parts by selectively depositing and freezing water droplets layer by layer.

From Filament / Paste

Fused Deposition Modeling (FDM) works by extruding a thin thread of molten plastic through a nozzle situated at the tip of a moving head that traces each slice of a part. The material is heated to a temperature slightly above its melting point within the head, then extruded though a nozzle to a substrate and cooled down until it solidifies and forms a layer. This is then repeated for each subsequent slice of the model. Often, the machine uses 2

---

[18] Chua C K, Leong K F, Lim C S. Rapid Prototyping: Principles and Applications. 3rd ed. Singapore: World Scientific Publishing Company, 2010, 165–171

deposition nozzles: One for the part material and another for the support material which is used to support overhanging parts[19].

The parts currently produced by FDM systems are reasonably strong plastic components that are well suited to basic functional testing and can easily be sanded and painted to reproduce the aesthetics of the production product thus also making them useful for consumer testing[20]. FDM is ideal for conceptual models, engineering models and prototypes for functional testing, when criteria like temperature, chemical exposure, precision, and mechanical load are of interest. The importance of this process is increasing, as it is an alternative method for the manufacturing of components in small lots[21].

Fused Deposition Modeling (FDM)[22] was developed in the late 1980s. The major manufacturer of FDM systems is Stratasys Inc. (USA).

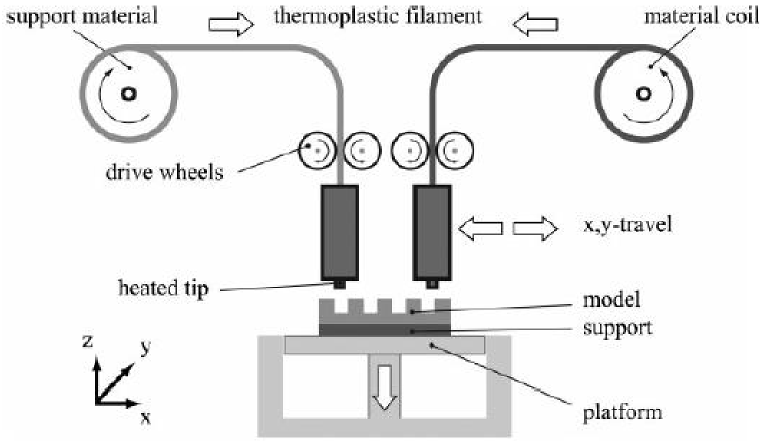


Figure 10: Procedure for fused deposition modeling. (Wendel et al.)

---

[19] Wohlers, T. Wohlers Report 2005, Worldwide progress report on the rapid prototyping, tooling, and manufacturing state of the industry, Wohlers Associates, 2005

[20] Diegel, O., Singamneni, S., Huang, B., Gibson, I., (2011), Curved Layer Fused Deposition Modeling in Conductive Polymer Additive Manufacturing, Advanced Materials Research, Trans Tech Publishers, ISSN: 1022-6680, Vols. 199-200 (2011), pp 1984-1987

[21] Wendel B, Rietzel D, Kühnlein F, Feulner R, Hülder G, Schmachtenberg E. Additive Processing of Polymers. Macromolecular Materials and Engineering. 2008

[22] Crump S S. Fused deposition modeling (FDM): putting rapid back into prototyping. In: The 2nd International Conference on Rapid Prototyping. Dayton, Ohio, 1991: 354–357

Robocasting: Technique that extrudes aqueous ceramic pastes layer by layer to fabricate a 3D part. In robocasting, ceramic paste is extruded through a nozzle and deposited on a substrate. In recent years many projects have been developed to transform low-cost FDM printers into robocasting machines, achieving interesting results such as those presented by designer Olivier van Herpt[23].The paste dries from a fluid-like state to a solid-like state normally within 10 to 15 s of being deposited.

Freeze-form Extrusion Fabrication (FEF) is similar to robocasting, but each layer solidifies by freezing the deposited aqueous paste. The entire machine is encased in a freezer box, maintaining the temperature below the freeze point of water in order to solidify the paste after it is extruded on the substrate[24].

Curved Layer Fused Deposition Modeling (CLFDM) is a process in which the layers of material that make up the part are deposited as curved layers instead of the conventional flat layers.

One of the weaknesses common to all current flat-layer RP technologies is a relatively poor surface finishes caused by the 'staircase' effect on curved surfaces and a lamination weaknesses in a direction perpendicular to the layer direction.

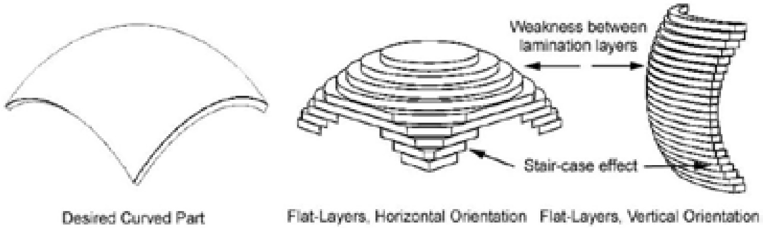


Figure 11: Staircase effect on curved parts (Diegel et al.)

A substructure of 'support material' to the curved part is first created through existing flat-layer methods using a soluble support material. This support structure forms the base onto which the curved layers of product material can then be deposited by having the deposition head precisely follow the contour of the part.[25]

---

[23] http://oliviervanherpt.com/

[24] Guo N, Leu M.C. Additive manufacturing: technology, applications and research needs. Review paper. Higher Education Press and Springer-Verlag Berlin Heidelberg.2013

[25] Diegel, O., Singamneni, S., Huang, B., Gibson, I., (2011), Curved Layer Fused

From Powder

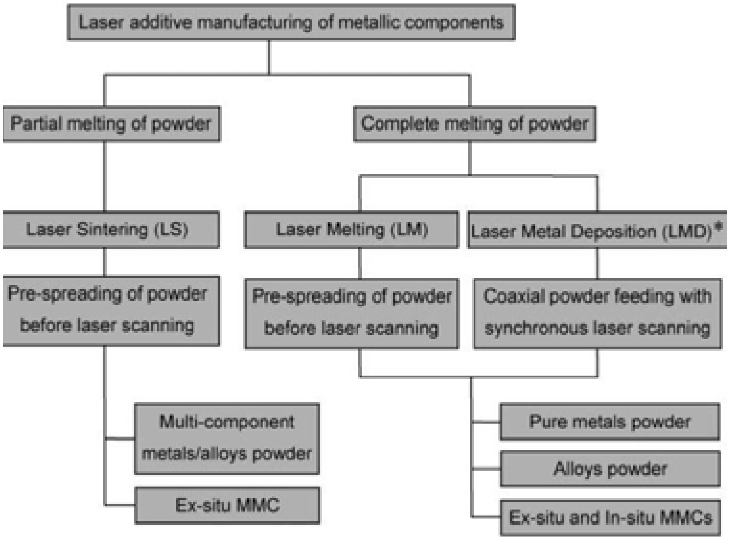


Figure 12: Classification of AM processes based on different mechanisms of laser-material interaction[26]

Selective Laser Sintering (SLS) or Laser Sintering is a process in which a layer of powder is scanned and solidified by the action of a laser. The layers are deposited to generate a thin bed over previous layers, and the laser travels the trajectory given by the parts cross section. SLS can produce parts from a relatively wide range of powder materials, including wax, polymers, polymer/glass composites, polymer/metal powders, metals, and ceramics. However, there is a limited spectrum of suitable materials, because many of the available materials are not in the right powdery form for manufacturing. It does not require support structures because the part being fabricated is surrounded by unsintered powder. Major commercial manufacturers of SLS equipment include 3D System and EOS.

LS has demonstrated the feasibility in processing multicomponent

---

Deposition Modeling in Conductive Polymer Additive Manufacturing, Advanced Materials Research, Trans Tech Publishers, ISSN: 1022-6680, Vols. 199-200 (2011), pp 1984-1987

[26] Gu D. D. Meiners W., Wissenbach K. and Poprawe R. Laser additive manufacturing of metallic components: materials, processes and mechanisms. International Materials Reviews 2012

metal powder and pre-alloyed powder[27][28]. When applied to metals, LS is often called Direct metal laser sintering (DMLS). The multicomponent powder mixture is generally composed of the high melting point metallic component, acting as the structural metal, the low melting point metallic component, taking as the binder, and a small amount of additives such as fluxing agent or deoxidiser[29][30]. DMLS was developed by the EOS firm of Munich, Germany.

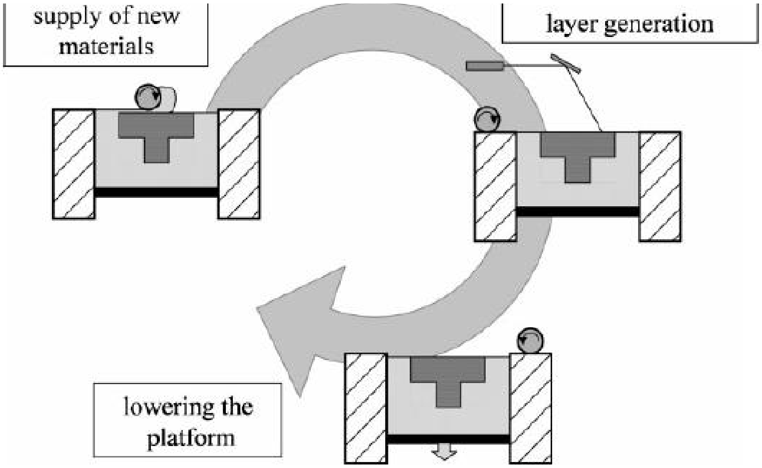


Figure 13: Schematic cycle of the SLS process

Selective Laser Melting (SLM) is similar to SLS with the difference that the laser completely melts the metal powder with a high-power beam to form a metallic part that is almost completely dense, comparable to bulk materials, and does not require post processing. LM shows better suitability to produce full dense parts approaching 99.9% density in a direct way, without post-

---

[27] Simchi, A., F. Petzoldt, and H. Pohl. “On the development of direct metal laser sintering for rapid tooling.” Journal of Materials Processing Technology 141.3 (2003): 319-328.Kruth, J. P. Levy, G. Klocke, F. and Childs, T. H. C.: CIRP Ann., 2007,

[28] Kruth, J.-P., Levy, Klocke, G. F. Childs, T.H.C. Consolidation phenomena in laser and powder-bed based layered manufacturing, CIRP Annals - Manufacturing Technology, Volume 56, Issue 2, 2007,

[29] Khaing M.W., Fuh J.Y.H., Lu L.,; 2001; Direct metal laser sintering for rapid tooling: processing and characterization of EOS parts; Journal of Materials Processing Technology; 113(2001);

[30] Kruth, J.P. Froyen, L. Rombouts, M. Van Vaerenbergh, J. Mercells, P. New Ferro Powder for Selective Laser Sintering of Dense Parts, CIRP Annals - Manufacturing Technology, Volume 52, Issue 1, 2003

infiltration, sintering or HIP[31]. This results in mechanical properties equal to or even better than those of rolled metal sheets. Another major advance of LM lies in its high feasibility in processing nonferrous pure metals; including stainless steel, cobalt chromium, inconel, and titanium. LM requires a higher energy level, which is normally realized by applying good beam quality, high laser power and thin powder layer thickness (i.e. long building time). A large degree of shrinkage tends to occur during liquid–solid transformation, accumulating considerable stresses in LM processed parts[32].

The manufacturers of commercial SLM equipment include the MCP Realizer, EOS and SLM Solutions.

Electron Beam Melting (EBM) is equal to SLM in every way except that it uses an electron beam rather than a laser beam as its energy source. The EBM process is developed and commercialized by Arcam in Sweden.

Laser Metal Deposition (LMD) In LMD, the powder material is locally supplied by a specially designed powder feeder that delivers powder into a gas delivery system through a nozzle and this powder is then completely melted by a laser beam. This results in fully dense parts without the need for post processing. Laser metal deposition can coat, build, and rebuild components having complex geometries and dimensional accuracy. Commercial vendors of the LMD process include Optomec (LENSTM), AeroMet (LasformTM) and Precision Optical Manufacturing (DMDTM).

---

[31] Poprawe R. Loosen, P. Hoffmann, H. D.: 'The future of high power laser techniques', Proc. 16th Int. Symp. on 'Gas flow, chemical lasers, and high-power lasers', Gmunden, Austria (ed. D. Schuö¨ cker), 634602; 2007, SPIE.

[32] Gu D. D. Meiners W., Wissenbach K. and Poprawe R. Laser additive manufacturing of metallic components: materials, processes and mechanisms. International Materials Reviews 2012

Three-Dimensional Printing (3DP) An ink-jet printing head is used to spray a liquid binder into a layer of powder in a powder bed, and the binder solidifies to form a solid layer. Post-processing steps including sintering and/or infiltration are applied in order to make fully functional parts. Parts produced by 3DP may be multi colored and visually resemble a finished product. However, it is a technology used mainly to produce non-functional models, due to the low mechanical properties that the part will offer if time-consuming post-processing operations are not performed. The system is commercialized by 3D Systems and Z Corporation.

Large Area Maskless Photopolymerization (LAMP) is a process in which parts are built by curing the suspensions of ceramic powders in monomer solutions using UV light.

From Solid sheet

In **Laminated Object Manufacturing (LOM)** a sheet of material is spread across a movable substrate, and a laser or blade cuts it along the contours of the part's geometry. The layers bond when a hot roller compresses the sheet and activates a heat-sensitive adhesive. The materials used in this process can be layers of adhesive-coated paper, plastic, or laminated metal. LOM system is from Cubic Technologies (USA)[33].

---

[33] Guo N, Leu M.C. Additive manufacturing: technology, applications and research needs. Review paper. Higher Education Press and Springer-Verlag Berlin Heidelberg.2013

4.1.3 Materials

Nannan Guo, and Ming C. Leu (Guo and Leu, 2013)[34] did a thorough investigation and review article on the different materials that are used in AM processes. A summary of their investigation is presented in the following section:

Polymers

Polymers are the most widely used materials in AM processes. Polymer materials such as photosensitive resin, Nylon, elastomer, ABS and wax can be used to produce parts with the SLA, SLS, FDM and 3DP processes, among others. Nylon, i.e., polyamide (PA), is one of the most widely used and investigated polymers in the SLS and FDM process because it melts and bonds better than other polymers[35].ABS is also a popular material for use in the FDM process[36]. In addition to industrial polymers, biocompatible polymers, such as poly-e-capro-lactone (PCL) and polyetheretherketone (PEEK) and starch-based polymers also have been investigated with the SLS, FDM and 3DP processes.

Metals

Metal products can be produced using AM processes in either an “indirect” way, in which a binder is used to bond metal particles forming a 3D part and post-processing is required after the AM process, or a “direct” way, in which metal particles are fully melted by the AM process to make the final part directly.

Stainless steels (304, 316, 410, 420, 17-4PH), tool steels (H13), nickel alloys (IN617, 625, 718), cobalt alloys (#6 Stellite, #21 Stellite), titanium alloys (Ti6Al4V, Ti-6-2-4-2), and a variety of hardfacing or cladding alloys have been processed successfully

---

[34] Guo N, Leu M.C. Additive manufacturing: technology, applications and research needs. Review paper. Higher Education Press and Springer-Verlag Berlin Heidelberg.2013

[35] Kruth J P, Levy G, Klocke F, Childs T H C. Consolidation phenomena in laser and powder-bed based layered manufacturing. CIRP Annals- Manufacturing Technology, 2007, 56(2): 730–759

[36] Ahn S H, Montero M, Odell D, Roundy S, Wright P K. Anisotropic material properties of fused deposition modeling ABS. Rapid Prototyping Journal, 2002, 8(4): 248–257

with LENS[37] and SLM[38] by companies including Optomec, EOS, etc. and research institutes. Titanium alloys (e.g., Ti6Al4V, Ti6Al4V ELI) and the CoCr alloy have been qualified for use in the EBM process by Arcam[39]. Other materials, such as the nickel-based super-alloys IN718 and 625, H13 steel, Stainless steels 316L and 17-4PH, and Aluminum alloys, have also been researched and developed. For example, the microstructure and mechanical properties of IN718 fabricated using EBM were investigated by Strondl et al[40]. H13 steel parts were produced using EBM by Cormier et al[41]. NiTi shape memory alloy was processed using EBM by Otubo and Antunes[42].

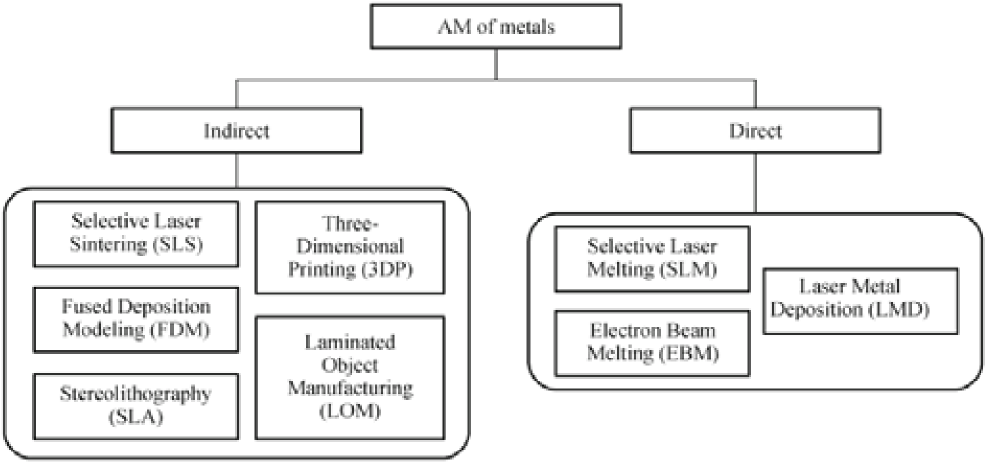


Figure 14: Classification of metal AM processes

---

[37] Mudge R P, Wald N R. Laser engineered net shaping advances additive manufacturing and repair. Welding Journal-New York, 2007, 86(1): 44–48.

[38] MTT Technologies Group. MTT selective laser melting. 2009

[39] Arcam A B. http://www.arcam.com

[40] Strondl A, Palm M, Gnauk J, Frommeyer G. Microstructure and mechanical properties of nickel based superalloy IN718 produced by rapid prototyping with electron beam melting (EBM). Materials Science and Technology, 2011, 27(5): 876–883

[41] Cormier D, Harrysson O, West H. Characterization of H13 steel produced via electron beam melting. Rapid Prototyping Journal, 2004, 10(1): 35–41

[42] Otubo J, Antunes A S. Characterization of 150 mm in diameter NiTi SMA ingot produced by electron beam melting. Materials Science Forum, 2010, 643: 55–59

Metal parts also can be produced using rapid casting by combining AM produced patterns, or casing shells and cores, and subsequently casting with molten metal, such as in investment casting and sand casting.[43]

Ceramics

Examples include alumina, silica and zirconia. Ceramics usually have great chemical resistance and ability to withstand high temperatures. Industrial ceramics (e.g., Si3N4,Al2O3,SiO, ZrB2), advanced ceramics (e.g., lead zirconate titanate (PZT)) and biocompatible ceramics (e.g., hydroxyapatite) have been investigated to fabricate porous and dense parts using AM processes such as FDM, SLS, 3DP and SLA. Structural parts in Si3N4, SiO2 have been fabricated by using ceramic loaded polymer filaments in the FDM process. For the ceramic FDM ceramic process, also called fused deposition of ceramics (FDC), the green part is built by a hot extrusion process in which a ceramic particle loaded thermoplastic filament is extruded through a small nozzle and then subjected to conventional binder removal and sintering processes to produce fully dense components.

Ceramic parts also have been produced by the SLA process, in which ceramic green bodies are created by laser scanning a ceramic suspension consisting of ceramic powder (i.e., silica, alumina, silicon nitride and PZT) dispersed within a photo-curable resin.

Composites

Composites are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties that remain separate and distinct at the macroscopic or microscopic scale within the finished structure but exhibit properties that cannot be achieved by any of the materials acting alone.

---

[43] Cheah C M, Chua C K, Lee C W, Feng C, Totong K. Rapid prototyping and tooling techniques: a review of applications for rapid investment casting. International Journal of Advanced Manufacturing Technology, 2005, 25(3–4): 308–320

Uniform composites fabricated using AM processes are usually done by employing a pre-prepared mixture of proper materials, such as a mixed powder bed for SLS, SLM and 3DP, a filament in mixed materials for FDM, a composite laminate for LOM, or a mixture of liquid photo-curable resin with particulates for SLA. The composite materials that can be produced with AM technology include a polymer matrix, ceramic matrix, metal matrix, and fiber and particulate reinforced composites. AM processes can be used to produce fiber-based composites include FDM and LOM.

In addition to SLS, 3DP also can be used to make composites, either by changing the component of the powder mixture or by infiltrating porous 3DP pre-forms with metal or alloy.

Designed Material

One of the unique characteristics of closed loop DMD technology is that multiple materials can be deposited at different parts of a single component with high precision. This capability can be utilized to develop a new class of optimally designed materials, i.e. a class of artificial materials with properties and functions that do not exist in natural environments. In other words, a material system can be designed and fabricated for a chosen performance.[44]

More important, the methodology for 'designed material' has been extended from the design of compositions/microstructures of materials to the creation of microscopic structures with particular behaviors. These microscopic structures are effectively artificially designed materials and their behaviors are essentially artificial properties. Many of these properties are technologically interesting (e.g. extraordinary piezo-electricity), physically unusual (e.g. negative Poisson's ratio) or unavailable in nature (e.g. ductile metals with negative thermal expansion)[45].

---

[44] Gu D. D. Meiners W., Wissenbach K. and Poprawe R. Laser additive manufacturing of metallic components: materials, processes and mechanisms. International Materials Reviews 2012

[45] Mazumder, J. "A crystal ball view of direct-metal deposition." JOM 52.12 (2000): 28-29.

4.1.4 Design for AM

One area of operations which has been proposed by many authors to be significantly changed with the adoption of AM is product design. A number of authors have commented on the impact of Additive Manufacturing on the design of products and designers themselves (Hague et al., 2003, 2004 [46][47]; Mansour and Hague, 2003[48]).

Gibson et al. (Gibson et al., 2010) [49]:presented the eight key steps in the generic process of CAD to part:

- Conceptualization and CAD
- Conversion to STL
- Transfer and manipulation of STL file on AM machine
- Machine setup
- Build
- Part removal and cleanup
- Post-processing of part
- Application

The comparatively high speed and low operational cost of the 3D printers means that a large number of models can be produced during the product development phase. Designers can go through several iterations having physical samples to evaluate each concept[50] [51].However, few designers understand the implications that AM can bring into the designing process. In spite of the designer's (and eco-designers) interest[52], the

---

[46] Hague, R., Campbell, I., Dickens, P., Implications on design of rapid manufacturing. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 217 (1). 2003.

[47] Hague, R., Mansour, S., Saleh, N., Material and design considerations for rapid manufacturing. International Journal of Production Research 42 (22), 4691–4708. 2004.

[48] Mansour, S., Hague, R., 2003. Impact of rapid manufacturing on design for manufacture for injection moulding. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 217 (4), 453–461.

[49] Gibson, I., Rosen, D.W., Stucker, B., 2010. Additive Manufacturing Technologies Rapid Prototyping to Direct Digital Manufacturing. Springer, New York.

[50] Hatsopoulos, M.I. (2000), "3D printing speeds design cycle", Design News, 21 August

[51] Thilmany, J. (2001), "Printing in three dimensions" Mechanical Engineering, May.

[52] Diegel O., Singamneni S., Reay S., Withell A., 2010. Tools for Sustainable Product Design: Additive Manufacturing, Journal of Sustainable Development, 3(3): 68-75.

breakthrough in manufacturing technology is yet to be followed by a breakthrough in design[53].

To take advantage of AM processes, it is necessary to identify and respect the several manufacturing constraints that the technology presents.To take advantage of AM processes, it is necessary to identify and respect the several manufacturing constraints that the technology presents.

Manufacturing Constraints

Manufacturing parameters govern the physical phenomena that occur during the manufacturing process[54]. These physical phenomena are sensitive to the environmental variations and interact with each other.

In several AM machines there is a feeding mechanism (nozzle) or a solidifying mechanism (laser or electron beam) that must stay parallel to the vertical axis. The movement on the x, y and z axis is usually created by a combination of the movement of this nozzle, laser and/or the platter that holds the part. Collisions between the part and the nozzle must be avoided, which might generate accessibility constraints. The part orientation must be done according to the functional surfaces and the global process characteristics which are: the dimensions of the machine work area, the kinematics and the required accessibility[55].

Variables such as the speed of material deposition, the height and amount of material deposition, and the speed of material solidification can affect the part's quality and stepping effect.

Temperature is also one of the biggest constraints. Heat dissipation is an important factor in layer-based processes such as SLS and FDM. To prevent unmolten powder beneath the

---

[53] Vayrne, B. Vignata F., Villeneuvea, F. 2012. Designing for Additive Manufacturing. Proceedings of the 45th CIRP Conference on Manufacturing Systems.

[54] Boddu M, Musti S, Landers R, Agarwal S, Liou F. Empirical modeling and vision based control for laser aided metal deposition process. In: Proceedings of the twelfth annual international solid freeform fabrication symposium; 2001.p.452-9

[55] Ponche R, Kerbrat O, Mognol P, Hascoet JY. A novel methodology of design for Additive Manufacturing applied to Additive Laser Manufacturing process. Robotics and Computer-Integrated Manufacturing. Elsevier Ltd. 2014

manufactured layer from melting while building, supports have to be used to dissipate the energy[56]. Temperature is used to increase adhesion of the first layers to the platter in FDM. The nozzle temperature in this technology must also be carefully selected to prevent material over-flow or burning.

Design Process

Vayrne et al.[57] presented a 5 step methodology for designing for AM, which is summarized below:

1. Analysis of the specifications

A part is defined by a set of functional surfaces, a volume defining the portion of space where material can be placed ("clearing volume"), and a specified behavior.

The functional surfaces purpose is either to help assemble the part onto other parts, transmit mechanical or thermal loads or assure liquid or gas tightness. The clearing volume helps to prevent the part from colliding with other parts as well as allow fluids circulation for example.

2. Initial shape

The aim of this step is to obtain a single or multiple rough shapes. The choice for this shape can either be expert-based, automated or made following guide-lines. The first approach can be ineffective since designers have sometimes the trend to stick to existing designs.

It is possible to provide the expert guidelines to prevent it from overlooking innovative solutions while benefiting from his expertise.

The designer has to start by defining the functional surfaces. These surfaces typically act as interfaces between the considered part and its neighbors.

56, 57 Vayrne, B. Vignata F., Villeneuvea, F. Designing for Additive Manufacturing. Proceedings of the 45th CIRP Conference on Manufacturing Systems. 2012.

Then these surfaces must be linked to comply with the specified behavior.

If the part is destined to be manufacture on a layer-based process, the initial shape can't have any closed hollow volume (in the case a single-process manufacturing) and the initial shape must make the powder removal as easy as possible.

3. Definition of a set of parameters

If the initial shape has been defined explicitly on CAD software by the designer, a set of parameters is associated with the part in order to be able to modify its geometry and to respect the specifications as well as the manufacturing constraints.

The only constraint concerns the different thicknesses that can't be smaller than the minimal diameter of the building spot.

4. Parametric optimization

In the case of additive manufacturing processes the manufacturing duration, use of raw material, energy consumption and global cost are all linked to the volume of the part. Optimizing a part for additive manufacturing can therefore be assimilated to minimizing its volume.

5. Validation of the shape

The last step is to validate the manufacturability of the optimized shape and define the remaining manufacturing parameters. This validation should be achieved by virtually manufacturing the part.

Ponche et al. propose a new numerical chain, based on a global DFAM methodology. It allows to determine an optimized process planning regarding the process characteristics and constraints directly from the functional specifications of a part (Ponche et al. 2014) [58]. Once the part orientation and optimal geometry are established, the manufacturing path must be optimized. It is proved that, for all the metallic Additive Manufacturing processes, the shapes of the manufacturing paths have a strong impact on the manufactured part quality in terms of micro-structure[59] and of mechanical behavior[60].

4.1.5 Future Research

Although AM technology recently has undergone significant development, it still is not widely accepted by most industries. Improving the technology to the point of changing this mindset and gaining industry acceptance, as well as broadening, developing and identifying manufacturing applications that are only possible with AM processes are the critical targets for the next 5–10 years (Guo and Leu, 2013)[61].

Many of the existing AM systems were built initially to create prototypes, and continue to have an architecture based on rapid prototyping. The produced parts therefore have different requirements than those needed to make the manufacturing process widely adopted by the industry for final production. Repeatability and consistency of parts over the build volume and between builds of each machine cannot be guaranteed, or across different machines of the same technology or even provider. This characteristic can be exploited by designers to create one-of-a-kind products, were the process leaves a unique footprint on the final product, but the commercial success and diffusion of this approach is still to be proven.

---

[58] Ponche R, Kerbrat O, Mognol P, Hascoet JY. A novel methodology of design for Additive Manufacturing applied to Additive Laser Manufacturing process. Robotics and Computer-Integrated Manufacturing. Elsevier Ltd. 2014

[59] Alimardani M, Toyserkani E, Huissoon JP, Paul CP. On the delamination and crack formation in a thin wall fabricated using laser solid freeform fabrication process: an experimental-numerical investigation. Opt Lasers Eng 2009; 47: 1160–8.

[60] Foroozmehr E, Kovacevic R. Effect of path planning on the laser powder deposition process: thermal and structural evaluation. Int J Adv Manuf Technol 2010; 51:659–69.

[61] Guo N, Leu M.C. Additive manufacturing: technology, applications and research needs. Review paper. Higher Education Press and Springer-Verlag Berlin Heidelberg.2013

Design:

AM is still a relatively new manufacturing paradigm that requires significant changes in the way products are conceived and designed. With the current tools, it is still difficult for designers to take full advantage of the unique capabilities of AM processes, including their ability to fabricate complex shapes, tailor materials and properties, and create novel functionalities. Both the conceptual design methods need to be modified to aid designers in the exploration and creation of applications for AM, as well as the technology to make these applications reality. Computer aided design (CAD) tools need to change to become more flexible and less limited in representing complex organic geometries that are not limited by parametric solid modeling boundaries. They also need to become more intuitive and friendly for non-experts, if AM pretends to become a solution for the DIY industry.

Furthermore, it is important that designers start to exploit to a greater extent the unique characteristics that differentiate AM from conventional manufacturing processes, such as anisotropy, as well as the production of epitaxial metallic structures, fabrication of functionally gradient materials, and embedding of components (e.g., sensors and actuators) during the fabrication process[62]. Thermal conductive parts, produced by FDM, can be used, for example, as enclosures to dissipate heat. For example, with some modifications to machinery, multi-material FDM parts can be processed that would allow the combination of good thermal and electrical properties in one part[63].

Materials

Many advances need to be made in material science to extend the offer and costs of materials for AM technologies. Materials suitable for 3-D printing can cost 10 to 100 times more than typical injection molding thermoplastics[64]. Material choices,

---

[62] Guo N, Leu M.C. Additive manufacturing: technology, applications and research needs. Review paper. Higher Education Press and Springer-Verlag Berlin Heidelberg.2013

[63] Wendel B, Rietzel D, Kühnlein F, Feulner R, Hülder G, Schmachtenberg E. Additive Processing of Polymers. Macromolecular Materials and Engineering. 2008

[64] Sherman, L. M. (2009). Additive manufacturing: New capabilities for rapid prototypes and production parts. Plastics Technology, 55(3), 35—45.

colors, and surface finishes suitable for 3-D printing are also more limited than with typical mass-production processes[65].

Today, 3-D printing works with plastics, resins, and metals, with a precision of around one-tenth of a millimeter[66]. According to one source, the robot arm of a 3-D printer needs to be 10 times more precise before it can compete with industrial engineering processes[67]. There are also some strength issues relating to weak bonding between layers that can lead to delamination and breakage under stress; additionally, the materials' strength, viscosity, dimensional stability, resistance to heat and moisture, and color stability need careful evaluation[68][69].

4.2. LED Lighting

4.2.1. Basics principles of Lighting

Through this section the basic principles of lighting will be briefly introduced and it will serve as a glossary and introduction to the following sections.

The Visible Spectrum

The visible light spectrum is the spectrum of electromagnetic radiation that is visible to the human eye. It ranges from a wavelength of 380 nm to 780 nm. These then are the waves that make up what we call visible light, because they are capable of activating the human eye's retina and produce a visual sensation. When we're looking at an object, it is because the object is being illuminated by visible light. Moreover, when we see that the sky is blue, the grass is green or someone's hair is black, it is because at that time we are receiving different wavelengths in the range of 380 nm to 780 nm. The white light perceived by the eye is a

---

[65] Berman, B. 3-D printing: The new Industrial revolution. Business Horizons (2012) 55, 155—162

[66] Print me a Stradivarius: How a new manufacturing technology will change the world. (2011, February 17). The Economist, p. 7.

[67] Rudd, M. (2011, January 16). Next, we'll print out a curly iPhone. The Sunday Times Review, p. 7.

[68] Sherman, L. M. (2009). Additive manufacturing: New capabilities for rapid prototypes and production parts. Plastics Technology, 55(3), 35—45.

[69] Stemp-Morlock, G. (2010). Personal fabrication. Communications of the ACM, 53(10), 14—15

mixture of all the visible wavelengths, which can be broken down using a quartz prism to reflect each of them separately.

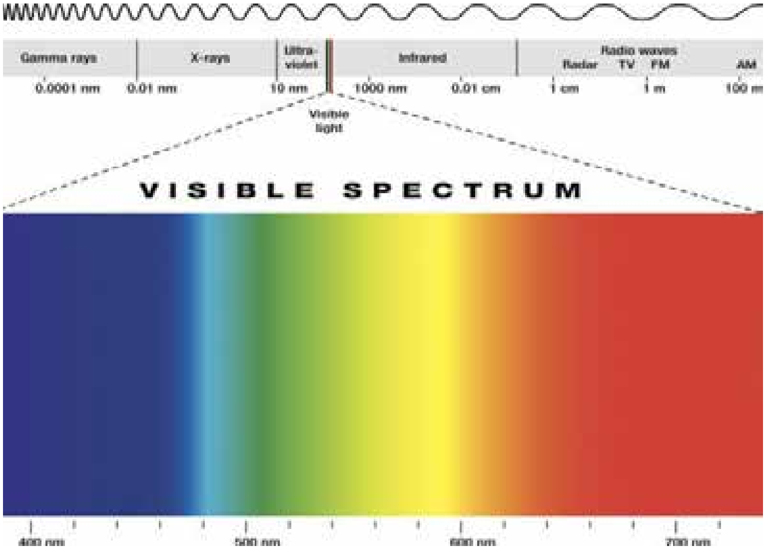


Figure 15: Visible Spectrum of light[70]

Luminous Flux

The luminous flux is defined as the power (W) emitted as light radiation in all directions to which the human eye is sensitive.

Symbol: Φ (Phi)
Unit of measurement: lm (Lumen)

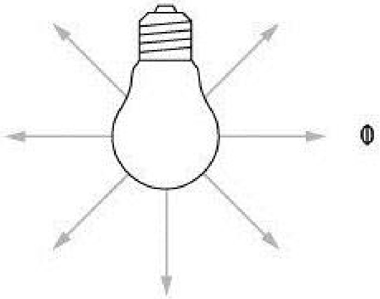
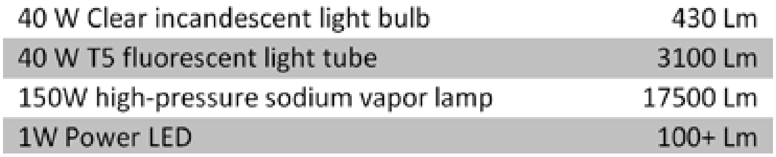


Figure 16: Luminous flux generated by a light source

---

[70] Peter Hermes Furian. Electromagnetic Spectrum and Visible Light. www.crated.com

The following table gives a clear idea of how much lumens does each type of light source emit:



40 W Clear incandescent light bulb	430 Lm
40 W T5 fluorescent light tube	3100 Lm
150W high-pressure sodium vapor lamp	17500 Lm
1W Power LED	100+ Lm

Illuminance

Illuminance is the luminous flux received by a surface. It therefore depends on the area of the surface (m2), the distance from the light source, and the luminous flux emitted by that source.

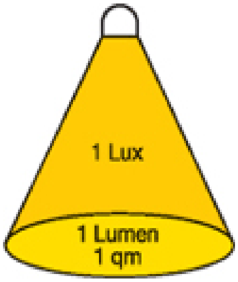


Figure 17: Iluminance

Symbol: E
Unit of measurement: lux (lumen/m2)

Examples are given on how much iluminance can be expected under certain conditions:

Full moon	0.2 Lux
Sunny day	120000 Lux
Bedroom	100 Lux
Standard Office	500 Lux

Luminous Intensity

The luminous intensity is the determination of the amount of light (luminous flux) emitted by a light source in a certain direction, and received by the surfaces determined by a fixed solid angle (steradian [sr]).

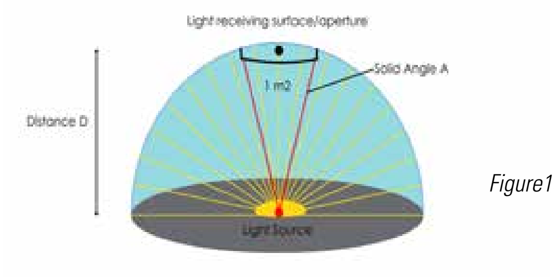


Figure18: Luminous intensity[71]

Symbol: I
Unit of measurement: Cd (candela)

Luminance

The Luminance of a surface or object is the amount of luminous flux reflected by it and perceived by the human eye. The light we see is luminance, because it is always reflected from surfaces or objects.

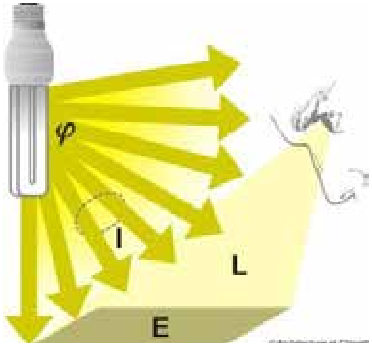


Figure19: Luminance[72]

Symbol: L
Unit of measurement: Cd/m2

Usually, a luminaire's photometric information is determined by the 1000 Lm luminous flux; for this reason the graph's values are expressed in cd/Klm. This way, it is possible to compare different light sources or luminaires.

---

[71] http://2bora.com/en/technologie/natezenie-swiatla

[72] https://www.educate-sustainability.eu/portal/content/photometry

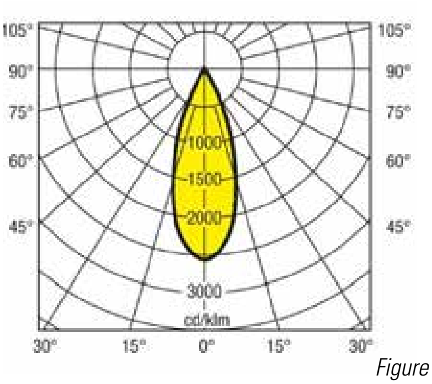


Figure 20: Photometric curve of a light source[73]

Color Rendering Index

Color Rendering Index (CRI or Ra) is a measure of the ability of a given lamp to reproduce colors of illuminated objects. The concept of color rendering is defined by the appearance of the colors in comparison with their appearance under a reference illuminant. In order to determine Ra, eight sample colors established by the standard DIN 6169 are lit by both the reference illuminant and the light source being analyzed. The color rendering of each sample is scored from 0 to 100 and then the average of the indexes of the eight colors is calculated.

In general, the higher the CRI, the better the light. A high CRI (80-100) makes people and objects look better in comparison to the light of a lower CRI. In the case of CRI=100, the colors obtained with the light source being analyzed are identical to those produced by the reference illuminant. It is assumed that the light source which is the reference point is ideal, but it is not always true. The maximum value of 100 is given to incandescent light bulbs and to natural daylight. However, the first render the color blue poorly, and the second renders the color red poorly, so this judgment system has its flaws and limitations. However, CRI is the only international system of color reproduction, which gives advice on sources of light.

Color Temperature

The Correlated Color Temperature CCT (Measured in Kelvin degrees) or color temperature is a scientific scale that describes how “warm” or “cold” a light source is. When a piece of metal is

---

[73] http://2bora.com/en/technologie/rozklad-natezenia-swiatla

heated it changes its color from red to orange then yellow, to blue and white. The color of light emitted by the incandescent object depends only on temperature. This dependence was used in determining the color of light as the light color temperature.

Scientifically, when a lamp is said to have a color temperature of 3000K, it represents the temperature a “blackbody” must be at in order to emit light of the same color as that of the lamp.

Color temperature depends on the distribution of the light emitted in the visible part of the spectrum. When in the light of a particular light source the predominant color is red, this light is considered “warm”. In contrast, if blue predominates, it is a “cool” light.

The lamps most commonly used light sources are divided in three groups of color temperatures:

- Warm white (ww). Color temperature under 3,300 K
- Neutral, or “fresh” white (nw). Between 3,300 and 5,000 K.
- Daylight, or “cool” white (tw). Over 5,000 K.

Figure 21: Light color range measured in °K

As extreme examples, an incandescent bulb has a color temperature of 2,700 K, while that of a daylight fluorescent tube's is 6,000 K. Note that two light sources with the same color temperature can have different color rendering properties due to their different spectral distribution.

Figure 22: Warm white, white and cool white

According to the use given to a particular luminaire, the color temperature is chosen differently[74]:

<2500°K
Bulk, industrial and security lighting 2700-3000°K Residences, hotels, restaurants, themed environments, some commercial office spaces.

2950-3200°K
Display lighting in retail and galleries 3500-4500°K Offices, schools, hospitals and some retail.

5000-7500°K
Special applications where color discrimination is critical; uncommon for general lighting.

Life

The life of a luminaire is the total operation time in which 50% of a large group of lamps is expected to fail. Lamp life for LED's is measured differently because they do not tipically fail, but continue to loose output over time. Their lamp life is measured when they lose 70% of their output.

---

[74] Karlen M, Benya JR, Christina S. Lighting Design Basics. John Wiley & Sons, Inc. Hoboken, New Jersey, USA. 2012. P.3,4

4.2.2. LED Basics

Features of a LED and how it works

At the beginning of the 19th century the emission of light was obtained for the first time by an electric current passing through a semiconductor. This physical phenomenon, which was defined electroluminescence, is the basis for the operation of LEDs. However, only until more than 150 years later were the first LEDs with usable luminosity created.

A LED is a light-emitting diode which has a semiconductor material inside that converts electricity to light when a small electric current is applied to it. Hence, light is not generated by heating a filament (which is the principle of incandescent and halogen lamps) but by a current travelling between the poles of the device. The color of the light emitted by this device will depend on the manufacturing materials. The semiconductor material determines the light color, which can be ultraviolet, infrared or any color within the range of light visible to the human eye.

The semiconductor currently used for lighting is always chosen on the basis of the desired coloration: to have elevated currents, the density of doping in the crystalline reticulum of the semiconductor is increased, and the junction size is increased (the chip of a power led is larger than the chip of a LED used as indicator lamp in an electronic device). Generally speaking there are two types of Power LED's:

· The first is based on the use of AlInGaP (Aluminum, Indium, Gallium and Phosphor) and it produces red-orange, orange, yellow and green light.
· The second, based on the use of InGaN (Indium and Gallium Nitrate), is used to produce blue, greenish-blue, green, and in combination with phosphors, white light[75].

The LED structure that has become most widely used is that which is based on concentrically arranged levels, each of which

---

[75] Palladino P, Spotti P. Illuminare con i LED. Principi e Applicazioni della Luce Elettronica. Techniche Nuove. 2012, Milano, Italia. P. 25.

applies a precise functional area. These areas are:

- Power supply
- Management of the luminous flux
- Thermal dissipation
- Structural support

These areas are distributed among three basic levels; the chip, package and system. Packages are the minimum usable unit for LEDs. They contain the LED chip (diode) and the lead wires and a protective epoxy shell. Their function is to create an interface between the chip and the illumination device.

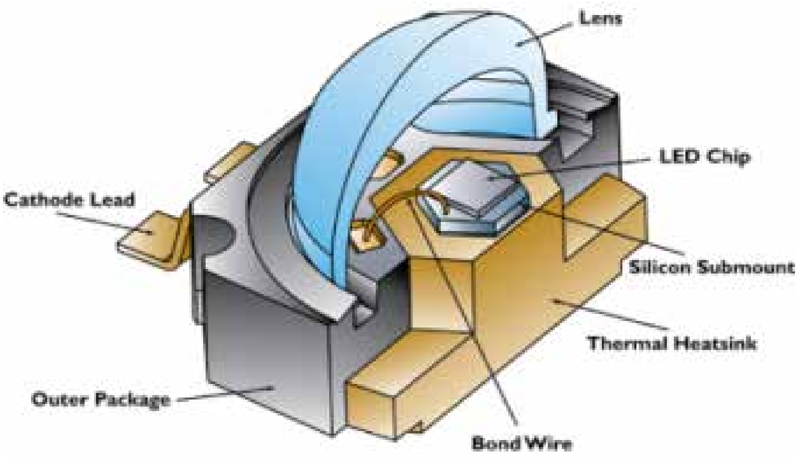


Figure 23: structure of a LED package[76]

However, there is often an intermediate level of assembly, the LED module or system. This sort of small lamp allows optimizing some characteristics of LEDs with components labeled as “secondary” to differentiate it from those within the package. They are basically a collection of LED packages with supporting electrical, thermal, optical and mechanical devices. There are three types of LED modules:

- modules that are integrated within the luminaire (cannot be replaced);

---

[76] http://www.electronicsweekly.com/news/wp-content/uploads/sites/16/2008/03/itemid-52190-getasset.jpg

- modules that must be incorporated within a luminaire;
- independent modules (that can also work outside of a luminaire).

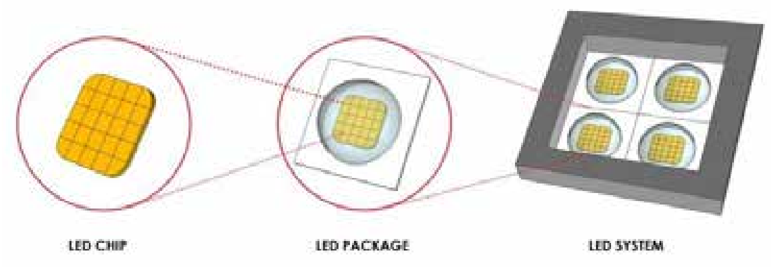


Figure 24: Three basic levels of LED[77]

There are many different kinds of LED modules available in the market. The most common will be described below:

Surface Mounted Devices (SMD):

Surface Mounted Devices or SMDs have LEDs directly attached to the printed circuit boards. A printed circuit board or PCB is an electric structural entity which carries various chips and electronic components connected together. The direct placement of LED on PCB results in less occupied space and efficient thermal connection. In fact, the advanced latest developments in SMDs have made them a reasonable replacement for incandescent bulbs and mercury-based lighting[78]. The most common types are:

- Constant Current Modules (CCM) are modules that do not present any electronic circuit on board and have to be driven by external constant-current power supply circuits. These modules consist in an array of power LEDs mounted on a flat board, usually with a square, rectangular (bar) or circular (disc) shape. By setting different driving current (350mA, 500ma, 700mA) various levels of light flux can be obtained by the specific CCM module.

---

[77] http://2bora.com/en/technologie/dioda-led

[78] COB LED vs SMD. Posted On: Monday, 30 June 2014 05:49:49 Europe/London by Focus LED UK Ltd. http://www.focusledltd.co.uk/blog/cob-led-vs-smd-led/

· Constant Voltage Modules or Low Voltage Modules (LVM) are modules that can be driven by external constant-voltage power supply circuits (12/24V DC). These modules are also arrays of Power LEDs mounted on circular or rectangular shape on rigid or flexible support. Popular LVM include circular panels used as replacement lamps in round fluorescent luminaires.

· Direct Driven Modules can be driven by main voltage network (220-240V AC in Europe), therefore they do not need a LED driver. These modules present integrated circuits that lower the voltage and keep it constant. The LEDs work with an alternating current (AC), reason why they have a constant flickering that cannot be perceived by the user. They also come in round or square flat formats.

· Spotlights are small modules that come with an integrated reflector, lens and heatsink. They are usually sold for re-lamping of existing spot luminaires, reason why they come with standard connection interfaces.

· Strips and Bars: These are commonly constant-voltage modules that are mounted on a long rigid (bar) or flexible (strip) support. They are usually sold by linear meters, and can be used independently, attached to surfaces using double-sided tape or adhesives, or they can also be mounted on a tube-like device similar to T5 or T8 fluorescent tube lamps.

Chip on Board (COB) LEDs:

Chip-on-Board or COB LEDs, as opposed to SMDs are segmented into numerous tiny pieces of semi-conductor crystals and are directly placed over a substrate. COBs are popular for their heat efficient behavior. They ensure minimum heat production and emit homogeneous light. The behavior is enhanced with the addition of a ceramic substrate which induces a cooling effect in addition to the homogeneous light production. COBs' assembling is relatively cheap and the LEDs have a longer life span[79].

Figure 25: LED panels, spot, strip and COB

Light emission

Colored LEDs emit light that is almost monochromatic. The wavelength of the emission depends on the materials with which the LED junction is built and the level of doping in the semiconductor. To produce white light there are three methods:

> I. The first, at the package level, consists of a diode that emits blue light mixed with phosphors that provide a yellow light. The primary blue light combines with the yellow one in order to create a spectrum of light large enough to give a white color. The phosphors may be placed inside the package or remotely, within the light diffuser. In the latter,

---

[79] COB LED vs SMD. Posted On: Monday, 30 June 2014 05:49:49 Europe/London by Focus LED UK Ltd. http://www.focusledltd.co.uk/blog/cob-led-vs-smd-led/

the diffuser has a double function; to distribute light among a wider surface area and to distribute the thermic charge over the phosphors. This approach will produce a more homogeneous light than the first, but will increase the amount and size of components. Also, the diffuser will look yellow when turned off, with the aesthetical implication that this carries for the luminaire.

II. The second method, also at the package-level, uses a ultra-violet LED and combination of phosphors that convert the radiation and provide a white light. This creates a reduction in the luminous efficiency, because part of the power consumption is dissipated during the conversion.

III. The third method consists in combining Red, Green and Blue LEDs which by synthesis create white light. This can be done at the package level, using sever monochromatic chips, or at the module level, combining different packages.

Binning

In the production of LEDs, a single round wafer is coated with various materials (epitaxial growth) to create the semiconductor which forms the heart of the blue LED. This is then sliced into extremely small rectangles (die). Wire bonds (or other electrical connections) are inserted and the phosphor is added either as a coating or suspension within the enclosure. The assembly is then encapsulated to create a finished white light LED package[80].

Minimal variations of the manufacturing conditions during the epitaxial growth and the phosphor application can change the color shade that will be perceived. For example, between 350 and 450 nm the color we perceive is blue, although in different shades. These differences are due to the fact that it is impossible to control precisely all the production parameters: substrate temperature, atomic level variations or gas mixture. For this reason, a selection process called BINNING (chip to chip variation) is carried out after manufacture. During this process, the LEDs are placed into groups according to their common

---

[80] Lithonia Lighting. White Paper: Binning and LED. 2010. P.1

properties, such as luminous flux, electric behavior or color shade. A BIN code is attributed to each of these groups. The BIN code could be thought of as the color card for LEDs, in the same way as RAL card for paint or Pantone card for ink[81].

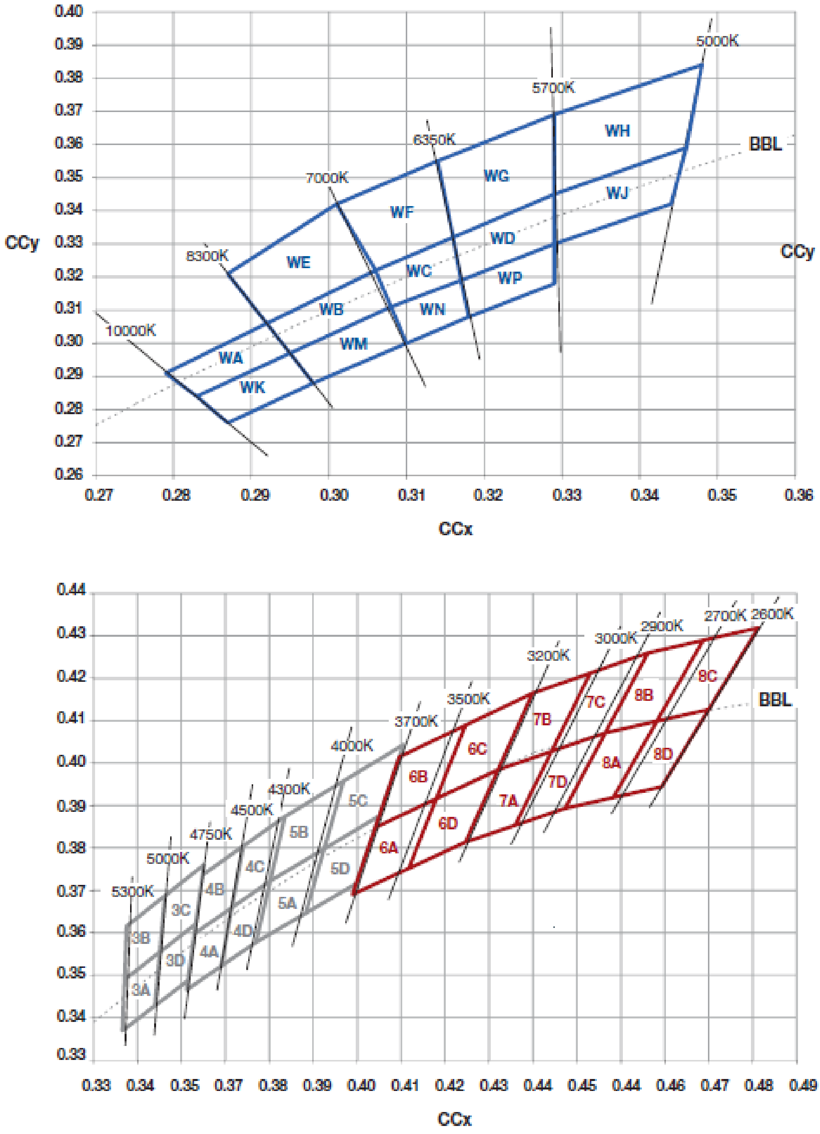


Figure 26: Segmentation for cool and warm light binning

---

[81] Basic Light Concepts- Binning. LEDs-C4 Architectural Light Catalogue 2013. P.13

4.2.3 LED Luminaires

There are four main factors affecting the efficiency of the lighting system[82]:

- Optics design: LED is a spot light source. This system emits it in one particular direction. With carefully designed lenses and reflectors, light is directed where needed, minimizing its losses.

- Design of power supply: This system has a direct impact on the lifetime of the LEDs, the amount of generated light and light color control of LED system as a whole. Precisely designed electronics provides adequate current supplied to the delicate structure of the LED semiconductor, thus ensuring a long and uniform illumination of the entire LED system.

- Lamp housing design: Since LED lamps are a light source that can operate for many years, the housing and the materials they are made of are an important aspect affecting the reliability of the entire LED lighting system. Housing carefully designed to protect the entire system from corrosion and moisture will ensure a long life of the LED lighting system.

- Heat dissipation design: If the temperature is too high this will shorten the LED's duration, lead to color changes and the reduction of the amount of generated light. A well-designed thermal system provides adequate cooling of the LEDs, thereby improving overall LED lighting system performance.

Each of these will be exposed in detail below.

Optics Design

LEDs are usually provided with a protective capsule that acts also as a primary optic. It protects the materials that compose the junction from the environmental agents that could generate,

---

[82] http://2bora.com/en/technologie/dioda-led

for example, oxidation. The material chosen for this capsule is usually silicon, due to its high temperature resistance and transparency.

To modify the photometric solid that comes out of the diode a secondary optic may be used. Secondary optics must be designed considering the characteristics of the primary optic with which they are combined with. Power LEDs destined to work with a secondary optic are almost always provided with a primary optic with lambertian emission. Figure 28 shows a lambertian reflection from a surface. Notice that the reflection follows the cosine law — the amount of reflected energy in a particular direction (the intensity) is proportional to the cosine of the reflected angle[83].

Secondary optics for LEDs are generally built in transparent polymers such as PMMA and PC, which have a high transparency and resistance to elevated temperatures. They work according to the principle of Total Internal Reflection (TIR), with the intention of modifying the light beam. Some might create a wider beam to illuminate a larger area, others a narrower beam to focalize the beam in a desired spot, and others might change the direction or the shape of the beam. The possibilities are infinite and they depend on the desired output. The lenses in Figure 27 produce viewing angles from 8° to 45° when used with compact emitter packages (all products shown are from LED Engin)[84].

Figure 27: Optics produced by LED Engin

---

[83] Alma E. F. Taylor. Illumination Fundamentals. Lighting Research Center. Rensselaer Polytechnic Institute. 2000. P.

[84] Wu Jiang and Kevin Schneider. TIR optics enhance the illuminance on target for directional LED modules. LEDs Magazine. February 2012.

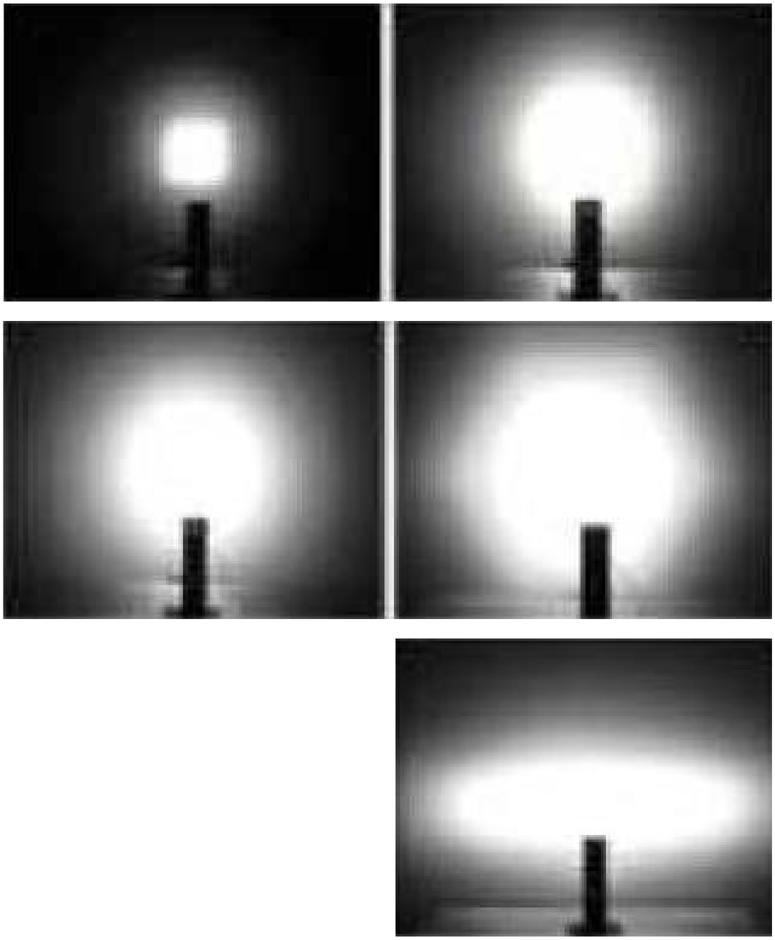


Figure 28: Halos generated from narrow, medium, wide and elliptical optics (LEDIL documentation)[85]

Many secondary optics work in combination with a reflector, which is usually constructed in a plastic material that is superficially treated with an aluminum deposition. Reflectors are optimal if beams wider than 80° are desired. They are also a necessary choice for chips with a large area. A repartition of the light beams occurs when the management of the luminous flux is performed by a reflector, because some of these beams are screened directly by the lens and some of them are reflected by the walls of the reflector and escape the apparatus. A collimator is an optical component that generates a parallel (collimated) beam out of a compact light source. It includes a central area

---

[85] Forcolini G. Illuminazione con i LED. Funzionamento, caratteristiche, prestazioni, applicazioni. Hoepli editore, 2011. P.87

that works in transmission and a peripheral area that works as a total internal reflector (Figure 29).

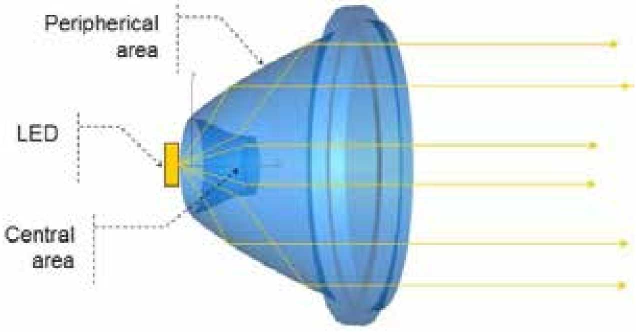


Figure 29: LED Collimator[86]

Design of Power Supply

As stated in previous pages, an electrical current needs to pass through a LED for it to emit light. In the extremities of the P-N junction, the active site where the electronic action of the device takes place, there is a potential barrier that impedes the free flow of electrons. To overcome this obstacle, an electric potential difference is needed, or in other words, electric voltage is required. This is the main task of the power supply unit. Additionally, in some cases it must transform the electrical current as it comes from the network (alternating current at 230V in Europe, 110V in America) into a constant current of less voltage which the LED unit can use. This is why it is sometimes referred to as transformer. However, if the power is taken from a battery or from renewable sources such as solar or wind energy, the power unit must not transform the current but instead stabilize it at a constant value.

Most solid state lamps consist of a significant number of high-brightness LEDs. These LEDs may be wired in any of a variety of configurations, each with their own advantages and limitations. The choice of the correct power unit will largely depend on the configuration choice. Bellow some of the most common

---

[86] Jean-Pierre Lauret. Solving optical problems for LED applications. SPIE International Society for Optics and Photonics. Retrieved 27 March 2015 from http://spie.org/x47766.xml

configurations are discussed.

Series connection

When a series of LED diodes is used, the power unit must provide all of them a current with the same amount of amperes, to generate a uniform luminosity. A single power unit can provide energy for more than one LED when the connections between the diodes are done in series. The voltage between the first and the last of the series is equal to the sum of the voltage drops that occur on each LED. The power of the driver is derived from the multiplication of the current by the sum of the voltage drops. To keep the circuit at a low voltage it is necessary that this sum does not exceed 60 V. In practice, considering the dispersions in the system as well as the fact that the voltage drops oscillate, in function of the LED type, between 3 and 4 V, a low voltage driver can generally serve a maximum of 12 or 14 LEDs.[87]

The series configuration is in theory the best because it allows a good control of the luminous emission, and the same current flows through all the LEDs, guaranteeing uniformity and decreasing the specifications needed of the power unit, being the most energy efficient solution. However, the inconvenience relies in the fact that if one of the LEDs is damaged, the whole series will become an open circuit and turn off. There is, however, a device called an open LED protector that acts as an electronic bypass, allowing the series to continue working if a LED fails[88].

Parallel Connection

The second connection typology consists in connecting the LED devices as parallel circuits. This will reduce the operating voltage; however, the problem will consist in guaranteeing the same current to all the devices to generate a uniform luminosity. The voltage will be the same for all the devices, therefore it will be low, but the current will be the sum of the individual currents of each device. If any given device failed open, the other LEDs would remain lit, but will carry the additional current that was

---

[87] Forcolini G. Illuminazione con i LED. Funzionamento, caratteristiche, prestazioni, applicazioni. Hoepli editore, 2011. P.19

[88] Palladino P, Spotti P. Illuminare con i LED. Principi e Applicazioni della Luce Elettronica. Techniche Nuove. 2012, Milano, Italia. P. 85.

previously destined to the failed LED. This situation will likely result in lower reliability as the remaining LEDs are subject to significantly increased stress.

Mixed (matrix)

This configuration consists in a mix of the previous two. Small series of LEDs (strings) are created and then these strings are connected in parallel. This will create a more homogenous light in each string but the problem of distributing the current uniformly in all the strings will subsist. One solution would be using a multi-channel constant current driver, to drive the LED strings independently. This would eliminate the problem of a single LED failing short. In this case, all other LEDs would be unaffected. The driver in this case would be somewhat more expensive having four independently regulated channels.

Usually, the following questions must be answered to select a LED driver:

1. Constant current, constant voltage or both? This question will be discussed in detail further below.
2. Will the luminaire be dimmable?
3. What is the expected lifetime of the luminaire?
4. What will be the imput voltage?
5. What are the output requirements (Watts, Amps, Volts)?
6. What are the dimensions that will fit the luminaire size and shape?

Constant Current vs. Constant Voltage

The electronic circuit powering LEDs is an important evaluation in the luminaire design. Many simple power units provide a constant voltage, meaning that the output current varies with the LED's voltage. A constant-voltage driver can cause early LED failure. As the LED's temperature increases, its threshold voltage drops, causing a constant-voltage driver to supply more current in response to the decreased LED voltage[89]. A current over a certain limit will damage the LED. Due to this, it is preferable to

---

[89] Ramchandra P., Boucar D., Solar Lighting. Springer-Verlag London Limited. 2011. P. 77

choose a driver that will supply a constant DC current, holding it steady as the LED voltage changes with temperature. However, constant-voltage drivers continue to exist for parallel circuit configurations with light bulbs or LED modules that have a built-in regulator (their label must mention 12VDC or 24VDC).

Dimming

Dimming can generate both advantages in the perception of a space, comfort, and energy consumption. As Scott Barney explains in LEDs Magazine:

"The human eye notices light changes on a scale which relates to what it's already seeing and the light output of an LED lamp is roughly proportional to the current going through it. As a result, dimming to 50% is hardly noticeable to most people and 10% is perceived as just a few degrees dimmer than that. Therefore, to have a discernable visual dimming effect, you need to be able to dim down to 1%. The lack of sensitivity doesn't mean that dimming to above 1% is not useful. In fact, the situation is quite the contrary. If you dim an LED light down to 10%, you've just saved 90% of its energy consumption, which is very significant. Dimming by any degree is worthwhile for energy-saving purposes, but if you want to have a dimly-lit room or theater, you must have drivers capable of dimming down below 1%."[90]

Life Expectancy

If the temperature of a LED array is properly controlled, it should still produce more than 70% of its initial light output after 50,000 hours. The lifetime of the driver should be accordingly long to avoid maintenance issues or replacements. The lifetime of an LED driver is determined by the lifetime of the individual electronic components inside. The weak link, in particular, is the electrolytic capacitors, which are like little batteries. The electrolyte inside is typically a gel that gradually evaporates over the life of the component, and this will depend on the operating temperature of the luminaire but also on the quality of the electrolytic capacitor.

---

[90] Barney, S. Simplifying the sophisticated: LED driver selection made easy. LEDs Magazine. April/ May 2014 Issue..

Input Voltage

The electric voltage provided by the network in different countries changes, and sometimes even within a country. In Europe the range is usually 220-240V, while in America the range is 110-130V. A universal input voltage product contains the components and capability for both high input voltage operation and high input current operation. A higher current is needed at a lower voltage. The tradeoff is that this feature will add to the driver's price. However, fixture OEMs don't often know what voltage the product will need, so it's usually worthwhile to pay for the more expensive universal input voltage feature.

Power Output

Traditional lamps, including incandescent and fluorescent, are sold in the market by the power consumption, measured in Watts. As the lumen/watt efficiency in these light sources is more or less constant, knowing the power consumption would give an idea of the luminous flux. In LEDs this efficiency is rapidly increasing, and a wide range of Luminous flux outputs can be expected (according to LED quality and cost) within the same power consumption. Therefore, the output value in lumens has gained importance to select a specific LED product. However, the power consumption continues to be available as a measure both of efficiency and as an important parameter for the choice of the appropriate LED driver. The driver must generate the amount of watts necessary to power the sum of all the LED'S connected to it.

Size and Shape

Finally, LED drivers come in all types of size and shapes. Narrow bars, flat discs, compact boxes, etc.; are just some of the available formats made to accommodate in the best way possible to the different luminaire housings. LED driver manufacturers will usually provide 2D and 3D models for luminaire manufacturers to evaluate and consider in their designs.

Figure 30: LED drivers by BAG electronics[91].

Lamp housing design

The housing of a lamp may have several functions, among these, to:

- · Assemble and contain the different electronic components
- · Protect these components from dust, humidity, and the environment in general
- · Aid in the dissipation of heat
- · Provide an interface (fixture) for the luminaire's installation
- · Isolate the luminaire to avoid potential electric shocks to the user, and provide a grounding conductor
- · Shade light, completely (opaque), partially (transluscent) or through a pattern or texture that will generate shadows
- · Direct light towards a specific area
- · Decorate, both when the lamp is turned on and off.

All of these functions require careful attention by the luminaire's designer, as they are vital for the correct functionality of the luminaire. If designed and manufactured correctly, the housing will guarantee that the luminaire will have a long life. Additionally, it often plays an important role in the market success of the luminaire, as it is the largest and most visible component, what gives the luminaire character and personality, what differentiates it from others.

There are different ways of classifying lamp fixtures, according to use, light output, technology, installation, etc. The broadest classification would be according to the light distribution, as this will indicate the type of fixture required. The 6 main types are

---

[91] BAG Electronics website. http://www.bagelectronics.com/

described below:

- Direct: The luminous flux is directed towards a specific area, without any reflection from an intermediary surface. This type is common in pendant lights, task lights and ceiling fixtures.
- Semi direct: Most of the luminous flux arrives at the work-plane without being reflected by room surfaces, but a smaller part of the flux is aimed at a reflective surface. This type is common in wall fixtures, table lamps and floor lamps.
- General diffuse: The luminous flux is omnidirectional, meaning that the light source will generate a light flux that will illuminate in every direction. This type is common in outdoor lighting and in other light sources besides LED (incandescent, CFL).
- Direct-indirect: This type of luminaire will generate an equally strong luminous flux directly and indirectly. It is common in pendant and floor luminaires that generate what is called down-light (towards the floor) and up-light (towards the ceiling).
- Indirect: In this type of luminaire the luminous flux arrives at the work-plane after being reflected by room surfaces. It is common in decorative luminaires, accent luminaires, wall fixtures and pendant lamps (chandeliers). Although less efficient, this lighting distribution technique is favored by many lighting professionals because indirect lighting minimizes shadows and glare.

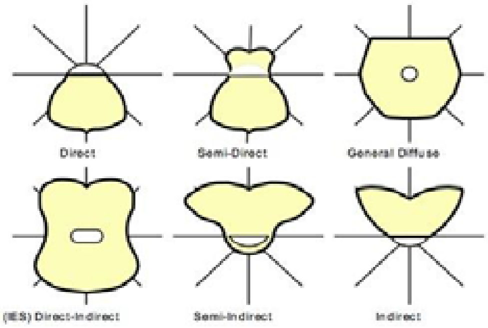


Figure 31: Types of light distribution in luminaires[92]

---

[92] Lighting Language. Light Logic for the 21st Century. http://ieslightlogic.org/lighting-language/

As seen in the previous classification, the type of light distribution has a close relationship with the type of fixture the luminaire will have. The most common types of fixtures are described below[93]:

Architectural: Architectural lighting is most often used as ambient lighting. The three most common forms of architectural lighting are cove, soffit and valance; all three are integrated into the room's structure.

> Cove lighting: located in a ledge, shelf or recess high up on a wall. Light is projected toward the ceiling or upper wall.
>
> Soffit lighting: located in a soffit or cornice near the ceiling. Light radiates downward, washing the wall with light.
>
> Valance lighting: located in a wood, metal or glass valance (horizontal shield) mounted above a window or high on the wall. Light bounces both upward and downward.

Recessed: Installed above the ceiling, this type of lighting has an opening that is flush with the ceiling. A recessed light requires at least 6 inches of clearance above the ceiling, and insulation is essential to ensure that condensation does not drip into the fixture. Recessed lighting sends a relatively narrow band of light in one direction; it can be used to provide ambient, task or accent lighting.

Track: Mounted or suspended from the ceiling, track lighting consists of a linear housing containing several heads that can be positioned anywhere along a track; the direction of the heads is adjustable also. Track lighting is often used for task or accent lighting (spot lights).

Undercabinet: Mounted under kitchen cabinets, this type of lighting can be linear or a single puck-shaped fixture. Undercabinet lighting is extremely popular as task lighting in a kitchen.

---

[93] Types of Lighting Fixtures. http://www.hgtv.com/remodel/mechanical-systems/types-of-lighting-fixtures Retrieved March 28, 2015.

Pendants: Suspended from the ceiling, a pendant light typically directs its light down, usually over a table. A pendant can enhance the decorative style of a room. Pendants can provide ambient or task lighting.

> Chandeliers: A sub-type of pendant lights, chandeliers are suspended from the ceiling, and direct their light upward. They can enhance the decorative style of a room. Chandeliers provide ambient lighting.

Ceiling: This type of fixture is mounted directly to the ceiling and usually has a glass or plastic shade concealing the light bulb. Ceiling fixtures have been common in homes for nearly a hundred years, often providing all the ambient light in a room. Some of these fixtures can also be installed in walls to provide ambient lighting for a hallway or room.

Wall Sconces: Surface-mounted to the wall, sconces can direct light upwards or downwards, and their covers or shades can add a stylistic touch to a room. Wall sconces provide ambient or task lighting.

Desk, Floor & Table Lamps: Made in a wide range of sizes and styles, lamps are extremely versatile and portable sources of light in a room. Most lamps direct light downward, with the exception of a torchiere, which is a floor lamp that directs its light upward. These lamps are often used as task lights, particularly for reading, but can also provide ambient light.

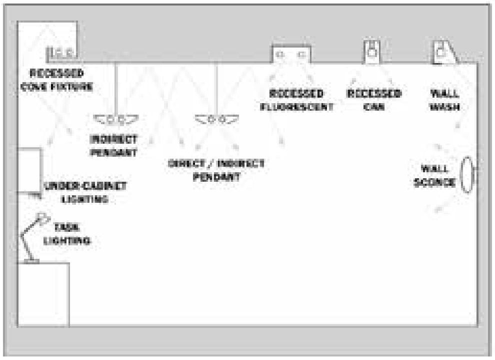


Figure 32: Light Fixture (Luminaire) Types[94]

---

[94] Light Fixture (Luminaire) Types. http://www.archtoolbox.com/materials-systems/electrical/lightfixtures.html

Heat dissipation design

Light is produced from a source through the conversion of electrical energy into radiant energy and heat. Unlike traditional incandescent lights, LEDs do not irradiate heat: they conduct it through the PN junction to the casing and hence to the dissipation system to which they are attached to. Without a correct thermal management the heat in the junction will increase. As the junction temperature (Tj) of an LED increases, multiple performance parameters are compromised. Quality of light is affected through color shift and white point instability. Quantity of light is lowered whilst using the same power, decreasing the energy efficiency. Life is also decreased through accelerated lumen depreciation.

The junction temperature is affected by the following parameters: Driving current, total thermal resistance within the junction and the atmosphere, LED power in function of the dissipation surface and room temperature. In general, the higher the driving current is, the higher the junction temperature will become. Because the junction is very small, the amount of heat generated per unit of area is very high. In order not to compromise the desired performance the excess heat must be removed and transferred to the environment.

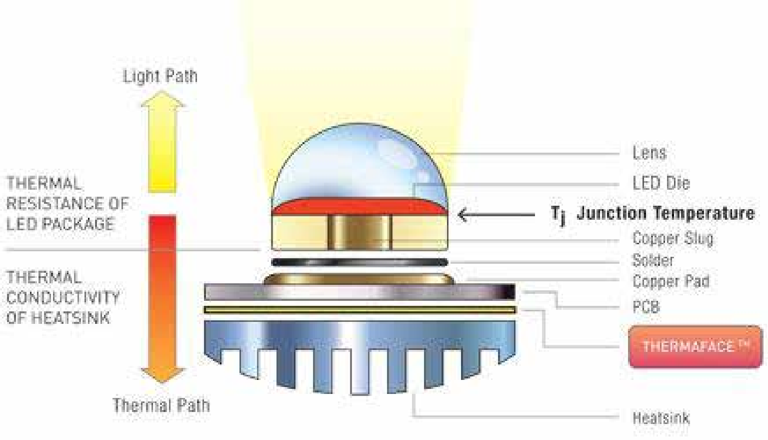


Figure 33: Example of LED thermal path

This removal of heat from the junction to the environment is usually done by a series of components that are characterized by having a high thermal conductivity, which allows them to dissipate the heat at a high rate. These components, of which the most noticeable is the heatsink, are in contact with the led and transfer the heat produced by it into the surrounding atmosphere through a mechanism of irradiation.

Heatsinks vary in size and shape, and their design is usually aimed at maximizing their surface area, in order to facilitate heat transfer with the atmosphere. Usually, they are made of aluminum or copper, because of their high thermal conductivity, and have a bulky shape with a series of fins or pins that maximize the volume/surface area ratio (Figure 34). Despite their effectiveness and low cost, heatsinks are used mostly on technical luminaires such as street lamps, reflectors, or on lightbulbs in the areas where they remain mostly hidden. Their presence in more decorative luminaires has been avoided by designers, considering them a hard compromise in aesthetics. Unlike other functional components in luminaires, such as drivers, wiring, etc.; heatsinks require a direct contact with the atmosphere, making them harder to hide inside casings.

Figure 34: Examples of common heat sinks

One of the largest benefits of LED lighting is their small size compared to other light sources such as fluorescent or incandescent. The amount of light generated by a compact fluorescent light bulb, of a size of 10cm x 5cm diameter can easily be produced by a COB the size of a 2 euro coin. LED types such as COBs and highly concentrated arrays of power LEDs are not only the most efficient light sources in terms of power consumption but also in regards to volume. However, this small size does not come without a downside, as the higher the lumen/area rate goes the higher the heat generated is and thus the more dissipation it will require.

4.3. AM applied to LED Lighting

This section will describe scientific literature that deals with research on the application of AM in LED lighting. Commercial applications will be described in chapter 5. There is extremely little scientific information available, as both Additive Manufacturing and LED technology are both relatively new. However, two interesting research projects will be described below, in the manner of case studies.

4.3.1. Case Study 1: Printed Optics: 3D Printing of Embedded Optical Elements for Interactive Devices. Disney Research[95].

This research project, conducted by the Diseney Research Center, presents an approach to 3D printing custom optical elements for interactive devices labeled Printed Optics. Printed Optics enable sensing, display, and illumination elements to be directly embedded in the casing or mechanical structure of an interactive device. Using these elements, unique display surfaces, novel illumination techniques, custom optical sensors, and embedded optoelectronic components can be digitally fabricated for rapid, high fidelity, highly customized interactive devices.

Custom optical elements have traditionally been expensive and impractical to produce due to the manufacturing precision and

---

[95] Willis, Karl, et al. “Printed optics: 3d printing of embedded optical elements for interactive devices.” Proceedings of the 25th annual ACM symposium on User interface software and technology. ACM, 2012.

finishing required. Recent developments in 3D printing technology have enabled the fabrication of high resolution transparent plastics with similar optical properties to plexiglasTM. One-off 3D printed optical elements can be designed and fabricated literally within minutes for significantly less cost than conventional manufacturing; greatly increasing accessibility and reducing end-to-end prototyping time. 3D printed optical elements also afford new optical form-factors that were not previously possible, such as fabricating structures within other structures, printing multiple materials within a single optical element, and combining mechanical and optical structures in the same design.

Process

3D printing allows digital geometry to be rapidly fabricated into physical form with micron accuracy. Usable optical elements can be designed and simulated in software, then 3D printed from transparent material with surprising ease and affordability. 3D printing of optical quality materials typically requires a photopolymer-based process. Each layer is fabricated in sequence by selectively exposing a liquid photopolymer material to an ultra-violet (UV) light source, causing the material to cure into a solid state. Traditionally this has been achieved using ‘stereolithography’, where a precise laser is traced through a vat of liquid photopolymer. Other approaches include controlled exposure to UV light using a projector or physical deposition of liquid photopolymer in the presence of a UV light source.

The range of photopolymer materials for 3D printing is rapidly expanding, with optical-quality transparent plastic available in the market. In this work an Objet Eden260V 3D printer and Objet VeroClear transparent material was used to fabricate optical elements. VeroClear has similar optical properties to Poly(methyl methacrylate) (PMMA), commonly known as plexiglasTM, with a refractive index of 1.47 (650nm light source). The Objet Eden260V has a print resolution of 600 dpi (42 microns) that is significantly higher than fused deposition mod-eling (FDM) 3D printers (e.g. Stratasys Dimension, Maker-Bot, or RepRap) that are typically around 100 dpi (254 mi-crons). High resolution printing allows the creation of visibly smooth models without internal gaps. Model surfaces can be further enhanced with a manual finishing process to achieve optical clarity. This process consists of removing support material, sanding the surfaces with incrementally finer sand-paper, and then buffing.

Results

The project served to prove several capabilities of the printed optics approach. Among these, the possibility to create optics with multiple materials, structures within structures and combined mechanical-optical design. The four categories of fabrication techniques are:

- Light pipes: 3D printed optical elements, similar to optical fiber, that can be used to guide light from point to point. These were used to create mobile projector displays, mobile touch sensing devices, and tangible displays. Light pipes were created using a combination of the VeroClear material for the core and the Objet Support Resin for the cladding, in order to create the difference in material density necessary for TIR to occur. Light pipes down to a diameter thickness of 0.25mm with a cladding layer thickness of 0.084mm were created.
- Internal Illumination: 3D printing was used to create inner forms and concavities within a printed model to be viewed from the outside and highlighted with illumination. Internal illumination can be used with interactive devices to display information ranging from simple indicators to complex volumetric displays.
- Mechanical movement sensors: 3D printing is used to create custom optical sensing embedded in interactive devices. Low-cost IR emitter/receiver pairs are used to sense common user inputs such as rotation, push, linear movement, and acceleration.
- Embedded Components: Components were dropped-in during the construction process to create parts with embedded capabilities such as sensing, display, and illumination. Drop-in embedded components are physically robust, enable tight mechanical tolerances, and allow easy compartmentalization. The authors envision that in a future these elements will be dropped-in automatically using part placement robots similar to those employed for PC board

> manufacture, and that eventually it will be possible to print 3D components in their entirety. Some applications include lenses, beamsplitters, and special light bulbs.

There are still some limitations in the production process to create optimal results. Surface finishing, especially in inner geometries, needs to be improved, and currently available surface finishing techniques are time consuming. Clarity depends on the model thickness, the print direction, the UV exposure and the surface quality; if all of these parameters are not optimized, the part will show blurriness. Hollow areas require support material inside the hollow, which will become enclosed with no means for it to be extracted. Geometries that have limited overhangs may be printed without supports, but this creates a limitation to the design space.

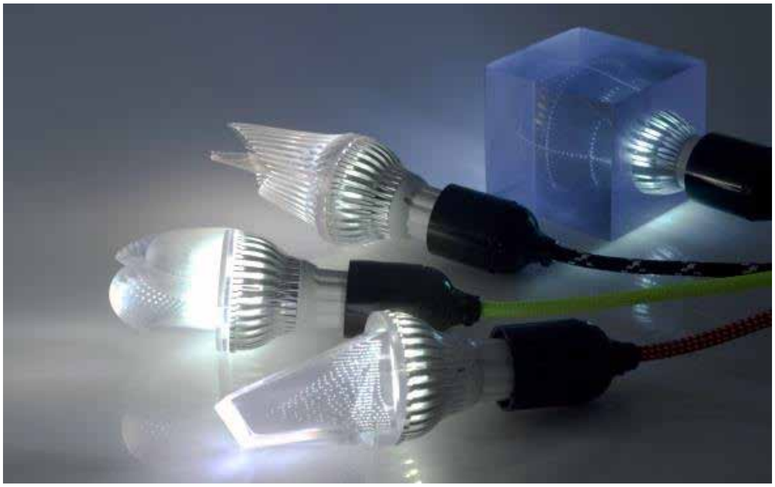


Figure 35: Series of special lamps created using embedded components and internal illumination[96].

4.3.2 Case Study 2: Advances in heat sink performance with DMLS. Technology Strategy Board[97].

Designing effective heat-sinks is a careful balancing act of a number of conflicting factors; these include the need to increase air flow and surface area while reducing pressure losses and

---

[96] http://www.disneyresearch.com/project/printed-optics/

[97] Advances in heat sink performance with DMLS. Innovation Results. An R&D Case Study by Technology Strategy Board. 2014

manufacturing costs. In order to satisfy these requirements heat-sinks for electronic applications are invariably produced as simple 2D sections extruded, pressed or forged to a repeated length.

If heat-sinks could be manufactured from a high thermal conductivity material with geometries that increase air flow and surface area while reducing manufacturing costs then more electronic products could be cooled by natural convection instead of resorting to more expensive and complex methods.

A standard extruded LED heat-sink was investigated to see how the DMLS process could be utilized to produce an alternative design that was more efficient at removing heat by natural convection.

Many different designs were made and the five heat-sinks that performed best in simulations using Computational Fluid Dynamics (CFD) were built by 3T RPD using DMLS and physically tested to confirm the earlier virtual analysis. In all five cases there was a consistent reduction in the heat source temperature using the DMLS heat-sinks when compared to the standard extruded heat-sink.

Figure 36: Heat sinks manufactured by DMLS

4.3.3. Case Study 3: Heat Transfer Enhancement by Finned Heat Sinks with Micro-structured Roughness[98]

This study investigated the capability of direct metal laser sintering (DMLS) manufacturing technique to produce micro-structured

---

[98] Ventola, Luigi, et al. "Heat Transfer Enhancement by Finned Heat Sinks with Micro-structured Roughness." Journal of Physics: Conference Series. Vol. 494. No. 1. IOP Publishing, 2014.

rough surface heat sinks. Usually heat sinks have been produced by milling manufacturing technique; surface roughness of those heat sinks is very low, around 1 micron. Through DMLS, heat sinks whose surface roughness can vary over a wide range of values were produced. The results showed that heat sinks produced by DMLS have better performance in heat dissipation than traditional ones produced by milling.

In this study average convective heat transfer coefficient of different heat sinks was measured using air as refrigerant fluid in turbulent regime. Copper heat sinks produced by traditional milling were compared to aluminum alloy (AlSi10Mg) heat sinks produced by DMLS. Effects of micro-structured roughness on thermal performance were shown. These are very large because little geometrical dimensions are involved in heat transfer phenomenon as usual in electronic cooling. The results offer an evidence of the possible impact of DMLS on electronic cooling since a 50% and 20% enhancement (compared to milled samples) is observed for flat and finned heat sinks, respectively. They also show that the lower thermal conductivity of aluminum alloy plays a negligible role on heat transfer performances in this setup. Enhancement on flat heat sinks is larger than finned sinks, because average roughness of the former is higher than that of the latter. Building rough fins is not as easy as doing rough flat surfaces, but in future studies this will be one of the first improvements that will be pursued from the point of view of DLMS machining. These results open the way for a huge boost in the technology of electronic cooling by DMLS.

Figure 37: Picture of milled copper and DMLS Aluminum alloy heat sinks

5. Analysis/ Feasibility

5.1 Applicability of AM Technologies and material according to purpose

As seen on previous chapters, Led luminaires are products with very specific functionalities, which, despite their versatility and improvements over conventional lighting technologies, still present numerous design considerations. Some of these considerations narrow the choice of AM technologies that could be used to produce them; the mechanical or thermal properties, optical properties, finishing, etc., of the materials used are not compatible with the performance required. The most critical considerations or design requirements are presented in the following segments and an analysis is done to select the most suitable AM technologies to use in each case.

5.1.1 Heat management

As seen in Chapter 4, LED types such as COBs and highly concentrated arrays of power LEDs are not only the most efficient light sources in terms of power consumption but also in regards to volume. However, this small size does not come without a downside, as the higher the lumen/area rate goes the higher the heat generated is and thus the more dissipation it will require. This, traditionally, means having a bigger heat sink or some means of forced dissipation, such as a heat sink with a fan attached to it. Using a larger heat sink will increase the overall size of the luminaire eliminating the benefit of using a small light source in the first place. Forced dissipation, on the other hand, will increase the energy consumption, reducing the advantage of using an energy efficient light source such as an LED, not to mention the noise generation and higher maintenance requirements (dust accumulation, failure of moving parts, etc.).

An alternative to this problem, adopted in recent years, has been creating a luminaire with a body or casing made entirely in a dissipating material, such as aluminum. If the heat dissipation is enough, the lamp will never reach a temperature that will make it dangerous to touch, and will preserve the LED within a safe temperature to avoid compromising its performance. A noticeable example of this approach is Artemide's Unterlinden (2014) pendant lamp designed by swiss architecture and design firm Herzog & De Meuron. Available in a brass or aluminum, the body of the lamp has a double function, to direct the light downwards and to dissipate the heat produced by the 4W COB it holds inside. Although the light output of 320lm is relatively low, the use of a COB within this small and clean lamp architecture, without the presence of noticeable heat sinks or other elements that would damage its smooth and simple appearance, presents a breakthrough in the industry.

Figure 38: Unterlinden pendant lamp, Herzog & De Meuron for Artemide (2014)

Another example is also Artemide's Florensis (2013) floor and wall lamp, designed by British designer Ross Lovegrove. In this lamp the body, made of extruded and machined aluminum, has the dual function of directing light and dissipating heat. This lamp holds a 43W dimmable power LED array, which is more expensive and less efficient than its equivalent COB, but produces less heat. This characteristic allows this luminaire to produce an impressive 2710 lumens, dissipated by a body of 23cm diameter, without the need of heat sinks beyond the luminaire's casing itself.

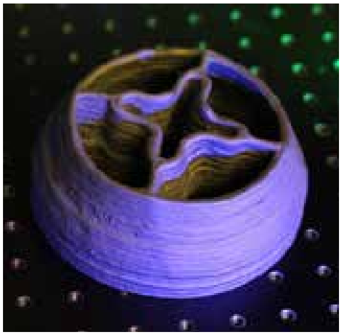
Figure 39: Florensis, Ross Lovegrove for Artemide (2013)

Continuing this approach with a 3D printed luminaire holds enormous possibilities. A basic design requirement of heat sinks, increasing surface area, is benefitted by complex shapes, which could theoretically be easier and cheaper to produce by these means. In the case of Florensis, the complex organic form of the body is achieved by a two-step process, described by the company in the following way:

"Florensis is a new concept in lighting aesthetics for all kinds of applications. Its floral bud has been arrived at through a unique way of creating form; the convergence of two different flows and processes.
The host form has been extruded in a linear way, suggesting upward growth, whereas the 'Bud' has been machined into its nature form, opening up beautiful botanical apertures and veins that diffuse both light and heat".

Although innovative, the process is surely time-consuming and expensive. Extrusion dies are expensive due to the forces they are subject to and numerical control machining is an expensive and time-consuming process that requires specialized machines and produces a lot of waste material. Other traditional metal part production methods such as die casting and investment casting require the production of molds that are only feasible if a large amount of parts is produced.

Although some 3D-printing processes such as DMLS (Direct Metal Laser Sintering) can also produce aluminum parts, they are expensive production methods, because of the long production times, the high cost of the metallic powder used, and the specifications of the machines used, which usually cost around 1 million euros. However, the use of dies or molds is avoided and thus the start-up costs and time are reduced. Additionally, heat sink's performance can be improved by the use of more complex shapes that optimize airflow and heat transfer. Such is the case presented on chapter 4.3, in studies performed by Technology Strategy Board[1] and Ventola, et al[2]. Low-cost additive manufacturing of metallic parts is also starting to become a big field of research and innovation. US based Weld3D is performing trials with a low-cost machine that uses a technology very similar to that of FDM, replacing the filament extruder by an arc welder. The results are still very rudimentary (see Figure 40), but the company promises to substantially improve them before the technology is put in the market. MatterFab is a company working on a powder based laser 3D printer, similar to the high end DMLS machines, at "an order of magnitude cheaper", which would set the machine at a much more affordable 100,000 euros approximately. The results achieved so far are impressive (Figure 41) although still small in size.



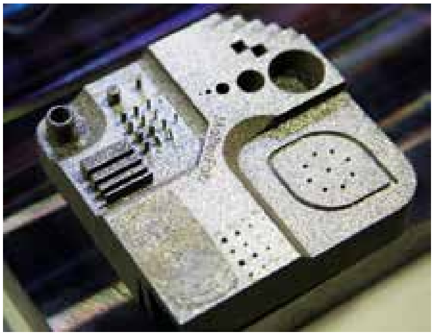


Figure 40: Printed and welded part made with Weld3D technology

Figure 41: Metallic printed part by MatterFab

Other alternatives such as metallization of printed plastic parts can be implemented. Cook et al investigated unit-cell-based custom thermal management through additive manufacturing, by studying the thermal performance of nylon printed heat sink created by SLS and then metallized through a copper

---

[1] Advances in heat sink performance with DMLS. Innovation Results. An R&D Case Study by Technology Strategy Board. 2014

[2] Ventola, Luigi, et al. "Heat Transfer Enhancement by Finned Heat Sinks with Micro-structured Roughness." Journal of Physics: Conference Series. Vol. 494. No. 1. IOP Publishing, 2014.

electroplating procedure. The resulting part (Figure 42) proved to be functional in dissipating heat, although it had a temperature limit set by the nylon core, of 200°C. Although nylon was an optimal choice because of its high temperature resistance, other polymers could be studied to undergo the same electroplating procedure. ABS is commonly electroplated in the industry, allowing printing the parts with low-cost FDM printers.

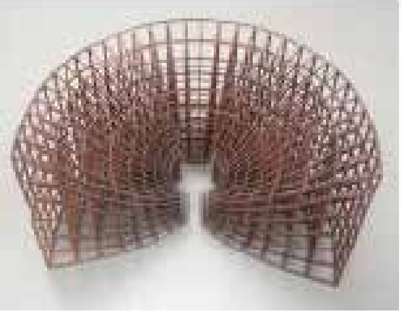


Figure 42: Custom nylon and copper plated heat sink.

Copper has a thermal conductivity of approximately 400 W/(mK), only inferior to that of silver. Aluminum has a conductivity of 210 W/(mK), still superior to that of most metals. Because only silver and gold have thermal conductivities that high, but are expensive, copper and aluminum are used in most thermal management applications. Both copper and aluminum can be plated on plastic. The plating of copper in ABS parts is performed regularly in the industry, a process which provides a fully metallic shell with a thickness that varies depending on the time of immersion. A chromic acid bath is performed to the piece which extracts the Butadiene from the ABS and thus creates a porous surface, to which a conductive solution is attached to. Once this solution covers the piece a normal electroplating procedure is performed to give it a copper surface or even subsequent materials can be applied like chromium. The copper exterior will have a shiny appearance if the plastic surface under is smooth. The cost is relatively low, representing a 10% of the printing cost. However, the disadvantage of this process is it's highly toxic to humans and the environment, and that the parts produced cannot be recycled afterwards. In the heat sink presented previously, the nylon part was electroplated with 50.8μm of copper at the US-based company RepliForm,

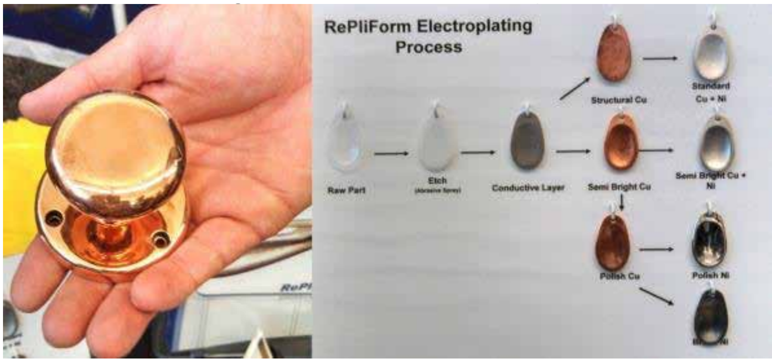


Figure 43: Repliform's electroplating process and results

Another method of metallizing plastic parts is vacuum deposition, a process that consists in depositing layers of material atom-by-atom or molecule-by-molecule on a solid surface. This process can be applied over any plastic surface, or even other materials such as glass or stone. Although this process is much less harmful, because it does not need to employ materials with eminent health risks like Nickel or materials which may cause environmental problems (hexavalent Cr) as it is used during selective electroplating, it has its own downsides. Usually the metallic layer is very thin, only a few microns (0.5…5), which is enough for decorative applications and even to give parts electrical conductivity but is insufficient for thermal applications. However, studies such as Andritschky and Pischow have proven the possibility of performing mass production of thick copper vacuum metallization on plastic parts. This possibility, if made industrially available, would allow this process to become an interesting alternative for manufacturing parts suitable for thermal management applications.

US Patent 2011/0242816, published October 6, 2011 and assigned to GE Lighting Solutions, refers to:

> "A heat sink that comprises a heat sink body, which in some embodiments is a plastic heat sink body, and a thermally conductive layer disposed over the heat sink body. In some embodiments the thermally conductive layer comprises a copper layer. A light emitting diode (LED)-based lamp comprises the aforementioned heat sink and an LED module including one or more LED

> devices in which the LED module is secured with and in thermal communication with the heat sink"[3].

5.1.2 Optical qualities

As seen in chapter 4.2.3 a very common component of LED luminaires is the secondary optic. This component is used to modify the light as it comes from the source. Each optic lens is usually designed with a specific purpose, which can be very different. In some cases the purpose is to diffuse light, in order to create a less concentrated light beam that can cover a broader area and will avoid dazzling. Another optic may have the opposite purpose of concentrating light within a focused beam, as is used with "spot" type luminaires. Optical lens are usually made in optical-grade transparent plastic, usually produced by injection molding, or in complex glass molds. Many luminaire manufacturers use generic lens because of their economic advantages, with the downside of having to adapt their luminaire designs to fit whatever lens is available in the market. Optic lens design is a complex process which requires a high level of expertise in order to achieve the desired results and effectively manage light. Not all luminaire manufacturers can afford to have this type of expertise in-house, and with traditional manufacturing technologies testing (trial and error) is not possible, due to the high costs of molds.

This situation creates a large opportunity for additive manufacturing, as luminaire manufacturers could create their own optics designs and test the effectiveness of their designs with a relatively low investment. Furthermore, they can continue to manufacture their lens by AM, if they plan to have many optical lens variants over a small series of lamps, because they would not have to manufacture molds and prepare production batches, inventories, etc. However, AM with optical grade results is very hard. Most AM technologies are immediately discarded because the layering in the part's interior and laddering effect in the part's surface modifies the direction of light and creates unwanted refraction. SLA, MJM and Objet are perhaps the technologies that could generate the best results (as evidenced in the Printed Optics research project by Disney Research

---

[3] Chowdhury, Ashfaqul I., Gary R. Allen, and Thomas A. Knapp. "Lightweight heat sinks and led lamps employing same." U.S. Patent Application 12/979,476.

presented in Chapter 4.3.1) because although post-processing is required to eliminate the ladder effect in the surface, the parts are mostly transparent beyond their surface. However, optical grade transparency cannot be obtained by these technologies, because some layering is always present and thus unwanted refraction will occur.

Luxexcel, a Dutch-based company, created a proprietary 3D printing method called Printoptical, that consists in the deposition of UV-curable acrylic ink droplets that are allowed to flow and merge before being cured. The result is printed optical-grade lenses that can even be used for fully functional eyeglasses. The parts require no post-processing and they can be produced in small batches or individually. Despite the benefits of this technology, it is still proprietary of the company and thus only available as a service for other companies. They additionally offer the design of new optics for luminaire manufacturers.

Figure 44: Results of Luxcexcel's patented Printoptical technology in comparison to other AM technologies

5.1.3 Electrical Conductivity

As with any other electrical appliance, the conduction of electricity is necessary for LED luminaires. This requirement has traditionally been accomplished by electrical wires that are allocated within the luminaires casing or exhibited as part of the lamp, as the case of pendant lamps. The latter approach has generated an array of unusually decorative wires, such as those covered in vibrantly colored elastomers or textile patterns; or thin cables covered by transparent plastic for stealth purposes. However, internal wiring has always been a headache for luminaire manufacturers, as it is for the most part a time-consuming operation that often requires manual procedures such as soldering and screw assemblies with connectors, drivers, light sources, etc. Additionally, it implies a hollow-form constraint to "hide" the cabling, which may conflict with some designer's desires, or with the production possibilities.

Several alternatives have been tested by luminaire manufacturers to avoid having internal wiring. Over recent years flat cables have been developed to make wires travel along the surface of an object. These wires will go barely unnoticed if painted over, because their thickness is similar to that of a thick tape. Another possibility is having the current travel throughout the lamp's body. Artemide's famous Tizio lamp designed by Richard Sapper and Nemo Lighting's Chain lamp by Ilaria Marelli are examples of this approach. The Line and Neutral currents are conducted by separate parts of the luminaire's body, being careful to keep them separated and isolated to prevent a short circuit.

Figure 45: Tizio, Richard Sapper for Artemide.

Several methods have been created to print electrically conductive parts through additive manufacturing technologies. Electrically conductive ABS, a material formed by mixing the polymer with carbon nanotubes or other conductive materials, is commercially available in filament form for FDM printing. It is often used within double-extruder printers where circuits can be printed inside an isolating matrix. The electrical conductivity is nonetheless low, which makes it suitable for low tension circuits but not for fully functional luminaires. Additionally, layering generates contact problems, as contact cannot be fully guaranteed between layers. Diegel et.al. propose a Curved Layer Fused Deposition Modeling in Conductive Polymer, to avoid layering problems and the laddering effect. This is described by the authors as a "Fused Deposition Modeling (FDM) process in which the layers of material that make up the part are deposited as curved layers instead of the conventional flat layers. This technology opens up possibilities of building curved plastic parts that have conductive electronic tracks and components printed as an integral part of the plastic component, thereby eliminating printed circuit boards and wiring". The electrical conductivity of the filament must still be improved in order to allow this technology to be used in fully functional luminaires though.

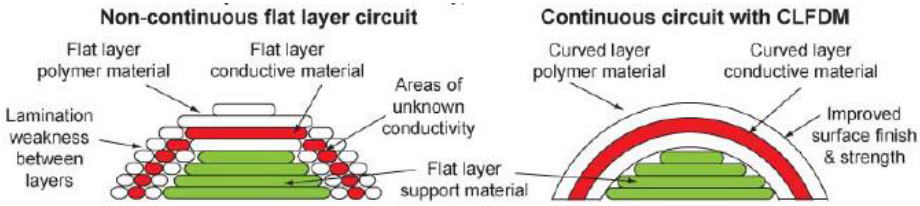


Figure 46: Diagram of curved layer deposition used to create continuous circuits

Another approach is to print around inserts, to create "embedded" circuits. As seen during the Disney Research case study, electrical components such as LEDs can be inserted within a printed matrix during the printing process. This approach creates permanent assemblies, which will not allow maintenance or part replacement, but it reduces assembly times and allows the creation of monolithic luminaires. Kataria and Rosen presented a methodology for fabricating complex structures with inserts using stereolithography. This methodology avoids problems such as laser shadowing and blocking the laser's trajectory with overhanging inserts. This approach has a fundamental conflict, if an LED is inserted within a polymer matrix, this matrix must be transparent or at least translucent with a low loss of luminous output. As seen previously, the AM technologies that allow the manufacture of transparent parts are SLA, MJM and Objet. These materials however have a low service temperature, presenting heat deflection and other loss of properties after 50°C. This constraint allows low Watt LEDs such as those used by Disney Research to be inserted. PowerLEDs and COBs, however, which generate even a moderate 1000 lumen output, cannot be inserted within a matrix of these characteristics because it would overheat it and eventually the luminaire would be ruined.

5.2 Analysis of Lighting Applications

Luminaires have been industrially produced for centuries, becoming an indispensible element of modern life. They have written some of the most memorable pages of industrial design's history, achieving an iconic status and catapulting their designers to world fame and recognition. Marianne Brandt's Kandem table lamp for Körting & Mathiasen (1928), Pier Giacomo and Achille Castiglioni's lamps for Flos such as Arco (1962), Toio (1962), Snoopy (1967) and Parentesi (1970); Richard Sapper's Tizio lamp for Artemide (1972), Vico Magistretti's Atollo lamp for O-Luce (1977), Michele de Lucchi and Giancarlo Fassina's Tolomeo lamp for Artemide (1986), and Alberto Meda's Titania lamp for Luceplan (1989); are just some noticeable examples of how luminaires have contributed to the development of the design profession as a whole and have inspired countless designers throughout the last century. This chapter will not make a comprehensive study of luminaires, a task that would merit a whole project in itself; but will instead concentrate on some examples of luminaires that are most relevant to this project. Amongst these, luminaires created by Additive Manufacturing and LED luminaires with a form factor that could possibly fall under the manufacturing capabilities of AM.

5.2.1 Luminaires Created by Additive Manufacturing

Additive Manufacturing has been used to create luminaires almost from its invention. However, the market introduction of low-cost 3D printers gave birth to of a wave of printed luminaires in the most varied shapes and colors. The possibility of creating expressive and complex shapes that could be accentuated by light seemed to spark the creativity of hundreds of designers that started posting their designs in file-sharing websites such as Thingiverse, Youmagine and GrabCAD, as can be evidenced by a simple search in them (Figure 47). Online 3D printing services such as Shapeways and Materialise quickly picked-up the interest and started offering ready-made lamp prints, full with the electrical components.

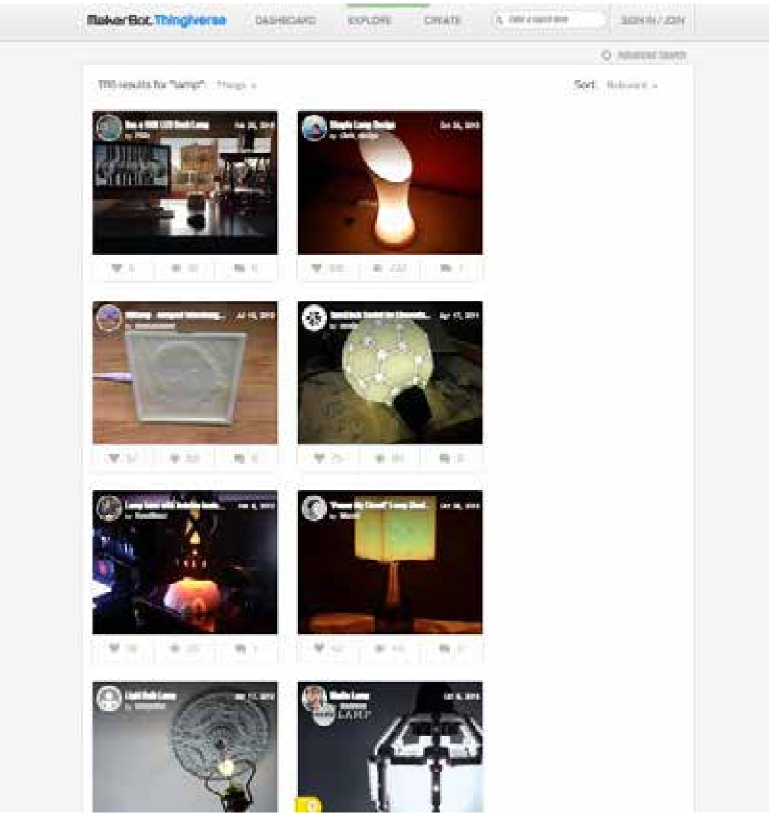


Figure 47: Searching the term "lamp" in Thingiverse produced 1116 results (15/03/2015)

Shapeways commercializes lamps created by their community, which includes design studios such as the Massachusetts-based studio Nervous System. They define themselves as

"…a generative design studio that works at the intersection of science, art, and technology. We create using a novel process that employs computer simulation to generate designs and digital fabrication to realize products. Drawing inspiration from natural phenomena, we write computer programs based on processes and patterns found in nature and use those programs to create unique and affordable art, jewelry, and housewares." [4]

The result of this process has been the creation of stunningly complex and sculptural lamps with names such as Hyphae, Pollen, Reaction, and Orbicular (Figure 48). They are all made by Selective Laser Sintering in nylon with UV protection. Their

---

[4] http://n-e-r-v-o-u-s.com/shop/search_tags.php?search=lighting

prices range from 200 dollars for the smallest pieces to more than 1300 dollars for the largest lamps. Most lamps come with 3 or 4 Watt LED light bulbs.

Belgium-based company Materialise offers 3D printed lamps

REACTION LAMP $320.00 on demand
POLLEN LAMP $780.00 on demand
SEED LAMP $1320.00 on demand
HYPHAE LAMP $300.00 on demand
ORB LAMP $173 - $202
ORBICULAR LAMP $470.00 out of stock
HYPHAE PENDANT LAMP $400.00 on demand
ARBOREAL LAMP $700.00 out of stock
BLACK HYPHAE LAMP $300.00 on demand
HYPHAE SCONCE $320.00 on demand

Figure 48: 3D printed lamps designed by Nervous System

Figure 49: Hyphae lamp by Nervous System, comercialized through Shapeways

through their website MGX by Materialise[5]. Again, they offer an array of complex lamp shades created through SLS mainly in Polyamide or Epoxy material. Their price range goes from 343 euros to a staggering 25000 euros. Some luminaires are intended for LED light bulbs, but most of them come with CFL or halogen lamps. Some of their lamps have won international design awards. For example the Quin lamp was selected by Time Magazine as one of the 100 best design objects of 2008, and was a Grand Designs Magazine Award Finalist in 2006. [6]The Lily lamp won the Red Dot design award in 2005, and the Bloom lamp won it in 2011, along with the Good Design award in 2010. Most lamps have been designed by independent designers and artists such as Bathsheba Grossman, Dan Yeffet, Jiri Evenhuis, amongst others.

Figure 50: Bloom lamp, MGX by Materialise

---

[5] http://www.mgxbymaterialise.com/

[6] http://www.mgxbymaterialise.com/webshop/order/family/detail/shopdetail/27?product=118

Figure 51: Lilly lamp, MGX by Materialise

One of the most interesting cases is Italian company .exnovo. This company located in the Trento region was established in 2010 by the industrial prototype manufacturer HSL, the first company in Italy and among the first in Europe in using Additive Manufacturing technologies. The know-how that this company had developed in more than 25 years in prototype making was used to create a professional 3D printing lighting company. In the company's own words:

".exnovo now creates, designs and produces small, limited production runs of exclusive designed lamps and furnishing accessories, in collaboration with young and talented designers and Italian artists and artisans, who hold high the value of Made in Italy"[7].

Exnovo is different to the previous cases because they are a company sustained only by the creation and commercialization of 3d printed objects, mainly lamps. The designers that have created their lamps are commissioned by the company, which launches a new collection each year, and operates similar to other lighting companies; participating in the design community more than the 3d printing community. This factor, along with the aesthetic qualities of their products, has broadened their scope

---

[7] http://www.exnovo-italia.com/

beyond that of the AM enthusiasts. Their unique production approach has also allowed them to create products that mix professional SLS technologies with traditional artisanship, including hand-made and hand finished pieces in wood, glass and ceramics.

Figure 52: Aphillia and Rhizaria lamps by .exnovo

Traditional lighting manufacturers have kept a distance from Additive Manufacturing, aside from Rapid Prototyping uses. One of the few exceptions is Ingo Maurer's Knot lamp (2013), made in Polyamide through Selective Laser Sintering. This lamp, with a price of €2,675.00, is interesting because it is one of the few examples of a 3D printed LED lamp with full luminosity, as it holds a built-in 14.5 Watt LED panel that produces 1800 lumens.

Figure 53: Knot lamp by Ingo Maurer (2013)

Despite how interesting all of these examples may be, and innovative they may seem, they represent a very traditional conception of lighting. They are all built in a way that follows the traditional architecture of a luminaire; a light bulb is covered by some type of lamp shade or shell. Their designers have all shown more or less the same approach; designing an elaborate lamp shade that will create some type of illusion or shading effect once the lamp is turned on. In none of these cases has the implementation of Additive Manufacturing modified the basic structure or functionality of the lamp. None of them have gone into technical aspects of LED; in fact, most of them are built around the E27 or E14 standards and could function equally well with a halogen, fluorescent, or even incandescent lamp bulb for that matter. It would seem, to whoever browses the more than 1100 models available at Thingiverse, that the ‘digital revolution’ is only a revolution of form and distribution. The means of production change, people get access to files which they can manufacture themselves, and even personalize and modify, but it all remains rather superficial. It is as much of a revolution as stamping a t-shirt at home, very nice for a DIY segment of the market but not really enough to become a “game-changer”.

Furthermore, for traditional luminaire manufacturers the incentive for switching to AM is still not enough. It would seem as if the two industries (AM and lighting) are working towards different goals, opposite even. On one hand, the AM industry is desperately looking for new applications for their production technology, not necessarily wanting to deepen their know-how in the industries they embark. With the same level of depth and research they go into manufacturing a lamp one day and a necklace or a flower base the next. On the other hand, the lighting industry has a long tradition and background, a well-cemented know-how of their industry, which often generates aversion to change and a fear of radical moves towards different technologies. They are still working under the industrial Fordist paradigm, each striving to create the new miracle lamp that will sell millions. The reality is, however, that only very few lamps achieve this massive status. Not all of Artemide’s products are “Tolomeo’s”, most are lamps that will probably go out of catalogue after a few years, and the same goes for small manufacturers which will often sell only a few hundred units of a product before it becomes commercially obsolete. This is all worsened by an industry that moves at a fast pace, both technologically and in regards to trends and fashion. Each year luminaire manufacturers are pressured to renovate their catalogue and present an array of new releases on the most important design fairs. Market interest for "old" products is quickly lost, and manufacturers get stuck with their investment on molds, with finished products tucked away in warehouses or on sale at discount prices. The opportunities for AM under this scenario are enormous, but the AM industry is not moving quick enough to present better solutions that really understand the necessities of the lighting industry.

5.2.2 Recent Commercial LED Luminaires

Two of the most interesting lamps analyzed in this project have already been presented; Artemide's Florensis and Unterlinden lamps. These lamps have innovations both in form and functionality that could be potentially improved or applied with AM technologies. This section will explore other lamps that have been released in recent years and have potentially interesting insights on the direction of luminaire design and production.

Chapo is a table lamp designed by Philippe Starck and produced by FLOS. It has a body entirely made in aluminum, with a chrome finish, that has the intention of holding the user's hat in a way that it becomes a lamp shade. The light source is an 8W COB, it has a photo-etched diffuser made in PMMA, a touch dimmer, and a USB dock that can be used to charge a cell phone. The lamp is interesting because it does not present a strong statement in itself, but through the interaction with the user, in this case his/her hat. It has a passive way of inviting this interaction and personalization, adapting to various personalities depending on the user's hat choice. This type of personalization is more plausible than envisioning a future where everyone will want to create CAD files to print their own products. Most people have the desire or need for personalization, but will not go through great lengths to achieve it, and will want to have some type of guidance to assure them of what they do. The designer must therefore not leave everything in the hands of the user, but create a canvas that is flexible within certain boundaries, that assure the user that whatever he/she decides to do with the product it will still function correctly.

Figure 54: Chapo lamp, Phillipe Starck for FLOS

Aplomb is a family of pendant, floor and wall lights designed by Studio Lucidi & Pevere and manufactured by Foscarini. They are made in cement and metal, and available in halogen and LED versions. Materials such as cement and clay, relatively recent in the world of luminaire production, have been achieving great visibility and appraisal in recent years, as seen by recent works by designers such as Benjamin Hubert for Decode[8], James Bartlett for Innermost[9], and German manufacturer GANTlights[10]. AM of cement and clay is relatively recent, but with incredible results, such as those achieved by designer Olivier Van Herpt[11]. Politecnico di Milano's +Lab has also been researching on low-cost 3D printing of ceramics with good results[12]. The high resistance to temperature and the aesthetical connections that concrete and clay can have with surrounding architectural elements create a big opportunity for these materials to be implemented further in luminaire design.

Figure 55: Aplomb, Studio Lucidi & Pevere for Foscarini

---

[8] http://www.benjaminhubert.co.uk/works/lighting/heavy/

[9] http://www.innermost.net/wp/portland-2

[10] http://gantlights.de/

[11] http://oliviervanherpt.com/functional-3d-printed-ceramics/

[12] http://www.piulab.it/1/ceramici_ceramic_848801.html

Figure 56: Clay printed parts by +Lab, Politecnico di Milano

Artemide's IN-EI is a collection of sustainably designed, foldable lampshades designed by Japanese fashion designer Issey Miyake. "Each of ten lamp designs utilizes special fabric derived from recycled PET bottles, processed using an innovative technology that reduces both energy consumption and CO2 emissions up to 80% when compared to the production of new materials. The designs are created using 2D and 3D mathematical principals to define their shape and extent of light shading". This collection, that has received the 2014 Compasso d'Oro ADI Award, proves a recent design trend for geometrical patterns and tessellations that requires a geometrical complexity hard to manufacture with traditional technologies. Tom Dixon has explored this trend in his Etch collection which is created by laser cutting and bending sheetmetal. Konstantin Grcic has also explored it in his acclaimed One chair and stool collection for Magis.

Figure 57: One Chair, Konstantin Grcic for Magis

Figure 58: IN-EI, Issey Miyake for Artemide

Figure 59: Etch, Tom Dixon

6. Design Configuration

This chapter establishes the beginning of a lamp design project that was developed as a case study to validate the research results presented in Chapters 4 and 5. A series of design requirements are established, and then a basic product architecture and configuration is achieved through a functional and morphological analysis.

6.1 Design Requirements

This section follows Karl T. Ulrich and Steven D. Eppinger's methodology for defining product specifications[1]. It takes common product client necessities expressed in phrases such as "the lamp is easy to install" and translates them into design requirements that are less subjective, such as "the average time to install the lamp is less than 5 minutes", which allow the designer to validate and measure the extent of the need's satisfaction for each design concept. It basically establishes what the product must do, without limiting the designer's creativity in regards to how the product must do it.

The following is a list of client necessities, demands and the designer's own desires interpreted as design requirements, which are expressed without a measurement yet:

Demand or desire	Design Requirement
Make enough light	The amount of light emitted by the lamp is sufficient
Make a beautiful light	The light emitted by the lamp is beautiful
Make a warm light	The light emitted by the lamp is warm

---

[1] Ulrich, Karl T., and Steven D. Eppinger. Product design and development. McGraw-Hill Education. 2004.

Look nice	The lamp looks nice
Save energy	The lamp is efficient in its power consumption
Be small	The lamp's size is small
Be easy to use	The lamp is easy to use
Require few or no maintenance	The lamp is maintenance-fee
Be safe to touch	The lamp is safe to touch The lamp's body is isolated
Be easy to carry	The lamp is light weight
Last long	The lamp lifecycle lasts long
Don't cost too much	The lamps cost is adequate
Make me proud	The lamp creates a sense of pride in its owner
Generate interest	The lamp generates interest in its observer
Be easy to make	The lamp is manufactured by available technologies
Be easy to assemble	The lamp's assembly is easy
Be easy to install/uninstall	The lamps installation is easy
Not become outdated	The lamp has a timeless aesthetic
Be safe for the eyes	The lamp avoids dazzling
Not be damaged by dust or humidity	The lamp is sufficiently protected of the environment
Be original and unique	The lamp can be produced in low production volumes
Have the latest technology	The internal components can be easily updated in new versions
Don't have to wait for light	The lamp lights on immediately

These design requirements are graded by their relative importance to the product's success, being given a mark from 1 (not very important) to 5 (very important). A series of lamps described in earlier sections of this chapter are evaluated from 1 to 5 in their ability to satisfy each of these needs. Most criteria were judged subjectively according to the information available on the product.

Table 2 (continues on pages 103, 104 and 105): Design Requirements evaluated for several commercial luminaires

Design Requirement	Importance	Ingo Maurer Knot
The amount of light emitted by the lamp is sufficient	5	3
The light emitted by the lamp is beautiful	4	4
The light emitted by the lamp is warm	3	5
The lamp looks nice	5	5
The lamp is efficient in its power consumption	4	4
The lamp's size is small	2	2
The lamp is easy to use	4	4
The lamp is maintenance-free	4	5
The lamp is safe to touch	5	5
The lamp's body is isolated	5	5
The lamp is lightweight	3	3
The lamp lifecycle lasts long	5	3
The lamps cost is adequate	4	1
The lamp creates a sense of pride in its owner	5	4
The lamp generates interest in its observer	5	4

exNovo Afillia	Artemide Unterlinden	Artemide Florensis	Foscarini Aplomb3
2	2	5	3
4	4	5	4
5	5	5	5
4	4	3	5
4	5	4	4
5	5	4	3
5	5	5	5
3	5	5	4
5	5	5	5
5	3	3	5
5	4	4	2
2	5	5	5
3	2	2	3
3	4	4	3
4	3	5	3

The lamp is manufactured by available technologies	3	3
The lamp’s assembly is easy	3	2
The lamps installation is easy	4	5
The lamp has a timeless aesthetic	4	4
The lamp does not dazzle	4	3
The lamp is sufficiently protected of the environment	3	3
The lamp can be produced in low production volumes	4	5
The internal components can be easily updated in new versions	4	5
The lamp lights on immediately	3	5
		372

The lamp that ranked highest is Ingo Maurer’s Knot lamp, mostly because of criteria that has been previously analyzed in this project and has a great importance to it, such as the possibility of producing low production volumes, updating designs to new components, and the fact that it’s plastic shape is easy to use and install. However, the second lamp that ranks highest is Artemide’s Florensis lamp, for different reasons, such as its high efficiency and light output, and the capacity to generate interest in the observer, due to its strange organic shape and configuration. These are all criteria that should be taken into consideration and combined in the new design.

The next step consisted in giving a metric, unit and value to the design requirements. Some requirements continue to be subjective and are therefore marked as such. Trying to quantify

3	3	3	3
3	3	3	1
5	4	4	3
4	4	2	5
3	2	2	4
2	5	4	3
4	3	3	2
3	2	2	2
5	5	5	5
356	359	366	352

for example if a product is “beautiful” may prove to be difficult, but must nonetheless be left as an important design requirement and considered by the designer at all times.

Table 3: (continues on page 107): Design Requirements with metric, units and values

Design Requirement	Metric
The amount of light emitted by the lamp is sufficient	Luminous Flux
The light emitted by the lamp is beautiful	Color Rendering Index (CRI)
The light emitted by the lamp is warm	Color temperature
The lamp looks nice	Subjective
The lamp is efficient in its power consumption	Luminous Performance or Efficacy
The lamp's size is small	LxWxH
The lamp is easy to use	Maximum number of possible operations
The lamp is maintenance-fee	Number of maintenance operations
The lamp is safe to touch	Max surface temperature
The lamp's body is isolated	Electrical current on lamp's surface
The lamp is lightweight	Weight
The lamp lifecycle lasts long	Time of useful life
The lamps cost is adequate	Retail price goal
The lamp creates a sense of pride in its owner	Subjective
The lamp generates interest in its observer	Subjective
The lamp is manufactured by available technologies	Amount of local production process providers
The lamp's assembly is easy	Time to assemble
The lamps installation is easy	Time to install

Unit	Value	Observations
Lumens	1000-1800	
Ra	80-100	
Kelvin	<3300	kitchen applications excluded
Lumen/ Watt	>60	
cm	< 25x25x25	Not counting structural elements such as a cables for suspension lamps or stands for floor lamps
#	2	on/off and dimming
#	0-1	
°C	50	
Volts	0	
grams	<500	Not counting structural elements such as a cables for suspension lamps or stands for floor lamps
Years	>15	
Euro	<750	Imagining a factor of cost*5
#	>3	
Minutes	<5	
Minutes	<5	

The lamp has a timeless aesthetic	Subjective
The lamp avoids dazzling	Unified Glare Rating
The lamp is sufficiently protected of the environment	IP Classification
The lamp can be produced in low production volumes	Minimum production units
The internal components can be easily updated in new versions	Lead time due to internal components
The lamp lights on immediately	Time to full light after turning on

The values are to be interpreted as design goals, which will hopefully be achieved by the design but may have to be reviewed in latter stages of the design, as they are subject to cost and feasibility studies. However, they will be the basis for creating and selecting the most appropriate design solutions.

6.2 Functional and Morphological Analysis

This section will study the functional structure of a luminaire, dividing it into a series of systems and studying the relationships amongst them. After this, a series of possible components that could fulfill the functional requirements of these systems will be analyzed. Several configurations will be proposed, arriving finally at the basic architecture possibilities of the designed product.

6.2.1 Functional Analysis

The process described in this section is based on the process to analyze functional interrelationship described in Engineering Design by Pahl et al[2]. The objective is to understand the inputs and outputs of a system, both external (as a whole) and internal (each sub-system).

The first step is to develop a black box diagram, in which the inputs and outputs of the system are represented as flows of energy, matter and signals, with an arrow indicating if they enter

---

2, 3 Pahl, Gerhard, et al. Engineering design: a systematic approach. Vol. 157. Springer Science & Business Media, 2007.

UGR	<22	
IP	2X and X3	
#	1	
weeks	<1	
seconds	<1	

or leave the system (Figure 60). The system is represented by a box with a verb written in the center, which represents the main function.

Figure 61 shows the black box diagram of a luminaire. Electric energy enters the system as a signal of on/off is given, and the system transforms it into light and heat.

Figure 61. Black Box analysis of a LED Luminaire

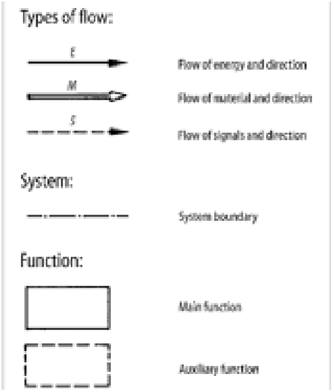


Figure 60: Symbols used to represent flows and functions throughout the system[3].

To understand how a luminaire functions internally, it is necessary to break-down the main function into a series of sub-functions. Figure 62 shows the internal sub-functions of a luminaire and the flows among them, which are mainly electric, in a diagram that the authors have named “Functional Structure”. The dashed line represents the system boundary, i.e. what was previously inside the black box. The same inputs and outputs continue to enter and leave the system. However, four main subsystems are identified, represented in the colors green, blue, orange and red. The green boxes represent the electric system, which has three main functions; to allow energy to pass into the system, transform this energy into a DC current (unless the system is direct driven, in which case this step is ignored); and to conduct this energy into the LED. The LED system has the function of transforming this energy into a luminous flux, which goes into the optical system, which has the function of directing and diffusing (or concentrating in other cases), this luminous flux until it exits the system. The LED however has also an undesired output, which is heat that is transmitted by conduction. This heat goes into the thermal management system which has the function of dissipating it by convection.

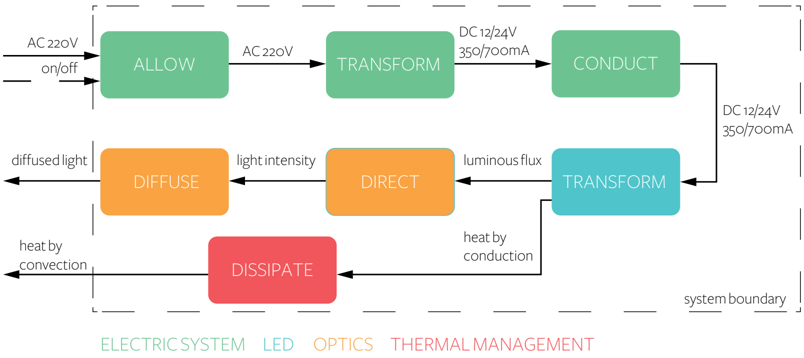


Figure 62: Functional Structure of a LED Luminaire

6.2.2 Morphological Analysis

The following step consists in identifying the necessary components that can fulfill the functions identified in the Functional Structure. Nigel Cross proposes a methodology to do so in his book Engineering Design Methods[3]. The result is what the

---

[3] Cross, Nigel. Engineering design methods: strategies for product design. John Wiley & Sons, 2008.

author calls a Morphological Chart, a graphical representation of all the sub-solutions to each function. At the end of this chart a series of combinations of sub solutions are identified.

Table 4 shows the Morphological Chart developed for the LED luminaire. Over the Chart three possible combinations are drawn. These combinations and the motivations for choosing them will be described further.

touch dimmer	wall switchc	able switchc	able dimmer	RGB controller	SWITCH
CC driver	CV driver	CC+CV driver	direct current	battery	ELECTRIC POWER SYSTEM UNIT
common	flat	body conduction	decorative	transparent	CABLING
LED strip	COB	SMD moduleL	ED bar	LED light bulb	LED
commercial	reflectorp	lastic diffuserp	rinted optics	printoptical	OPTICS
commercial	print + CuA	dissipating body	I DMLS	integrated bulb	TERMAL MANAGEMENT

OPTION 1 OPTION 2 OPTION 3

Table 4: Morphological Chart of a LED Luminaire

For each of the four sub-systems individualized in the Functional Structure, at least five different sub-solutions were identified. The Electric System was further sub-divided into switch, power unit and cabling, as multiple solutions can be obtained for each of these functions.

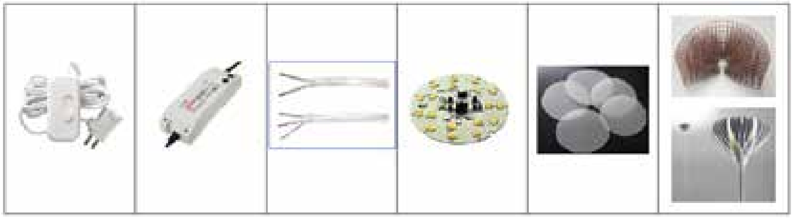
As previously anticipated, 3 possible combinations of sub-solutions were identified. Each of these is described below:

OPTION 1

The first configuration consists in a wall switch, a CC/CV driver, common commercial cabling, a COB LED, a combination of reflector and diffuser, and a dissipating body made in printed plastic with a conductive copper layer. The COB was chosen for its reduced size, superior efficiency, thermal capabilities, and light flux quality, all described in chapter 4. The optical design requirements of the luminaire consist of optimizing the luminous flux (reflector) while avoiding dazzling the user (diffuser). Finally, the option of printing a body that can dissipate the heat through the application of a Cu layer was chosen for its innovative and aesthetical possibilities. The electric system was chosen generic, to guarantee a good performance and avoid additional costs to the luminaire.

OPTION 2

The second configuration option consists of a cable switch, a decorative cable, a COB that works with direct current, a printed optic, and a heat sink that is 3D-printed in metal. This option represents a state-of-the art in AM applied to LED illumination. It combines the most advanced research that is being done at the moment, described in chapter 4.3. The drawbacks to this option are that it would require two very expensive AM manufacturing technologies (SLA and DMLS) and materials, which would, under current conditions, render the product economically unfeasible. As a research possibility it is absolutely interesting for a medium-long term future, but the literature review demonstrates that there are already other research groups working on this possibility.



OPTION 3

Option 3 is similar to option 1, with the difference that instead of a COB it contains a SMD module. As these types of modules come in a large amount of shapes and can even be designed and produced according to specifications, this possibility gives a larger flexibility in terms of form and design. However, it represents a step-back in terms of technology and efficiency, as COB LEDs are more efficient and produce a superior quality of light.

All of the three options are valid, but Option 1 seems to be the most innovative and interesting. COBs are the latest and best development in LED technology and they are currently being ignored by some luminaire manufacturers for their heat dissipation requirements. It is difficult for a company that wants to sell aesthetically pleasing decorative luminaires to accommodate a big chunk of finned aluminum in their products. This is why some companies like Artemide and FLOS (Chapter 5) have chosen to fabricate lamps that have a dissipating body, in order to take advantage of the possibilities of COB's without having to sacrifice their product's appearance. It seems that under these conditions there is a big opportunity to create new solutions and explore interesting innovations like the metallization of 3D printed parts. Option 3 is similar to option 1, with the difference that instead of a COB it contains a SMD module. As these types of modules come in a large amount of shapes and can even be designed and produced according to specifications, this possibility gives a larger flexibility in terms of form and design. However, it represents a step-back in terms of technology and efficiency, as COB LEDs are more efficient and produce a superior quality of light.

All of the three options are valid, but Option 1 seems to be the most innovative and interesting. COBs are the latest and best development in LED technology and they are currently being ignored by some luminaire manufacturers for their heat dissipation requirements. It is difficult for a company that wants to sell aesthetically pleasing decorative luminaires to accommodate a big chunk of finned aluminum in their products. This is why some companies like Artemide and FLOS (Chapter 5) have chosen to fabricate lamps that have a dissipating body, in order to take advantage of the possibilities of COB's without having to sacrifice their product's appearance. It seems that under these conditions there is a big opportunity to create new solutions and explore interesting innovations like the metallization of 3D printed parts.

6.2.3 Product Architecture

The next step in the process is to assign a relative shape and volume to the respective elements that Option 1 comprises, and to conform several configurations (architectures) that can be achieved with these elements, considering the interactions among them.

Figure 63 shows basic 2D and 3D representations of the elements in Option 1.

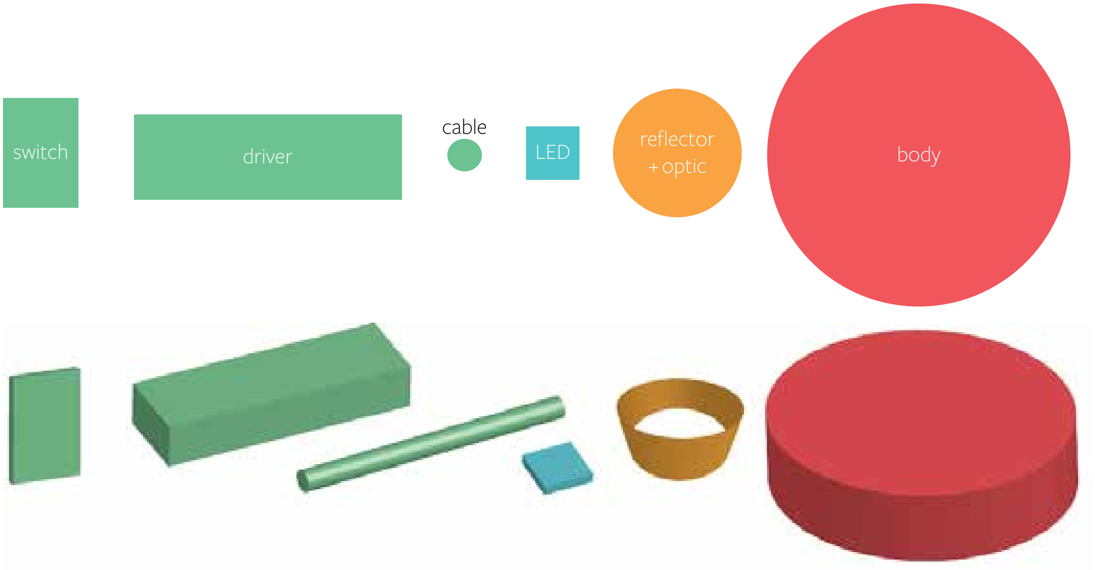
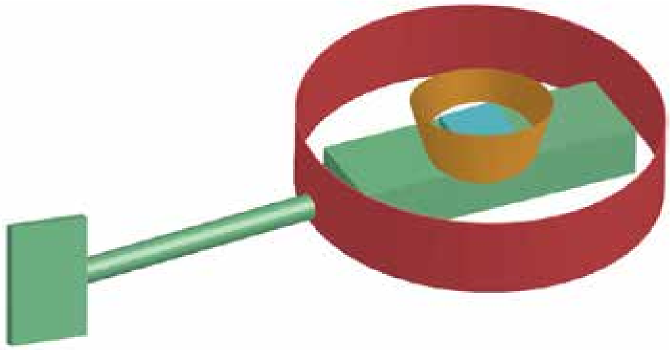
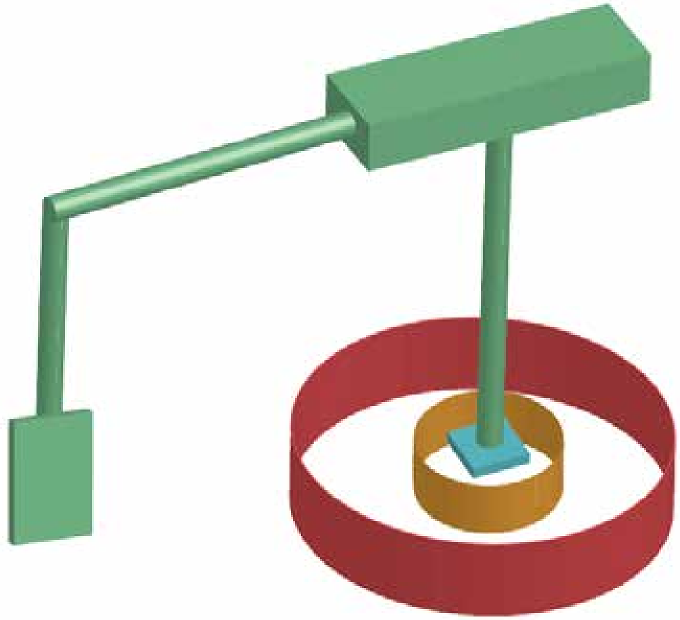


Figure 63: Volumetric representations of the elements that constitute the luminaire

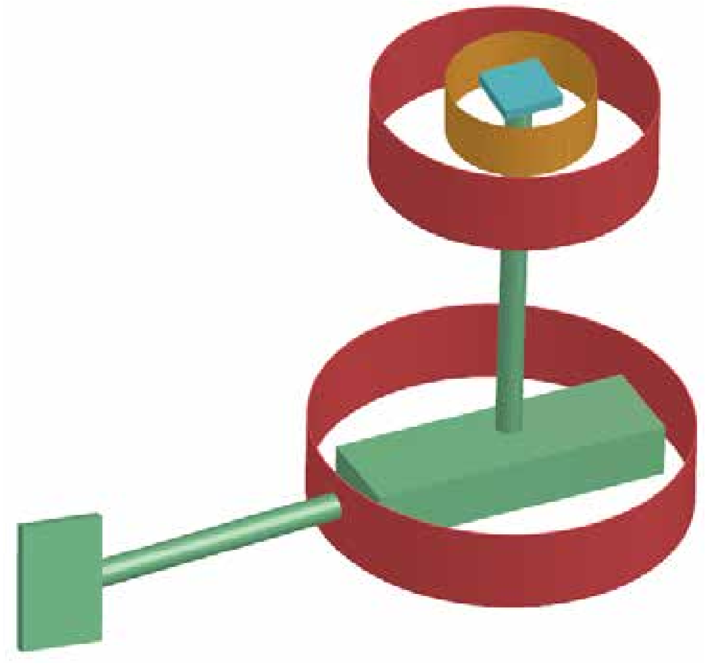
These representations do not have accurate dimensions because they are useful only as a tool to evaluate the compatibility between them and the different arrangements that can be made by composing them in different ways. Three of these arrangements are depicted and described below:



The first composition creates a very flat architecture, useful for lamps such as wall or ceiling fixtures. The LED and optic are positioned directly over the Driver and all of them are positioned inside the body. A cable exits the luminaire and a wall switch activates the electric flow.



The second configuration has the driver outside of the body. This architecture can be useful for pendant lamps, where the driver would be placed inside the canopy, or in floor lamps, where the driver would be placed inside the base or the cable.



The third and last configuration has the LED and the optic far from the driver. The driver is still inside of the body, which has to be larger as it must also contain the LED and optic. The switch in this case can be positioned in the cable. This architecture is especially useful for table lamps.

All of these architectures are equally valid, and they will be the functional basis for the creation of design concepts, presented in the next chapter.

7. Design

The concepts and product designs presented in this chapter are the result of a methodical research and analysis of how AM can influence the production of better luminaires. The designed product has the goal of proving, or disproving, the various theses that have been generated throughout this research.

Most product designs are directly commissioned by a company. The product therefore must be done in accordance with that company's brand identity, market goals, and technical and economical capabilities. Additionally, they must consider the expectations, desires, preferences and economic possibilities of the company's clients and market target. This project has a very different goal however, as it is not intended for any company or client in specific. The design requirements established in chapter 6 are mostly generic, or arrived at through a technical analysis done in previous chapters. In other words, as to aesthetics, emotion and design concept, this project has no biases or limitations. The drive in regards to these aspects of product design is more expressive and personal, and represents the vision and taste of its designer. The possible user and context are also a choice based on preference rather than intent, as the goal is to demonstrate technical feasibility, not market appeal. This is a debatable approach, as some may argue that design must always have a social dimension. In this case though, the social intention, rather than to create a definitive solution, is to create a method, a possibility: the possibility of designing and producing lamps using this approach. Under this light, the design solutions are just a given embodiment of a design method, which is the object of evaluation, not the embodiment in itself. If the method is proven to work, many different embodiments may be produced, for many different users, under many different contexts.

7.1 Design Concept

One of the most important aesthetical considerations is what a product communicates. What does it say? What will a person think when he/she sees the product for the first time? Will he/she be intrigued? Captivated? Amused? Or will they find it repulsive? Awkward? Boring? There are three basic goals in regards to communication in this design:

1. Communicate the process: As with any project done by a novel process, it is important to communicate it. It must be clear that this product is made by AM, and it must be clear that it may not be done by any other means.

2. Communicate the functionality: If the product has a special, innovative functionality, this too must be communicated. In this case the most innovative functionality is its ability to dissipate heat.

3. Amuse / engage: This product must attract attention. It must do this because it needs to spread a message, that something new has been done and that it is exciting. Otherwise it will not generate the necessary interest for it to develop further and become a feasible industrial alternative.

One of the strategies to achieve these goals was to create a complex but pleasant form. Most products manufactured by AM have a complex form simply because it’s possible. It is creative liberation and an exploitation of an available resource at the same time. Furthermore, to whoever has a basic knowledge of manufacturing a complex shape will immediately recall AM. It will also probably generate more interest in the general audience, as it will stand out more because most products in the world are done in simpler geometries. This said, however, there is a risk of becoming too complex and boring the audience by over-doing it. Form should always have a purpose, and as Dieter Rams puts it “good design is as little design as possible”. Complexity in form does not have to be an enemy of simplicity in attitude, of essentialness. A lamp should be an essential item in a person’s home that generates a beautiful light but looks great when it's turned off too.

7.1.1 Conceptual references

One way of approaching complex geometries without the risk of "over-doing it" is through the use of patterns, tessellations and algorithms. These allow a form to grow without losing control. One of the fields of design that has studied this principle is Generative Design. In the words of Politecnico di Milano's professor Celestino Soddu, one of Generative Art's pioneers:

"Generative Art is the idea realized as genetic code of artificial events, as construction of dynamic complex systems able to generate endless variations. Each Generative Project is a concept-software that works producing unique and non-repeatable events, like music or 3D Objects, as possible and manifold expressions of the generating idea strongly recognizable as a vision belonging to an artist / designer / musician / architect /mathematician"[1].

In Generative Design form has a fundamental mathematical principle, or algorithm, from which an endless array of possibilities will develop. This same behavior occurs in many, if not all, natural organisms. The structural similarity between a tree and a leaf is used by surrealist artist René Magritte's "tree-leafs" that appear in many of his works, starting from La Géante of 1935. It perfectly illustrates how a small part of a natural element creates a larger element through growth and repetition, stemming from an individual cell into a complete organism. This mechanism of growth allows each tree to be unique, but have a common and recognizable structure and aesthetic. Generative design has been used to create AM lamps, most noticeably in Nervous System's Hyphae lamp, among others (view chapter 5.2.1). Without the desire to enter the realm of Generative Design and mathematics, a study of natural tessellations can also be performed in search of inspiration. One of the richest visual alphabets of the natural world was created by German biologist Ernst Haeckel in his 1899-1904 series of lithographic and halftone prints gathered in the book Kunstformen der Natur

---

[1] http://www.soddu.it/design/GA_soddu_e.htm

(known in English as Art Forms in Nature)[2]. Some of these prints, especially those reproduced in this report, served as great inspiration for development of forms.

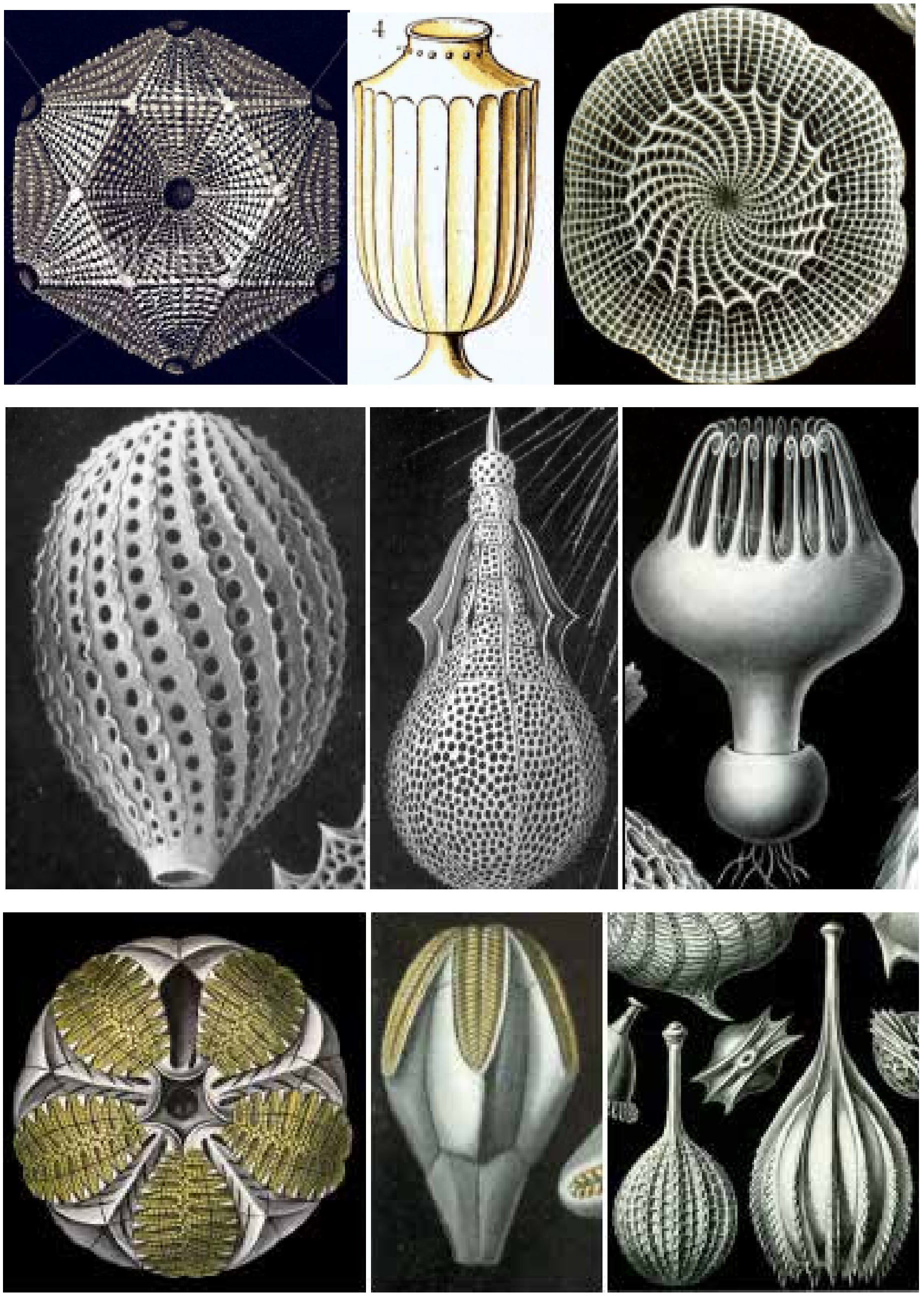


Figure 64: Lithographic prints by Ernst Haeckel

a) Hexacoralla, Sertulariag, Tetracoralla.

b) Cyrtoidea (2) and Basimycetes

c) Blastoidea and Thalamophora

---

[2] Haeckel, Ernst. Kunstformen der Natur. Bibliographisches Institut. 1899-1904 Leipzig und Wien

A second approach to patterns is a less organical, much more mathematical and geometrical one. In this case, patterns achieve a crystallized, fragmented aesthetic. The use of these design patterns has been discussed in chapter 5.2.2, with examples such as Issey Miyake IN-EI Collection for Artemide, Tom Dixon's Etch Collection, and Konstantin Grcic's One chair and Stool for Magis. One of the most representative contemporary artists that uses geometrical patterns is the Rochester, New York based digital artist Andy Gilmore. The scope of his work has been described as "broad, ranging from soothing, almost-kaleidoscopic geometric patterns to bold, fractal-inspired loops"[3].

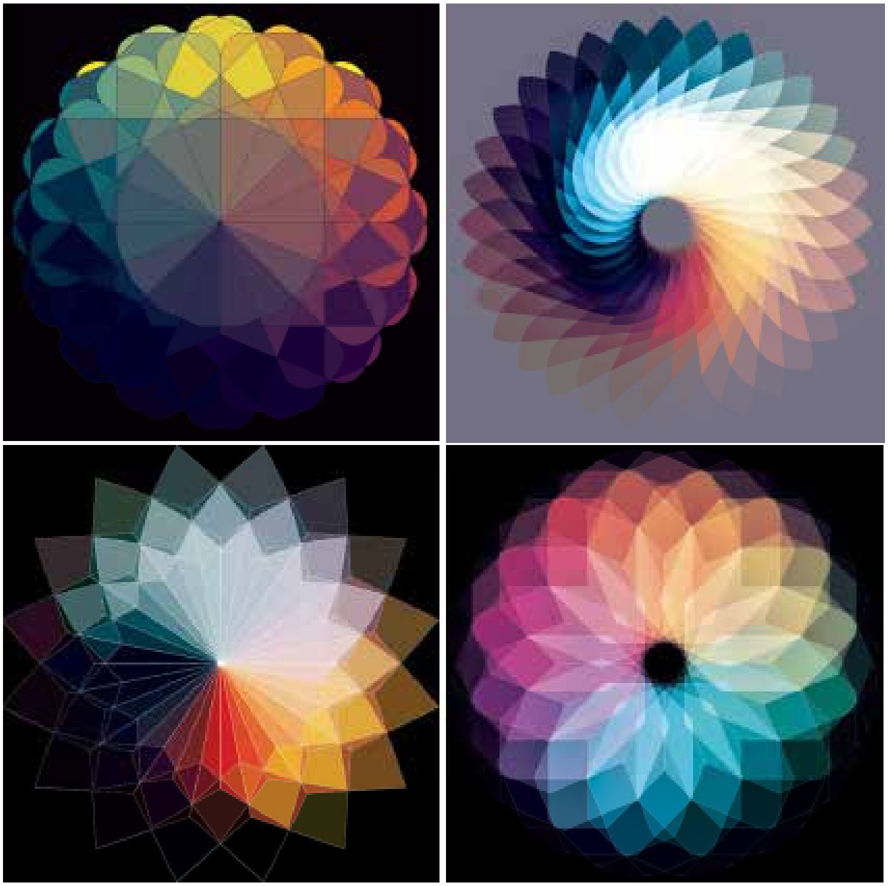


Figure 65: Four examples of artwork by digital artist Andy Gilmore[4]

---

[3] http://www.theverge.com/2013/8/13/4617076/andy-gilmore-ghostly-international-video

[4] Artist website: http://crowquills.com/

The previous images were used to do a formal exploration. Some of the initial exploratory sketches are shown in Figure 66:

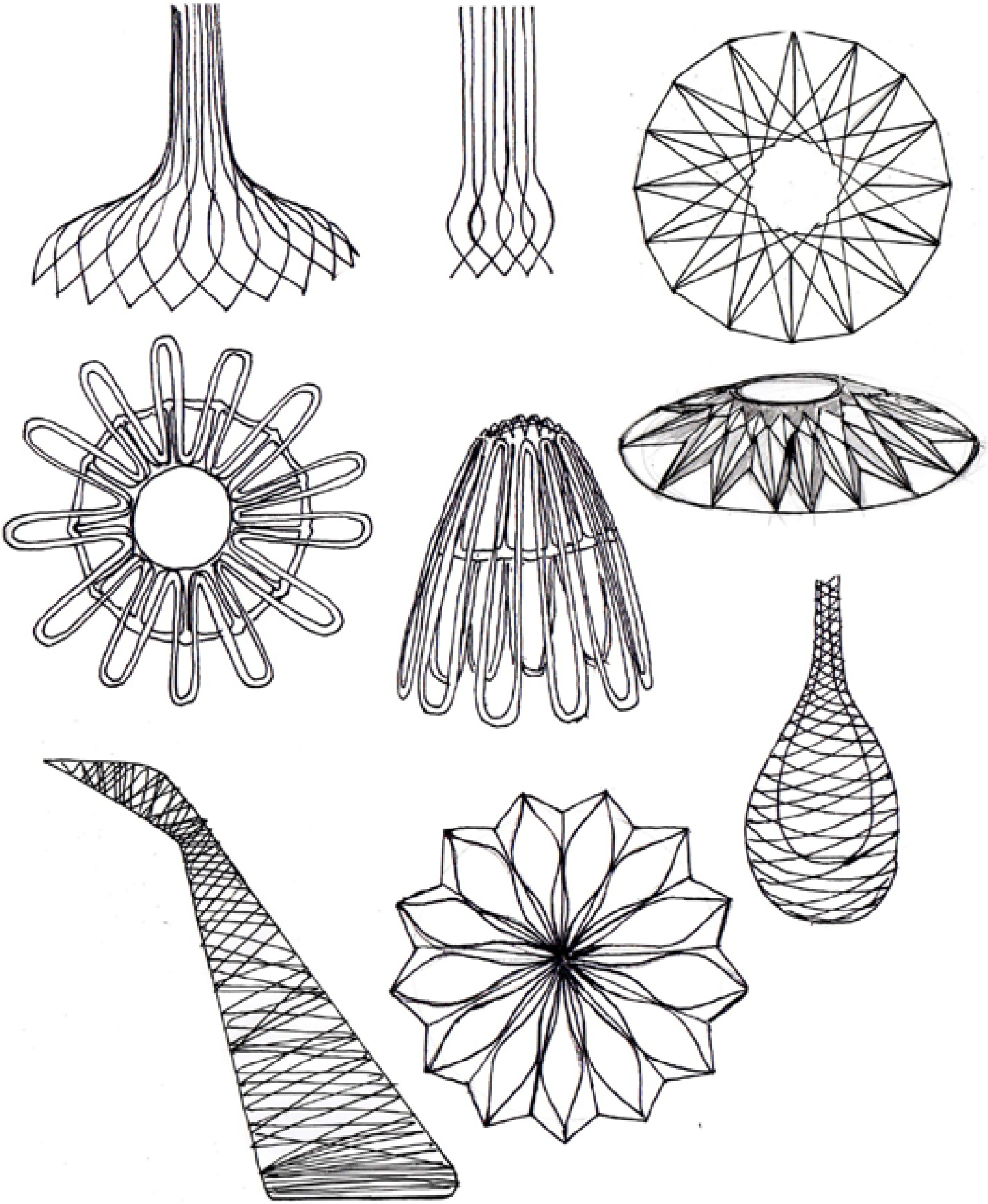


Figure 66. Initial exploratory sketches

7.1.2 Design concept 1: Arista

Arista in Spanish means edge. This simple word defines the concept in two aspects, the evident fact that it is very geometrical and made of straight edges, and the fact that it is at the edge of innovation and technology.

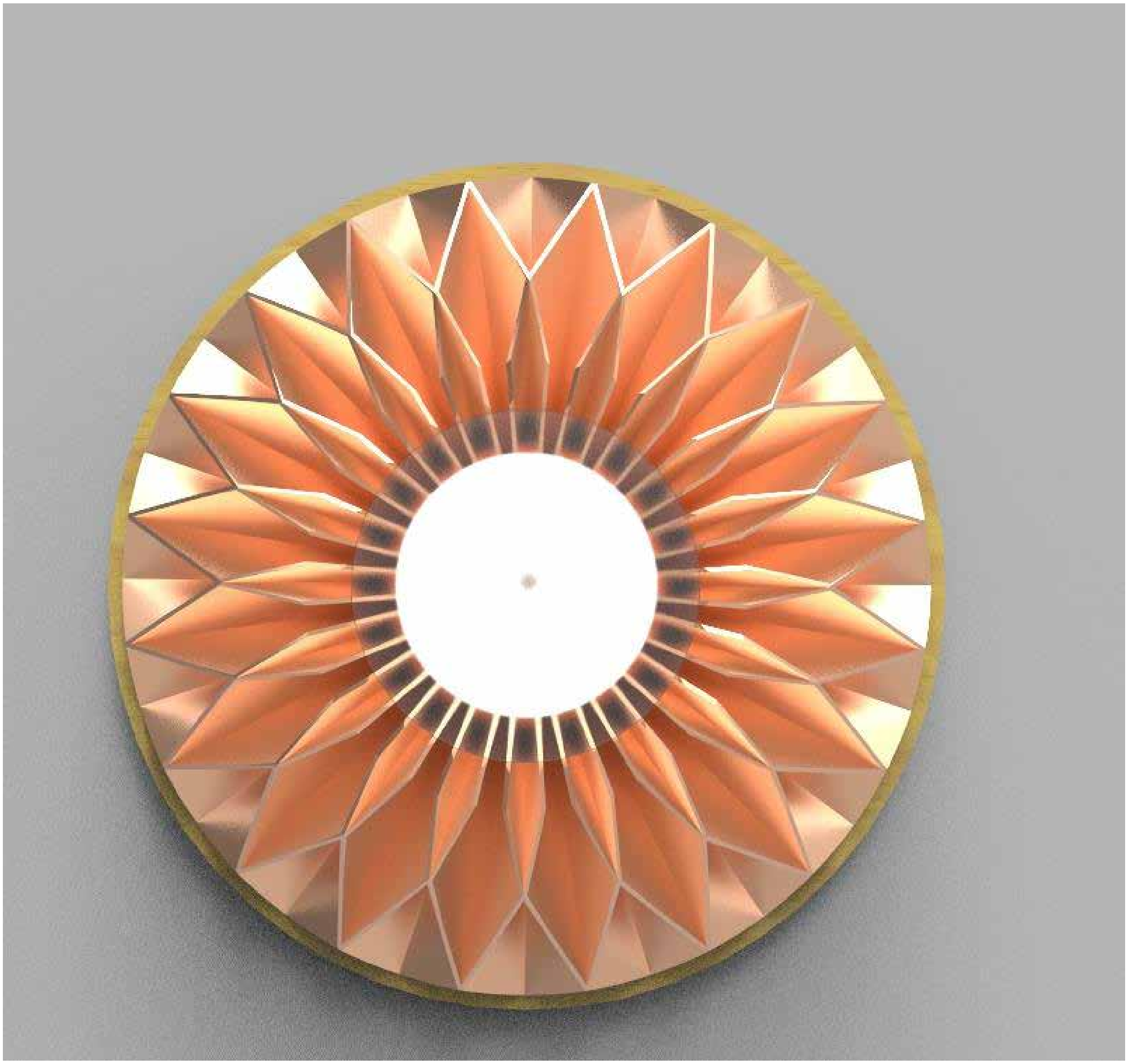


Figure 67: Arista ceiling fixture concept design

The structure of this concept corresponds to the first product architecture (chapter 6.2.3), and the lamp is initially intended as a ceiling fixture or applique. The height of the lamp is 5 cm and the diameter is 25cm. It was proposed with a wooden base as a decorative element.

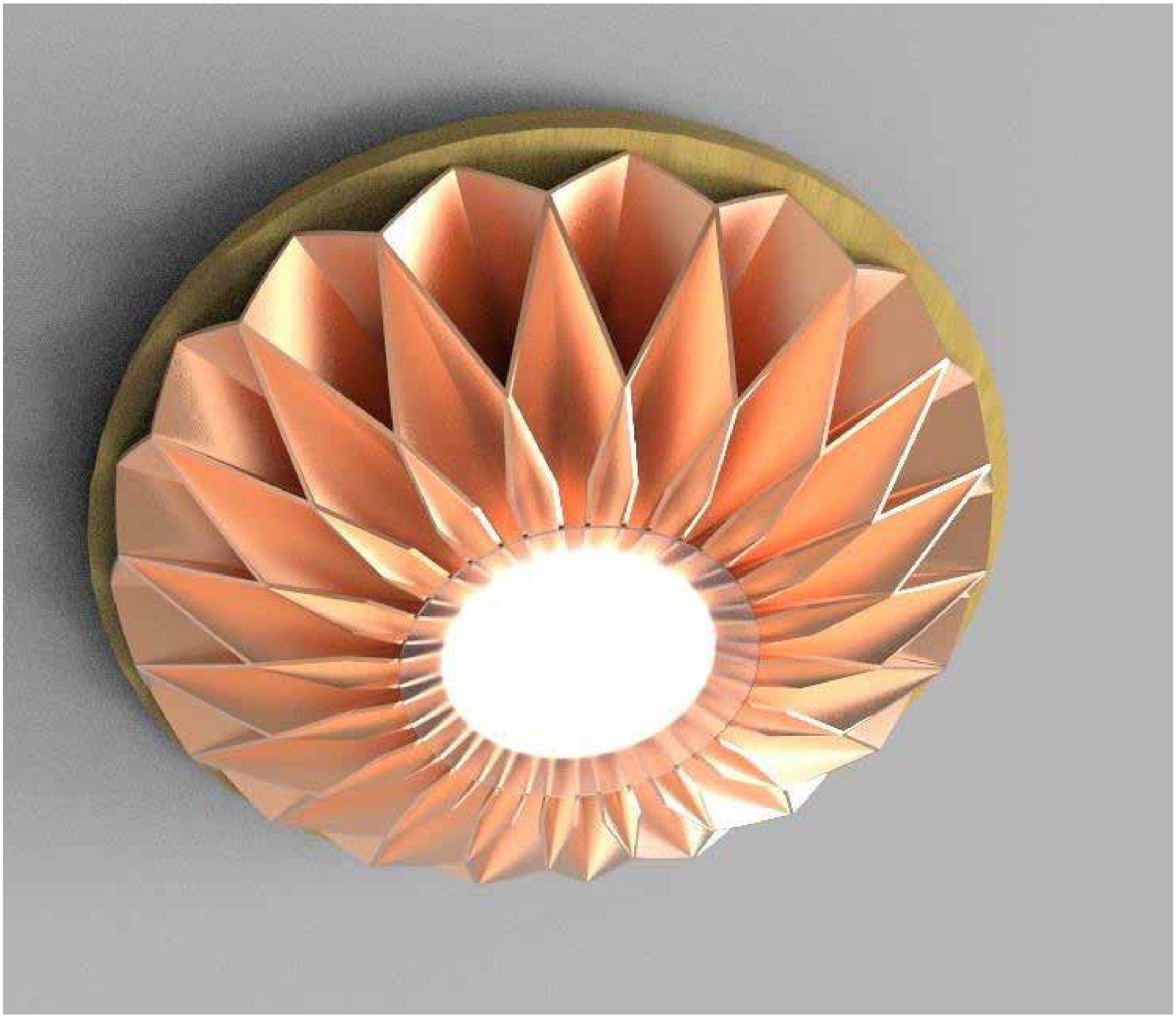


Figure 68: Arista ceiling fixture concept design (2)

A sectioned view of the lamp shows it has a COB positioned o ver a reflector in the center, and a diffuser. The ultra-thin driver would be located in the center of the wooden base.

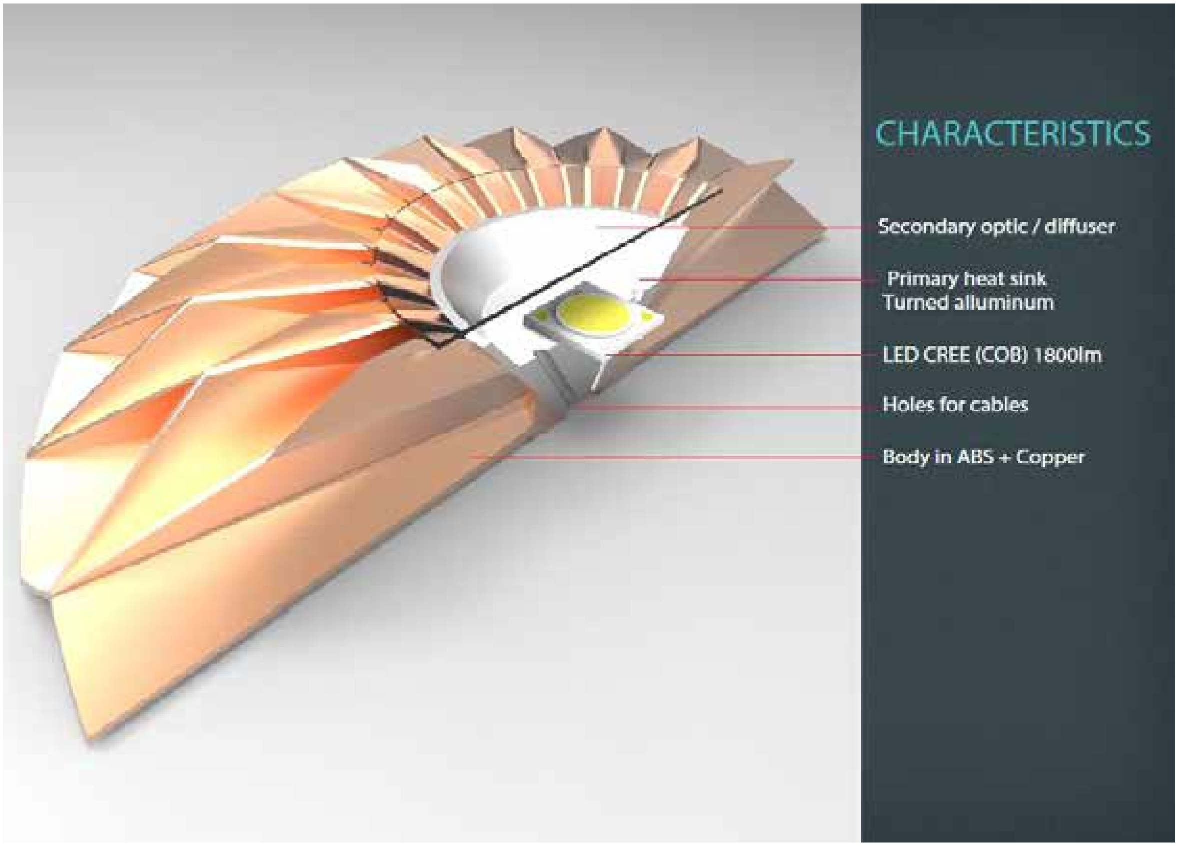


Figure 69: Arista ceiling fixture characteristics and components

Some of the benefits of this concept are the following:

- Compact size makes it easy and cheap to print
- The form is complex but natural at the same time; it is intriguing but not disruptive.
- It expresses the heat sink function (although not literally) as it resembles a radiator in some ways.

The drawbacks/ unsolved doubts are:

- There is still no clarity to where and how the driver will be positioned
- The “primary heat-sink” is a rather complex element manufactured by aluminum turning. It may significantly increase manufacturing costs and times and reduce flexibility in form.

· This heat sink additionally will have to conduct heat to the rest of the body. If the fit is not precise heat conduction will be reduced.

7.1.3 Design concept 2: Air on the G String

Air on the G String is August Wilhelmj's arrangement of the second movement in Johann Sebastian Bach's Orchestral Suite No. 3 in D major. This famous and beautiful piece of classical music gives the name to this concept, as it perfectly expresses the emotion that was intended. All of the notes in this aria can be played only on the G string chord of the violin. The amazing beauty that can come from the movement of a single chord is amazing. The idea of 'pattern' was interpreted as rhythm; the repetition of a single form in slight variations creates this rhythm and musicality.

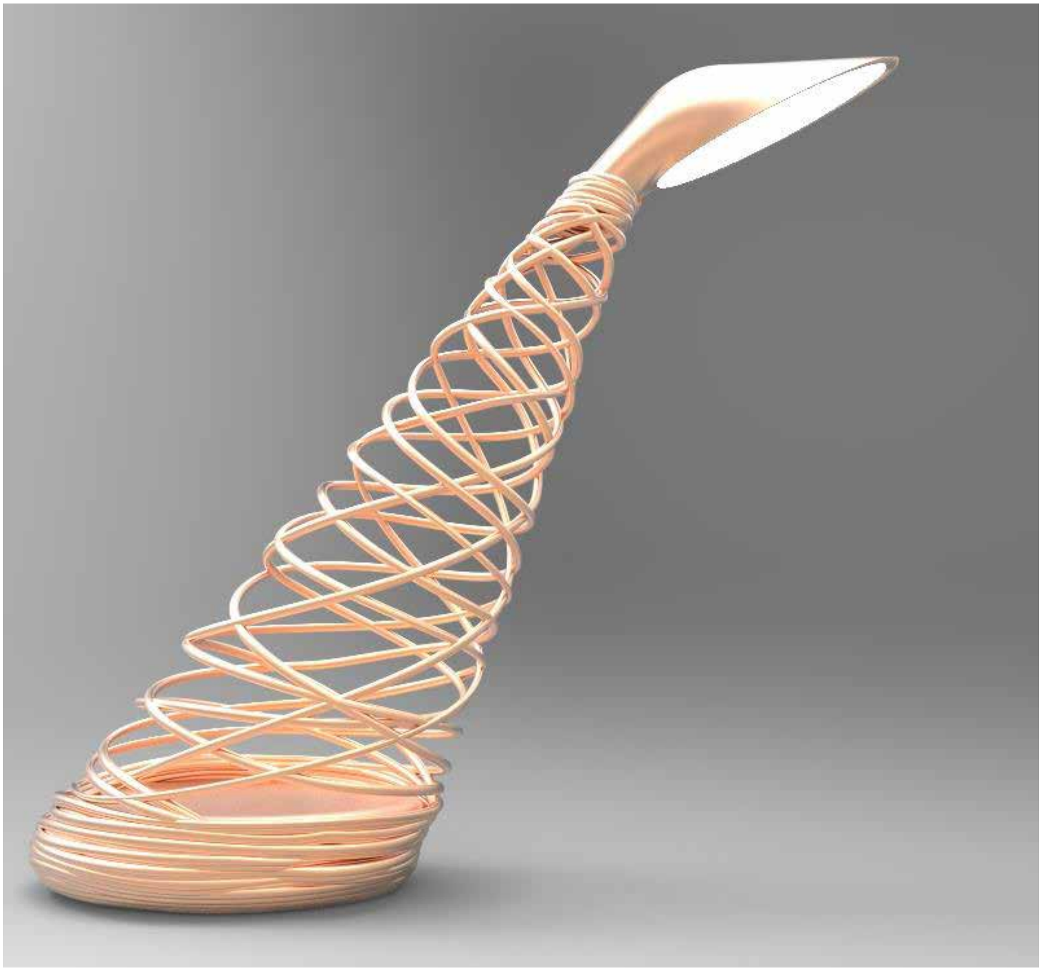


Figure 70: Air on the G String concept design

The lamp concept was created using the third product architecture. It has a height of 35cm and it is intended as a table lamp, although it could also work as a wall lamp (indirect light).

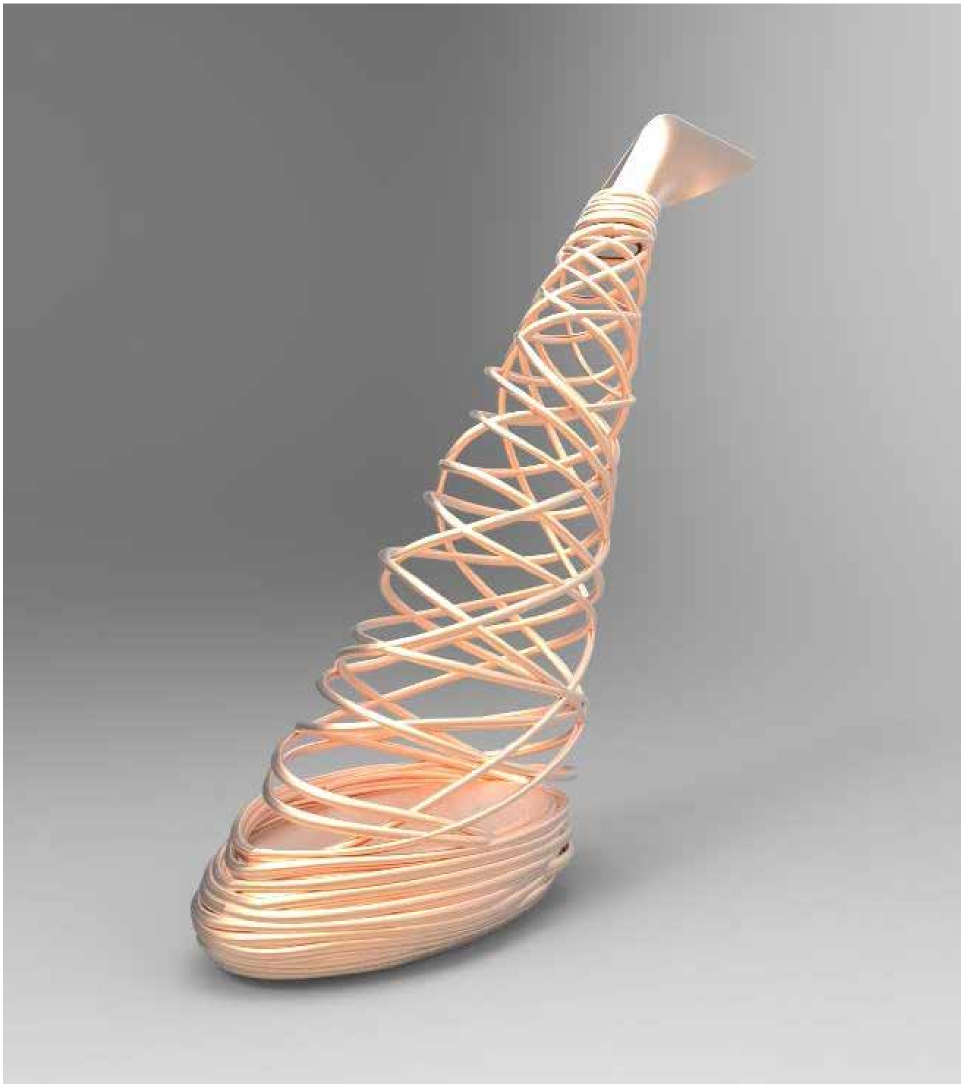


Figure 71: Air on the G String concept design (2)

A sectioned view of the lamp shows that it has a COB on the head, which has the form of a reflector, and also has a diffuser. The driver is positioned in the base of the lamp, where most of the weight is concentrated, to give the lamp stability.

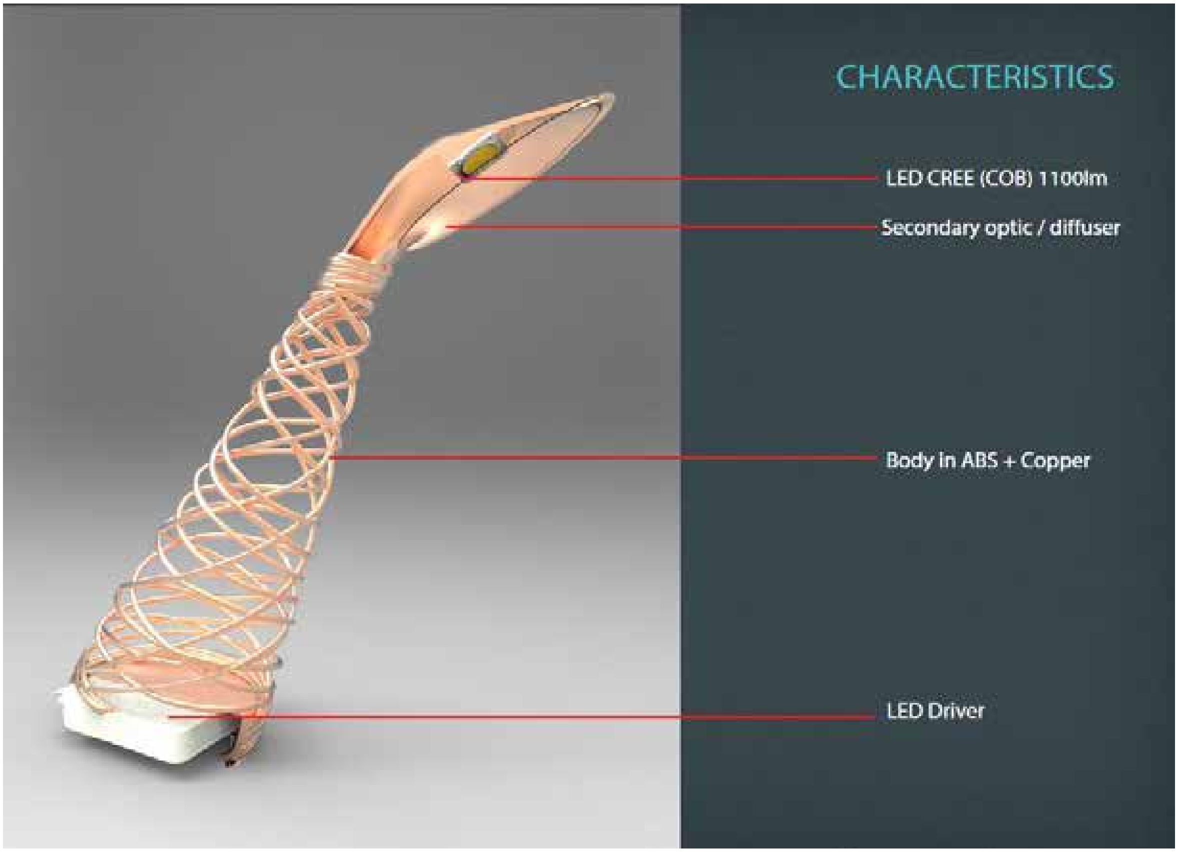


Figure 72: Air on the G String components and characteristics

- It can work for both table and wall positions with minimal changes, making it versatile
- It can generate the desired attention, as its sculptural shape is unusual.
- It has the driver far from the LED, which protects it from the heat generated by it

Some of the drawbacks/ unsolved doubts are:

- The form is complex and has very thin profiles, which makes it very hard to print, even impossible in some technologies.
- As a table lamp it is not very practical because it has no freedom of movement, no way of adjusting the light direction, which makes it hard to use it as a task light for reading, for example.
- There is no clarity on how to transmit energy from the

base to the head. Simply passing a cable through the center would ruin the aesthetics.

7.2 Concept selection and development

To evaluate and select the concept designs, it is useful to return to the communication objectives:

1. Communicate the process: Both concept designs have forms that are impossible to create in one unique process by any other technology than AM. However, the second concept design has a wire mesh, and copper wire is very common. A distracted observer may believe this lamp has been made by manually twisting copper wires. Although the Arista concept design could also be made by bending and welding copper sheets, it would look very different, as the thickness would vary, the welds would be visible, etc. It is therefore harder for a person to confuse this.
2. Communicate the functionality: The first concept design communicates better the function of dissipating heat, because it slightly resembles a radiator or heat sink, whereas the second concept design has no connection with the function.
3. Amuse / engage: Both designs are equally attractive, but this is also a subjective appreciation. There is no reason to believe one is more attractive than the other, so further testing and surveys would have to be performed.

Functionally, both designs would seem to operate correctly, at least at the level of development in which they are at this point. However, the “air on the g string” concept design lacks in usability, as the light direction cannot be graduated. In regards to feasibility, the first design is also superior, as it is easier to print and has a more compact shape that allows a shorter build time.

Summing up all of the previous analysis, the Arista concept design is superior in most aspects and in regards to the accomplishment of design goals. However, this concept must be tested with different design architectures to verify if it has enough depth. If a concept only works with a particular design embodiment, it lacks depth, meaning that the result is too arbitrary. Most companies do variations of a luminaire to create a product family. A concept must prove itself to be versatile enough to withstand these variations without changing its essence.

7.2.1 Pendant, floor and wall variations

The concept behind Arista, of a geometric pattern with a radial star-like pattern, was evolved into pendant, floor and wall variants of different sizes. Two main variants were produced, which could be adapted to different fixtures according to complimentary elements. The variants, henceforth named Arista 2 and 3, are presented below:

Figure 73: Arista 2 pendant and floor variations

Figure 74: Arista 2 wall and floor variations

Arista 2 was the first variation made to Arista. A narrower and deeper geometry was created to allow it to stand out independently by acquiring more three-dimensionality. The diffuser was removed as the narrow shape renders it obsolete. The driver must be positioned outside of the luminaire's body, in the cable or the canopy, just as the second architecture variation.

Despite its versatility, this design has some flaws. The narrow, thin walls make this model it harder to print. The model must be positioned starting from the circular opening, which has a contact area so small that it is hard to guarantee the model will not move during print. Additionally, it creates a narrow light beam that is not practical under many applications.

The second variation, Arista 3, is mostly a pendant version, although it could also work as a torchère. It consists of a flatter and wider body than Arista 2, and a smaller cone to do the transition into the cable. Overall, it is more balanced, and the cross-sections have more surface area which makes them easier to print. It can have a reflector inside and a wide diffuser, which has been given a concave shape to give harmony to the shape.

Figure 75: Arista 3 variation shown as pendant lamp.

Beyond the specific problems or doubts that result in these variations, the Arista concept has been proven to work under multiple embodiments. It could easily become a product family or collection, applying minimal variations. This is important to the design of AM parts, because the process allows for these variations to be made and manufactured with a low investment of time and resources. The creation of a new design concept must be made with care and time, as it is something that will become iconic and representative of a brand and its identity. However, the adaptability of a concept in time, the capacity it shows to update and modify according to technical or market requirements, will guarantee its permanence in time.

7.3 Detailed design

As presented in the previous section, the Arista concept was selected. The ceiling fixture, for its small size and high printability, was the first embodiment selected for detailed development. This would consist in a selection of internal components, assembly, design for AM, and simulation.

7.3.1 Selection of internal components

As decided through the process described in Chapter 6, the luminaire should have 3 components: A COB LED, a CC+CV driver, and a reflector + diffuser.

LED

According to the design requirements established in chapter 6.1, the COB should:

- generate a minimum of 1000 and a maximum of 1800 lumens,
- have an efficiency greater than 50 lumen/watt,
- generate warm white light (2700- 3300°K),
- have a CRI higher than 80
- have a viewing angle of at least 110°

Cree Inc. is a market-leading innovator of lighting products, LED components, and semiconductor products for power and radio-frequency (RF) applications. It manufactures some of the best COB LEDs available in the market. Browsing through their catalogue, three of their products were chosen for a comparison using their Product Characterization Tool[5]. For the 1500-lumen

---

[5] http://pct.cree.com/dt/index.html

target, a 92% optical efficiency and 85% driver efficiency were estimated. A solder point temperature (TSP) of 65 °C was also estimated.

The results, shown in Figure 77, show that the best option is the CREE XLamp CXA 2530 (Figure 76). At 700mA, and a Tj of 85°, the COB should give an output of 1700lm. With an optical and electrical efficiency of 85%, the luminaire would still generate an output of 1450 lumens, which is enough for this application.

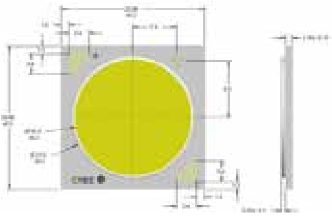
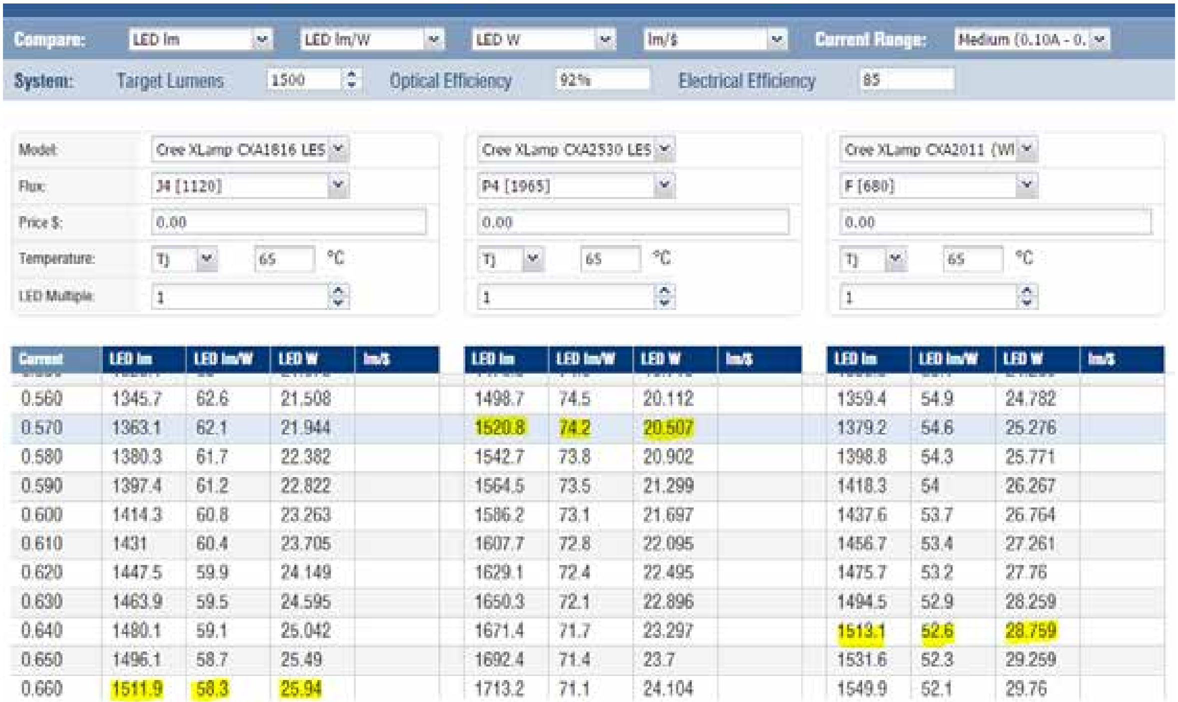


Figure 76: CREE XLamp CXA 2530



Compare: LED lm | LED lm/W | LED W | lm/$ **Current Range:** Medium (0.10A - 0.

System: Target Lumens 1500 Optical Efficiency 92% Electrical Efficiency 85

Model:	Cree XLamp CXA1816 LES	Cree XLamp CXA2530 LES	Cree XLamp CXA2011 (WI
Flux:	J4 [1120]	P4 [1965]	F [680]
Price $:	0.00	0.00	0.00
Temperature:	Tj 65 °C	Tj 65 °C	Tj 65 °C
LED Multiple:	1	1	1

Current	LED lm	LED lm/W	LED W	lm/$	LED lm	LED lm/W	LED W	lm/$	LED lm	LED lm/W	LED W	lm/$
0.560	1345.7	62.6	21.508		1498.7	74.5	20.112		1359.4	54.9	24.782	
0.570	1363.1	62.1	21.944		1520.8	74.2	20.507		1379.2	54.6	25.276	
0.580	1380.3	61.7	22.382		1542.7	73.8	20.902		1398.8	54.3	25.771	
0.590	1397.4	61.2	22.822		1564.5	73.5	21.299		1418.3	54	26.267	
0.600	1414.3	60.8	23.263		1586.2	73.1	21.697		1437.6	53.7	26.764	
0.610	1431	60.4	23.705		1607.7	72.8	22.095		1456.7	53.4	27.261	
0.620	1447.5	59.9	24.149		1629.1	72.4	22.495		1475.7	53.2	27.76	
0.630	1463.9	59.5	24.595		1650.3	72.1	22.896		1494.5	52.9	28.259	
0.640	1480.1	59.1	25.042		1671.4	71.7	23.297		1513.1	52.6	28.759	
0.650	1496.1	58.7	25.49		1692.4	71.4	23.7		1531.6	52.3	29.259	
0.660	1511.9	58.3	25.94		1713.2	71.1	24.104		1549.9	52.1	29.76	

Figure 77: Comparison of different COB lamps using CREE Inc.'s Product Characterization Tool. The highlighted values show the output of interest (1500 lumen approx.)

Driver

The driver for this downlight can be located over the body, in a separate container, which might partially go inside the body, to hide it. The main requirement in regards to size is height, as the greater the height the greater the distance will be between the body and the ceiling or wall. There is no need to design a custom driver for this reference design so a constant-current off-the-shelf driver was chosen. Italian electronics manufacturer QLT has a model called Flat box (Figure 78), which is only twenty millimeters tall, and has the required specifications to drive the COB (700mA, 23W).

Figure 78: QLT Flat Box 700mA, 23W

Optics

The diffuser in this project is a disc cut from a polymer film. The most common materials used are PMMA, translucent PP, PC, and PS. This material choice was left to be decided through trials with the physical prototype. Simulating the material is very difficult, and most luminaire companies conduct these trials with physical samples. The thickness given was 1mm, although this too could change after the trials.

The reflector was chosen from the LEDiL catalogue which has reflectors made specifically considering the CREE COB LEDs. For the CXA 2530 they have several models, of which the Angelina model (Figure 79) was chosen for its even distribution of light and high efficiency.

Figure 79: LEDiL's Angelina reflector designed specifically for CREE COBs.[6]

7.3.2 Detail design of the body

The detail design of the body was guided by two main goals:

- Optimize the body to make it easier, faster and cheaper to print.
- Guarantee the correct assembly of all the components and their proper performance

To address the first goal, the model was confronted with the opinions of the 3D-printing experts at Politecnico di Milano's

---

[6] http://www.ledil.com/node/2/p/13522

+Lab. This specialized 3D printing lab would eventually print the first prototypes, and it was important to know their opinion on the model's "printability". Additionally, they would recommend the best printing technology and material. Figure 80 shows the initial recommendations given to improve the model. It was decided to print the lamp by FDM, as the size and characteristics of the model allowed to do so and it is the most commonly available low-cost AM technology.

The most important modifications done to the model were to unite fins to create a closed model that self supports itself during the printing phase, and to have surfaces with an angle always equal or less to 45° from the vertical plane. This is important to avoid overhanging surfaces that need supports. The resulting model is shown in Figure 81.

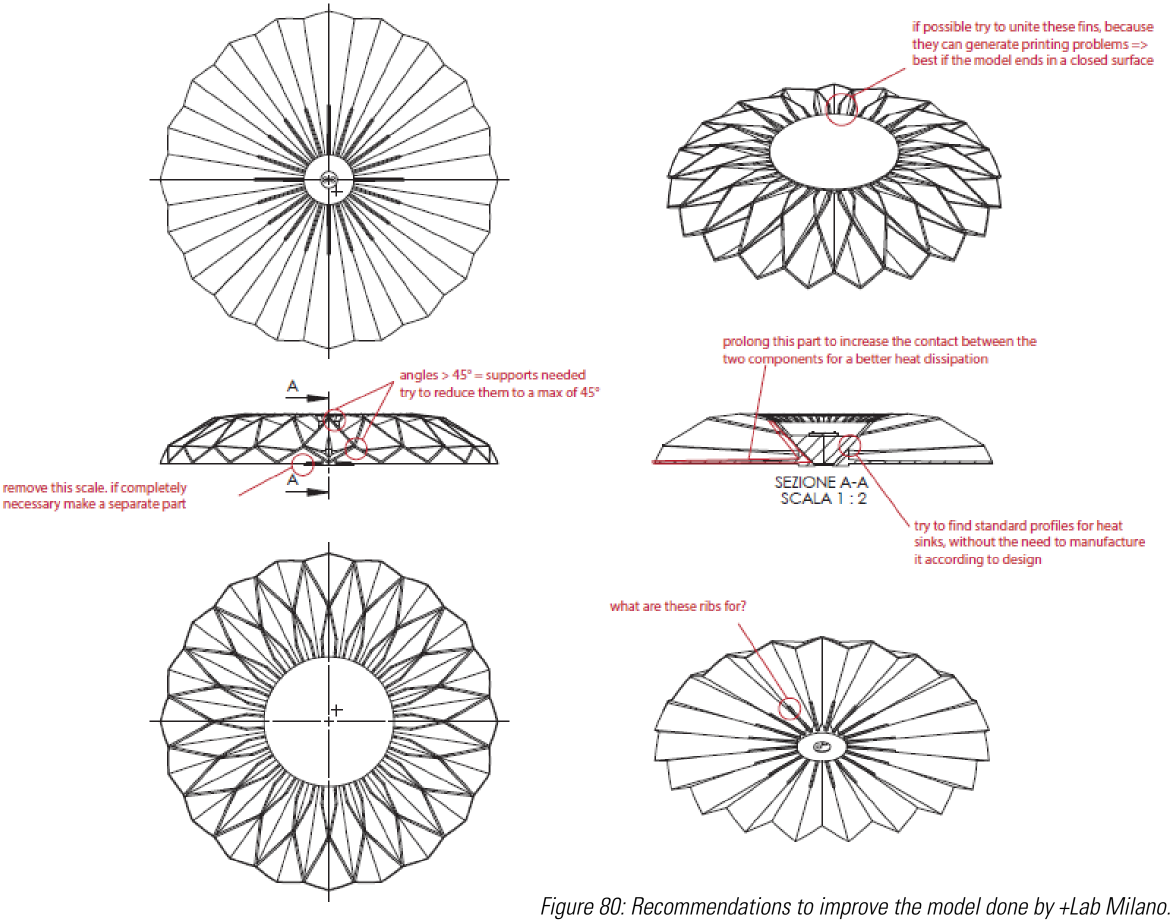


Figure 80: Recommendations to improve the model done by +Lab Milano.

Figure 81: Arista body with modifications

The second objective was to allocate the different components chosen for the luminaire. The LED must be positioned over an aluminum part, that has a very flat surface (to increase contact with the LED) and that absorbs the initial blast of heat from the LED. As the junction temperature could rapidly increase to 150°C, it would not be smart to have a copper plated surface directly below, because the polymer in the interior can melt. This part was initially designed as a specially designed aluminum part that would be manufactured by CNC turning. This would increase costs however, and production times. The part was modified to a simple cylinder; which can be cut from a standard aluminum shaft. Instead of diagonal holes to let the cables pass a straight hole was made, which is easier to drill.

A dedicated component was designed to house the LED driver. It consists in a two-part assembly; a back plate that would be fixed to the ceiling and would hold de driver in place and a crown-shaped ring that would be attached to the lamp and would assemble with the back plate through a twist-and-lock mechanism. The points of this crown-shaped ring would close the geometry and prevent the driver compartment from accumulating dust. A 1cm tall cylinder was excavated from the body of the luminaire to house part of the driver inside. This way, the driver's compartment only protrudes 1.2 cm from the main volume, creating a separation of the body from the ceiling of an equal magnitude. Including or not the reflector was left as optional: It will increase the efficiency of the luminaire but it will also prevent light from escaping through the lateral holes, which creates shadow effects, so the choice is left to the desire of the luminaire's user. These modifications are presented in Figure 82.

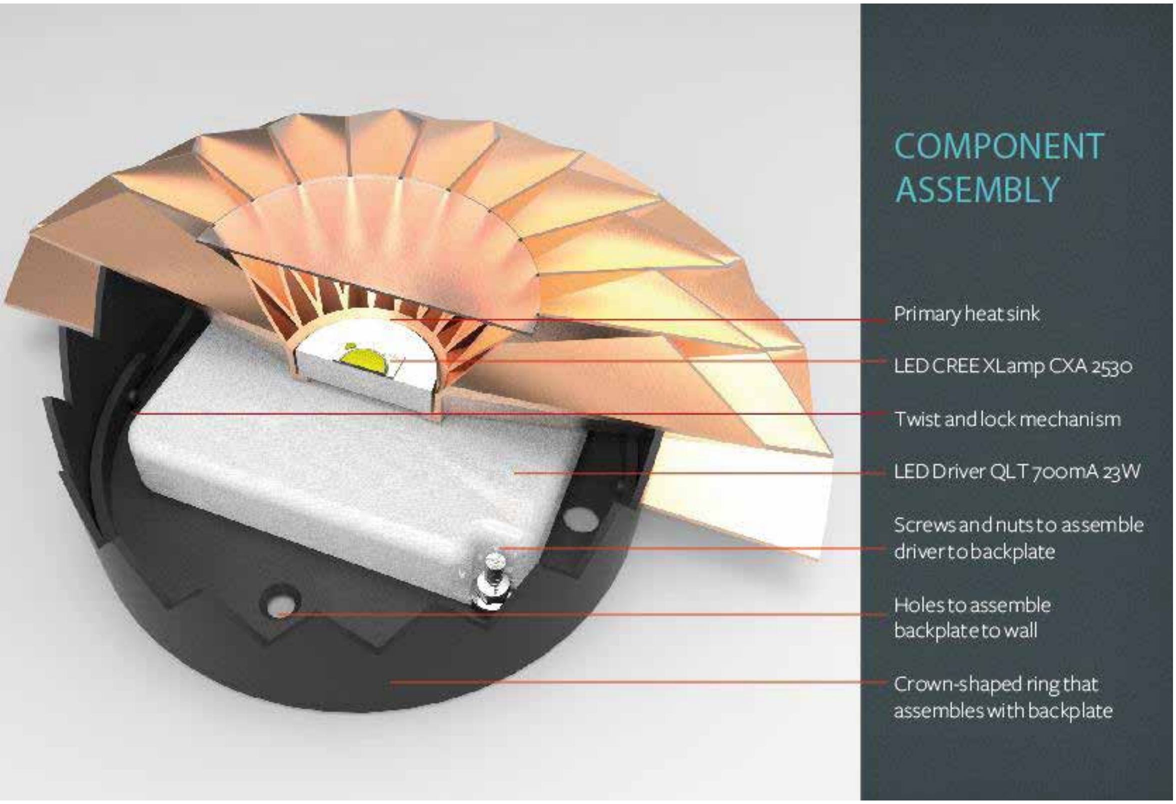


Figure 82: Section view showing the component assembly

8. Validation and results

This chapter presents the validation of the product design, the results of this validation, and the modifications derived from these results. The validation consisted of manufacturing a prototype and testing it. Results were obtained and analyzed in regards to the products printing process, copper plating, assembly, and use (including its ability to dissipate heat). These results were used to generate a second design with improvements, which was also prototyped.

8.1 Design validation

As stated earlier, the validation of the design consisted of manufacturing a prototype and testing it. The prototype was manufactured using the FDM machines and expertise of +Lab Politecnico di Milano[1]. Electronic components, including the LED and driver, were donated by NEMO Lighting[2], a luminaire manufacturing company based in Milan, Italy.

8.1.1 Printing Process

After the initial validation of the model done during the design phase, a final model was prepared for printing. A 1:5 scale model was generated first, both to test the "printability", and to use this model for electroplating tests. This print was performed with an Ultimaker 2 FDM printer[3] using PLA first, then ABS. The results are shown in Figure 83.

---

[1] http://www.piulab.it/

[2] http://nemolighting.com/

[3] https://ultimaker.com/

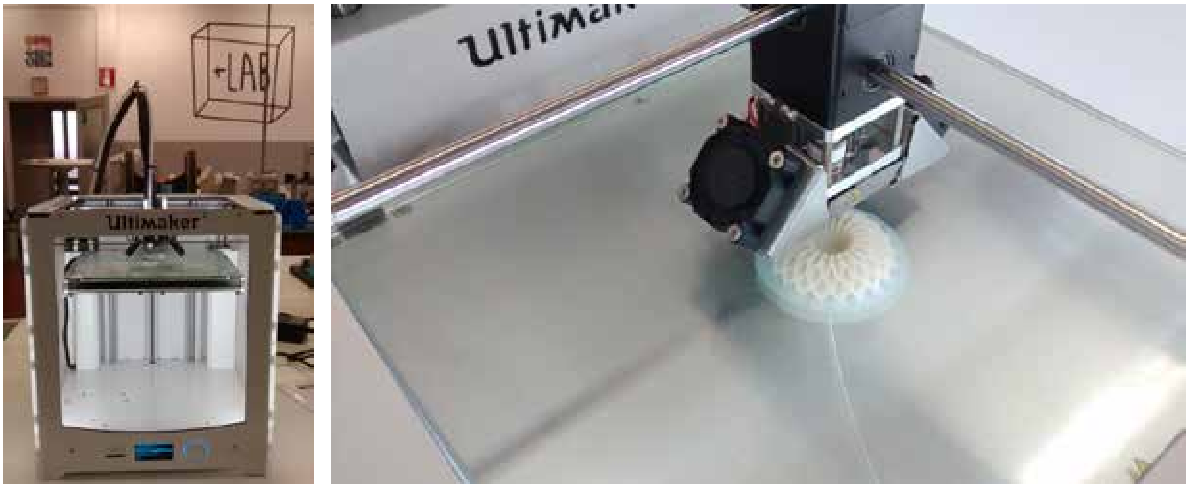


Figure 83: Printing a 1:5 scale model of Arista's body using Ultimaker 2 FDM printer at +Lab.

The good results obtained during this validation confirmed the possibility of printing a full-scale model. The machine selected to do the print was a Wasp Delta 40x70 FDM Printer[4]. The reason for choosing this printer was the luminaire's 25cm diameter, as all other printers had a 20cmx20cm print area limit, and this DELTA has a 40x40cm print area. The model would be printed using white ABS for two reasons: ABS is the most common material used in electroplating processes, which means it would be easier and more affordable to find a company to copper plate it; and ABS has a high temperature resistance; it's operating range goes up to 80°C but its glass transition temperature rises to 105°C. White as a color choice was irrelevant, as the entire part would be eventually copper plated and this color would be covered.

An STL model was generated from the original SolidWorks CAD model. This STL was inserted into Cura, software developed by Ultimaker useful for preparing G-Codes[5], the file that goes directly into the FDM machines and gives the printing instructions to it. The G-Code was prepared by Chiara Capuzzo, an expert in AM that works at +Lab. To prepare the G-code, the STL model must be positioned within the virtual printing space, supports must be given if necessary, the printing parameters selected

---

[4] http://www.personalfab.it/en/products/deltawasp-40x60-2/

[5] https://ultimaker.com/en/products/software

(printing speed, nozzle height, temperature), and the amount of infill if necessary. After this process was performed for Arista's body, the software calculated the amount of material necessary (213g) and the print time (15 hours).

The print was done over-night, results are shown in Figure 84. The results were fairly good, although towards the end of the printing process the model partially broke away from the base, causing the geometry to be slightly curved in the bottom. This problem, known as "withdrawal" is a common problem in FDM, especially with some materials such as ABS. To prevent it, there are several solutions:

- Printers, such as the DELTA, come with a hot bed: The glass surface over which the part is printed is heated before and during the print to increase adhesion with the part.
- Applying a coat of varnish to the surface also improves adhesion. This first print was done with ordinary hair spray; the subsequent prints were done with specialized 3DLAC varnish for 3D printers[6].
- The model must have the largest possible surface area in the initial layers, which is the surface that guarantees adhesion. 3D printing software usually adds a thin layer of additional surface to the model, called the "brim", which can be easily ripped out after the print is finished. However, it is best if the model's design also foresees having a large surface area in contact with the printing bed. This was a problem in this model, as the bottom surface consisted of 20 edges, with no flat surfaces in contact with the bed.
- Tape can be added after the brim is printed to prevent it from breaking off the surface.

---

[6] http://www.3dlac.com

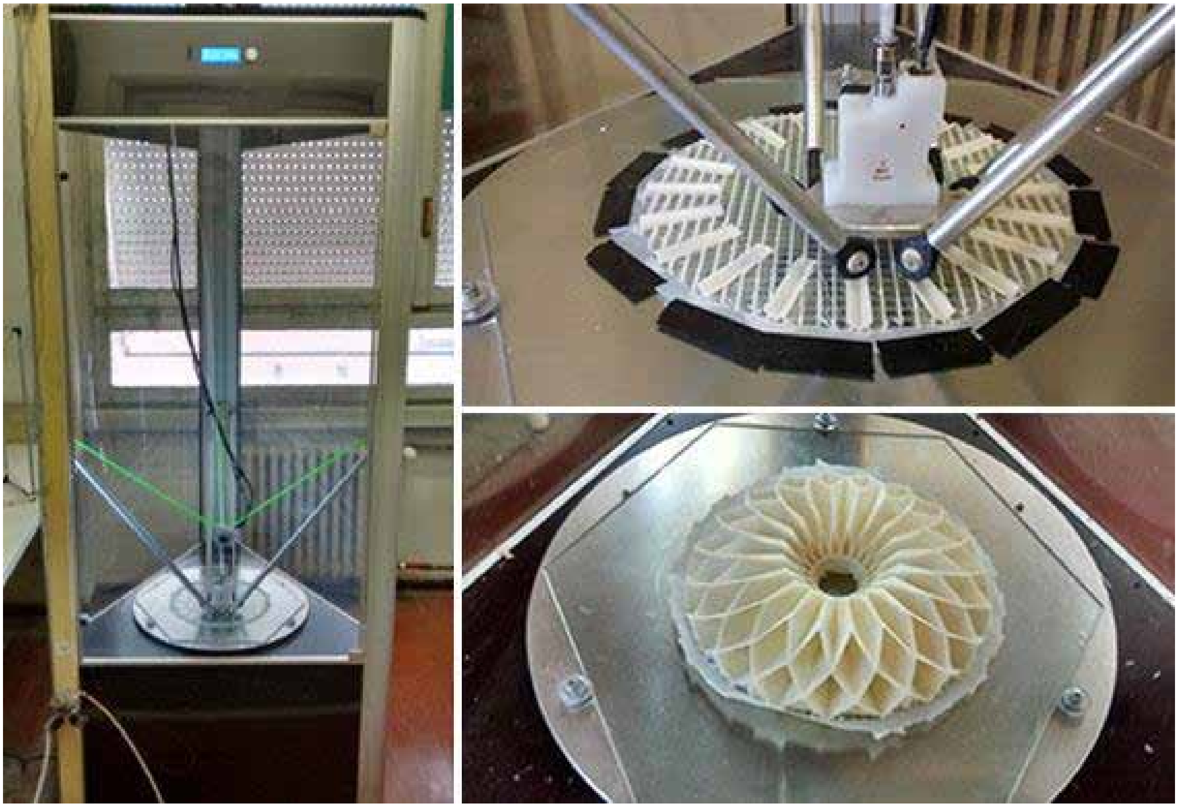


Figure 84: Printing process and results with the DELTA 40-70 FDM printer

After the model was printed it underwent a post-processing process. The brim and all the supports it had were removed with manual tools (Figure 85). The surface inside the driver compartment, which was at a higher level than the base, required supports. Surfaces that have supports usually present a rough finish, as the supports leave traces when they are removed, so they must be sanded off. However, it was convenient that these surfaces remained hidden in the inside of the compartment, and not in the visible areas of the lamp.

The crown-shaped ring and base plate were also printed. These were printed in a PowerWasp EVO FDM printer[7] in black PLA. This material was chosen because it did not have to be copper plated, and it gives the best printing results in most cases, as it has less withdrawal than ABS. It is also cheaper than ABS and biodegradable, and it is currently the most commonly used

---

[7] http://www.personalfab.it/shop/powerwasp-evo/

material in FDM. The results of the print can be seen in Figure 86. The base plate was printed as a full flat disc and this caused a very uneven and porous surface finish.

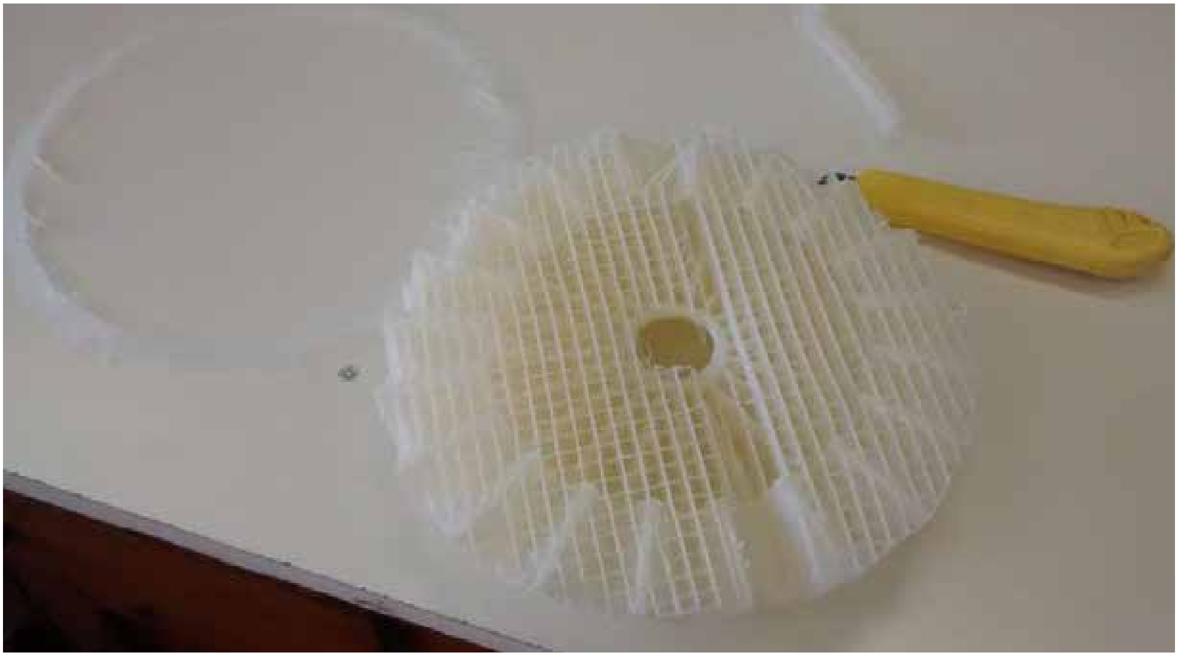


Figure 85: Removing the brim and the supports

Figure 86: Crown-shaped ring and base plate prints

8.1.2 Part assembly

The assembly of the crown, body and base plates with the electronic components can be seen in Figure 83. These parts had numerous problems. The crown's points did not fit perfectly well within the body and they broke off easily, because they would crack between layers. The twist-and-lock mechanism did not work well either due to the friction generated by the part's poor surface finish, so it ended up breaking off one of the legs also. Some of the aforementioned problems can be seen in Figure 87.

The COB was assembled with the aluminum disc by a thermally conductive double tape. The diameter of this disc was 2mm less than the hole left in the body to fit it inside. This tolerance was left because at the moment there was uncertainty of the final thickness of the copper plating. The gap could be filled however by a thermally conductive silicone. The reflector and diffuser would be assembled by small indentions in the body that would snap-fit the diffuser, which would in turn hold the reflector in place. This feature however was left-out of this model as the diffuser material and thickness was unknown at the moment and testing could be performed by holding the diffuser with a silicone adhesive.

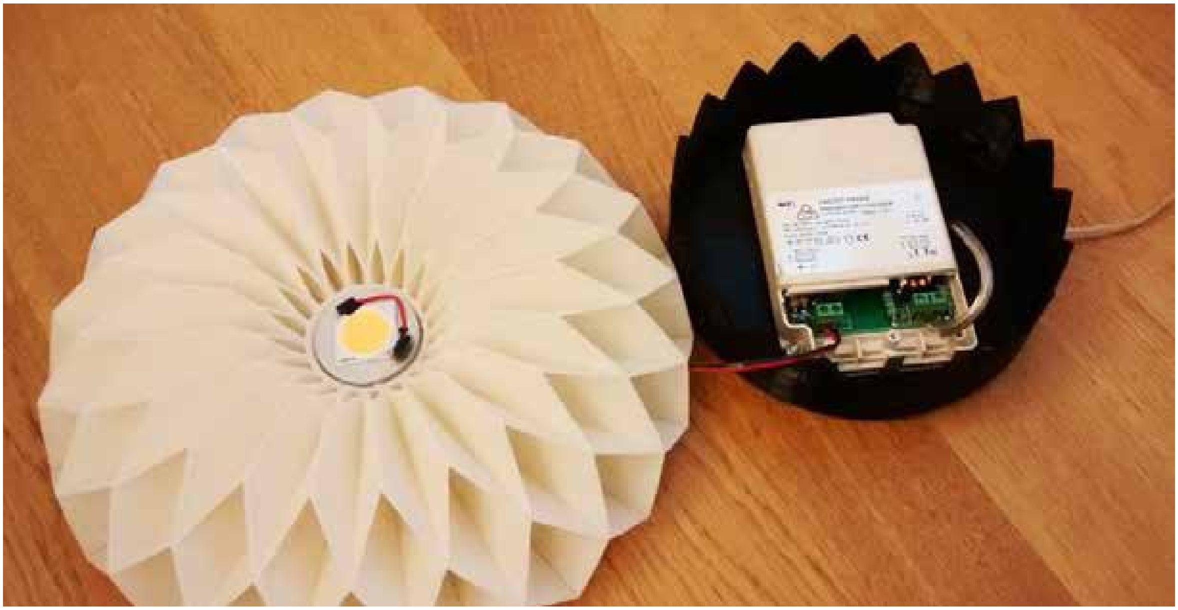


Figure 87: Assembly of electronic components and printed parts

Figure 88: Problems with Crown-shaped ring and base plate

8.1.3 Copper plating

The next necessary validation was to know if the part could be copper plated. The process selected was traditional copper plating, as the more eco-friendly vacuum copper deposition was only available at industrial facilities and the minimum production amount was fifty units. Several tests were conducted at Politecnico di Milano's chemistry department, using the 1:5 scale models of Arista's body. The first tests, conducted with PLA parts, were only partially successful (Figure 89). The tests performed on ABS parts, however, had better results, which allowed assuming that the results on a full scale part, of an ABS copper plating procedure performed at a specialized company, could give good results. The full scale part was finally copper-plated at a company that specializes in the metallization of plastic parts in Medellin, Colombia. The results can be seen in Figure 90.

Figure 89: PLA copper plating tests at Politecnico di Milano. Acid bath, conductive layer and Cu layer

Figure 90: Arista body after copper plating

The part was left in the copper plating tanks for one hour, to generate a thick layer. This thickness was not officially measured, but it should be superior to fifty microns. An additional thin layer of clear varnish was applied after to avoid oxidation. The aluminum disc with the COB was attached using Kafuter K-5202 thermally conductive silicone[8]. The gap was still approximately one millimeter, so at least two grams of this silicone were required. Figure 91 shows a detail of the assembly.

Figure 91: Detail of the assembly between the COB, the aluminum heat sink and copper body

8.1.4 Light generation

Once all the parts were assembled, the luminaire could be turned on. After testing with many different polymer samples provided by Nemo Lighting's technical department, a 1mm thick PP sheet was selected. This sheet has a different surface finish in each of its faces which allows it to diffuse light through its entire surface (Figure 92).

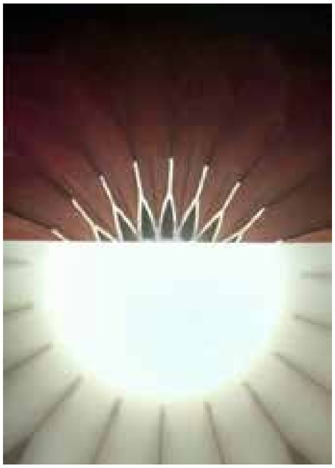


Figure 92: Luminaire shown with half of the light beam covered by the diffuser sheet

---

[8] http://www.alibaba.com/product-detail/LED-Kafuter-K-5202-Silver-Insulation_1246850542.html

Figure 93: Lamp lit

Figure 93 shows the lamp as it looks turned on (with the light dimmed to 50%) with the diffuser but without the reflector. The light flux generated by the luminaire with the diffuser, but without the reflector, was measured at 1890 lumens, which is as about as much light as three 60W incandescent light bulbs emit. At a distance of 1.5 meters (the approximate distance of a table's surface from the ceiling) this flux generated 300lux, which is a confortable light level for simple tasks such as eating or reading. Figure 90 shows the luminaire illuminating a thirty square meter room by itself, from an altitude of 2.3 meters. The luminaire generated a very nice light in the room (and created faint shadows in the walls), but it dazzled if looked at straight. The possibility of reducing the luminous flux with a dimmer, coupled with a larger diffuser, could help solve that problem.

Figure 94: Room illuminated by Arista positioned in the ceiling

In case that the reflector is desired there is a second option to use for the diffuser. LEDiL produces specialized secondary optics that assembles directly with their reflectors. Their model F13671_ANGE-RZ-LENS (Figure 91) is a diffusing lens that assembles directly with their Angelina reflector.

Figure 95: F13671_ANGE-RZ-LENS manufactured by LEDiL[9].

8.1.5 Heat dissipation

One of the most important features of the luminaire that had to be tested and validated was its capacity to dissipate heat. An effective way to perform this test is to take a thermal photograph (or video) of the luminaire while it is working. The photographs show the "hot-spots" of the luminaire as well as the heat distribution, and it measures the temperature at some given points. Figure 96 shows thermal photographs of the lamp after 8 minutes of working. Results show that most of the heat is concentrated in the center, in the aluminum disc. They also show a bright yellow, almost white ring around this disc. This ring is the thermally conductive silicone, which failed to conduct the heat properly to the rest of the lamp. After a second review, it was evident that adding so much of this silicone was a huge design error. The thermal conductivity of the silicone (0.8 W/mK) is not nearly close to the conductivity of aluminum (237 W/mK) or copper (401 W/mK). It is used because it is still much greater than the conductivity of air (0.024 W/mK), so it replaces imperfections in the surface, but it must be applied in a very thin layer so that the direct metal-metal contact does most of the heat conduction. It was important therefore to precisely measure the fit between the aluminum disc and the body in order to make it as close as possible. However, the thermal tests weren't a complete failure. The amount of heat that did manage to pass to the body was evenly and efficiently conducted through the body, which kept a stable temperature throughout the test. As the room temperature was measured at 25°, the luminaire's body raised its temperature to an average of 10° higher, which it managed to hold constantly throughout the test. The results allow assuming that the luminaire will function as designed if the interface between the aluminum part and the copper plated body is improved.

---

[9] http://www.ledil.com/node/2/p/8548

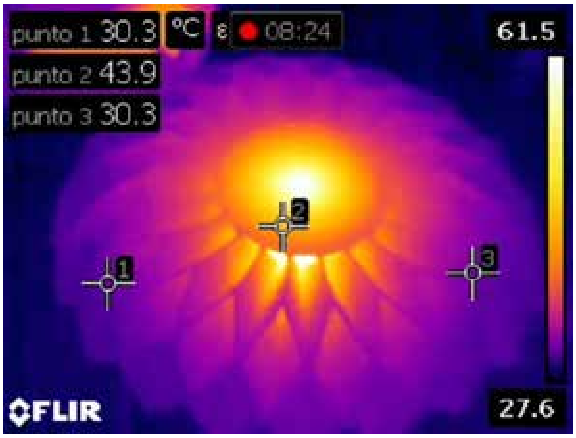


Figure 96 (a): Thermal image of the lamp with diffuser after 8 minutes and 24 seconds.

Figure 96 (b): Thermal image of the lamp without diffuser after 9 minutes and 08 seconds.

Figure 96 (c): Thermal image of the back of the lamp after 8 minutes and 11 seconds. Point 2, in the aluminum disc directly below the LED, shows a temperature of 152°C, which exceeds the LED's safe temperature limit of 150°C max.

8.2 Design Improvements

In this section a re-design of the luminaire will be presented with the corrections made to the first prototype. Some of these corrections were validated through the production of a second prototype.

8.2.1 Arista V2

Figure 93 shows a general view of the second version of Arista, labeled Arista V2. The main corrections made were in regards to the driver compartment, to make it stiffer and to improve the assembly between components. This compartment, shown in Figure 98, was completely re-designed, eliminating the crown-shaped ring, which was incorporated into the body's geometry. The twist-and-lock mechanism was replaced by a push and snap mechanism, which stresses the parts in the direction perpendicular to the layer deposition direction, which offers a much better strength. The base plate was hollowed out and replaced by a circular grid, reducing the amount of material used, and improving the surface finish.

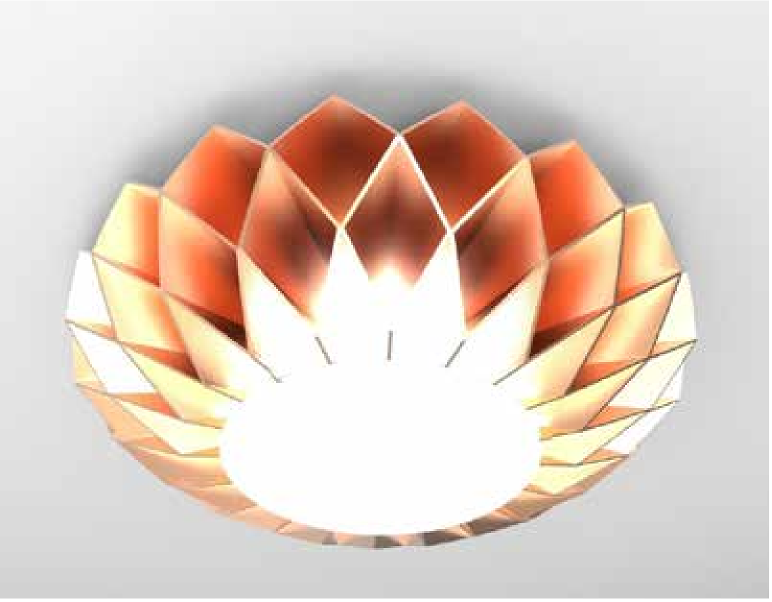


Figure 97: General view (render) of Arista V2 lit

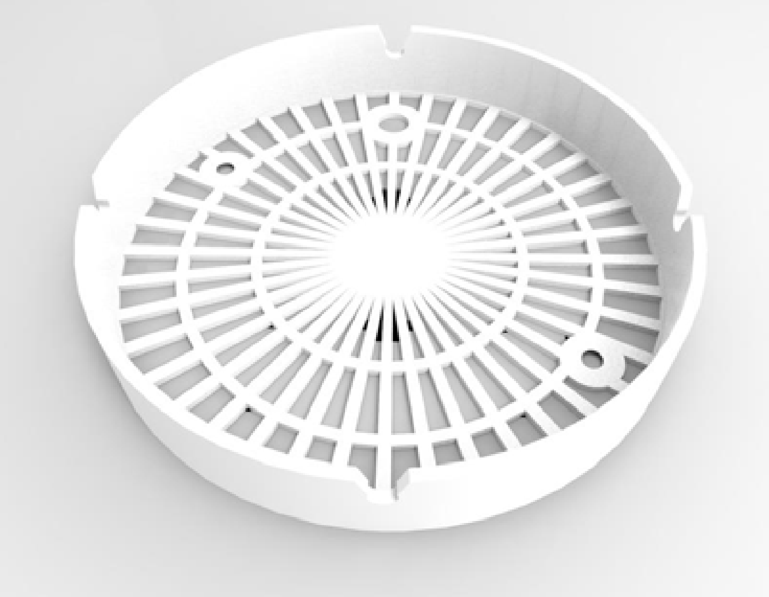


Figure 98: Driver compartment

Another part of the design that was improved is the LED-heat sink assembly. The gap was reduced to 0.1mm, which is the expected copper layer thickness. The reflector was left as optional, but a thin disc was designed to cover the COB's cabling, which could be visible through the body's gaps. This disc is assembled to the body by three extensions in the form of fins that go inside the body's gaps. The disc must be cut in very thin reflective foil, allowing it to bend to insert the fins

Figure 99: Exploded View of Arista's components

in the gaps. Another modification made is the diffuser's size. The current diffuser does not cover the entire 115° angle of the LED's luminous flux, and the led can be seen directly at certain angles, which dazzles and is dangerous for the eye. Figure 100 shows that a diffuser of at least 120 millimeters in diameter is necessary to cover the 115° flux.

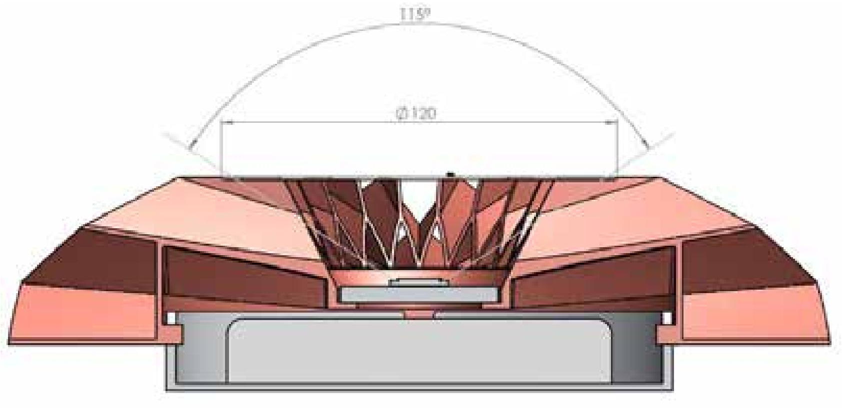


Figure 100: Minimum diffuser size to cover the light flux angle

8.2.2 Printing and copper plating of Arista V2

The second version of Arista was printed using the same Delta 40-70. The printing time and materials used were the same also, and the printing setup was also the same. The results, shown in Figure 101, were much better, because the ring that was added in the base of the body helped to create a more stable print and to avoid withdrawal, which didn't occur.

Figure 101: Printing results of Arista V2

Figure 102: Sanding the edges of Arista V2

This second model was sanded carefully to give it a better suface finish than the first prototype. The intention was not to hide the small staircase effect that is visible in the surface, because it is intrinsical to the printing process and the intention is to communicate it, but to smooth out the edges to get a cleaner and completed appearance.

Arista V2 was also copper plated, as can be seen in Figure 103, with good results. The sanding largely improved the surface finish and the final result was much better. The fit between the aluminum disc and the body was also improved, resulting in a thinner layer of thermal silicone.

Figure 103: Arista V2 with copper plating assembled with aluminum disc and LED

The driver compartment was also printed, in white PLA, with good results, as shown in Figure 104. The changes made proved to work, as the component resulted to be sturdy, the surface finished improved a lot and the assembly with the body and the driver could be easily done.

Figure 104: Driver compartment printed in white PLA

8.2.3 Arista Pendant

As an additional validation, the pendant version of Arista was also printed. The model had be added more supports due to the overhanging surfaces in the bottom. However, the final result, as seen in Figure 105, was very good. A first print was done in a 1:5 scale, and then a full-scale model was printed. No copper plating or assembly was done with this model, but the results should not differ from those obtained with the ceiling fixture.

Figure 105: Arista pendant version printed in white ABS

8.3 Cost Validation

Another important aspect to validate the feasibility of this approach is its cost. Although AM costs are continually decreasing, both in terms of printing service providers, materials and printers themselves, it is important to validate the current costs to have a reference point towards the future.

The prototypes in this study were printed using FDM printers at Politecnico di Milano's +Lab for no cost. The machine that was used however, has a market cost of five thousand euros. One kilogram of white ABS costs thirty seven euros, and is enough material to print three lamps. An online quotation of the Arista body made in high density ABS by FDM was quoted at seventy two euro[10], with a delivery time of four days. The driver compartment was quoted at twenty five euros.

Copper plating the part cost seven euros. Vacuum deposition of the part was quoted at two euros per part, with a minimum production quantity of fifty units. The aluminum disc has a cost of two euros. The thermocunductive silicone has a cost of five euros and is enough for ten lamps.

The CREE COB used has a cost of twenty one euros. The QLT driver has a cost of forty euros. The plastic diffuser has a cost of two euros. The LEDiL reflector has a cost of three euros and a

---

[10] http://www.makexyz.com/

half, and the optic that can assembly directly with it has a cost of one euro.
The previous information es summarized in the following table

Item	Provider	Cost (Euros)
Body in ABS by FDM	MakeXYZ	72
Driver compartment, ABS, FDM	MakeXYZ	25
Copper plating body	Metalplast	7
2000 lumen COB	CREE	8
Dimmable driver for COB	QLT	25
Aluminum disc	Cortamos CNC	2
Thermally conductive silicone	Kafuter	0.50
Reflector	LEDiL	3.5
Diffuser	LEDiL	1
TOTAL		**144**

Table 5: Costs of manufacturing 1 Arista luminaire

The total cost of producing one luminaire, without counting transportation and assembly, is 144 euros. Scale economy for a larger production would only apply to commercial electronic components, which account for only 37% of the total cost, however the lamp could probabably go down to less than 100 euros. Considering that the retail price goal established in the design requirements was less than seven hundred and fifty euros, with a factor of five in regards to cost, the design goal is accomplished. In fact, considering that transportation, assembly, and packaging costs could raise the total cost to aproximately one hundred and fifty euros, a factor of five would still set the retail price at seven hundred and fity euros. Considering that the price range for 3D printed luminaires of a similar size and output rise well above 1000 euros, a retail price of 750 euros would theoretically have a good market appeal.

9. Conclusions and analysis

9.1 Project conclusions

There are several ways to analyze this project. As to the results obtained with the product design, they are mostly positive. Out of the twenty four design requirements established in chapter six, three of them are subjective, and nineteen out of the remaining twenty one were accomplished. The only two that were not are due to problems that the luminaire has only partially solved, but still require attention. The first is heat dissipation, as the only temperature test performed showed that the LED would over-heat after eight minutes of use. A possible cause was individualized and corrections were made but these are yet to be tested on further prototypes. The other issue is that the luminaire dazzles when looked at directly. A greater focus must be given to optics design in order to guarantee that this problem is solved without having to sacrifice the luminous output. The accomplishment of the three subjective requirements must be validated by a wide, representative survey. However, initial, non-representative inquiries show that most people find the design to be interesting and beautiful, and would feel pride in owning it.

However, as it has been emphasized in previous chapters, the objective and value of this project is not so much in the creation of a final design solution, but in the creation of an alternative; the production of LED luminaires through AM. This alternative initially was an unknown, something that sounded promising but had not yet been explored enough to become a certainty. At the end of this project, it is still hard to say if AM is the best solution for the production of LED luminaires, but it evident that it is certainly a feasible alternative. One that might not suit every kind of company, but that might be the best for some. Companies that have a small infrastructure, that cannot allow themselves the costs and time required to constantly create molded parts, that are strongly dependent on aesthetics and design and have a customer base that looks out for innovation, technology and exclusivity, could be very interested in this AM approach. To know that this approach has been thoroughly researched and tested through the creation of a fully developed project can lower the perception of risk and allow it to spread and develop further, to become an industrial reality. Although, as presented in chapters 4 and 5, Arista is by no means the first lamp created by AM, it is certainly unique in its approach to the lighting industry. It is born out of a rigorous analysis of the characteristics, requirements and flaws of this industry, and presents a solution that considers them in first place.

No solution will be beneficial if it is born out of a biased view, it must consider all of the stakeholders, all of the parties possibly interested in that solution. The 3D printing community, and it seems the scientific, academic, and part of the industrial community as well, are all eager to find new applications for AM, deemed the 3rd industrial revolution. However, it seems there is still a big gap between the offer and the real industrial demand. It seems, at least throughout the research for this project, that desire to spread 3D printing is not coming hand in hand with rigor and depth into the industrial possibilities it can achieve. Many of the 3D printing enthusiasts are becoming technicians in their field of knowledge, creating communities of “makers” and participating only within these communities. There is a big risk that AM becomes a sub-culture, a genre of products, disconnected from the rest of the manufacturing world. If this happens, it would not achieve its call to revolutionize the industry, to change the world.

Many luminaire manufacturers are not closed or even keen on any manufacturing technology in particular; they belong to one of the industries that are most open to innovation and change. They can, and actually have, been early adopters of many technologies, including AM. However, their field of expertise is lighting, not AM. It is not up to them to create the necessary innovations in AM to make it feasible and interesting for their industry. AM providers might argue the same, that their expertise is not lighting and that it is not up to them to dig up the specific requirements and necessities that this particular industry has. Both are right, and wrong, at the same time. Most importantly, they are both missing out on opportunities that could arise from collaboration. To collaborate, there must be communication, which in turn requires interest and awareness. This project pretends achieving precisely this, interest and awareness, and a common language to communicate, to collaborate. Arista is a product that should generate enthusiasm in the lighting industry, for its technical, structural and aesthetical improvements; and in the AM industry, for its novelty and as an unexplored opportunity.

The results obtained out of the initial research could have taken many directions, as many different design projects could be derived from those results. As explained earlier, the value of this research is that it provides an alternative, and this alternative cannot be constrained from the beginning. However, it was necessary to validate this alternative through the creation of at least one feasible embodiment of this design approach. This product design, Arista, proved to be the perfect example, and a spokesman for the cause.

9.2 Future research

Although the product designed performs relatively well, it still requires subsequent testing and validation. Finite element analysis could be performed to design and optimize the luminaire's heat flow. However, to achieve reliable results, the materials must first be characterized better. FDM printed ABS has anisotropic characteristics that are currently not easy to model using FEM software, as well as copper plating with a highly variable layer thickness. Nonetheless, through further research into the metallization of printed polymer parts and large scale testing a characterization of these materials could be achieved to use as input for a subsequent computer analysis. The use of this approach to create low-weight, aesthetically unique, well-performing heat sinks holds great promise for the lighting industry, as well as for other applications that require thermal management. However, the metallization of 3D printed parts must also focus efforts into healthier and more environmentally sustainable metallization processes. The creation of conductive polymer components to avoid additional conductive layer deposition; of intrinsically porous parts to avoid acid baths, and the development of other techniques such as thick vacuum deposition, could all contribute to make metallization a more sustainable alternative.

The research results exposed in this project should also be integrated with promising results shown by other research groups, which are still in a phase of development. One of the most promising is the research into printed optics, which allows the creation of personalized luminous outputs, movement sensors, embedded components and displays. Although still very experimental, it holds a great promise for the near future.

Finally, as exposed earlier, the most important future research is into the collaboration of the lighting and the AM industries. Interdisciplinary research groups should be created that can develop the integration and synergic growth of these technologies. Both industries can benefit from this collaboration, as it is a fertile ground for innovative developments, and at the end, those who will benefit the most are the consumers, who will enjoy the innovations and improvements generated by a society that works for a brighter future.

10. References

10.1 Bibliography

1. Advances in heat sink performance with DMLS. Innovation Results. An R&D Case Study by Technology Strategy Board. 2014
2. Ahn S H, Montero M, Odell D, Roundy S, Wright P K. Anisotropic material properties of fused deposition modeling ABS. Rapid Prototyping Journal, 2002, 8(4): 248–257
3. Alimardani M, Toyserkani E, Huissoon JP, Paul CP. On the delamination and crack formation in a thin wall fabricated using laser solid freeform fabrication process: an experimental-numerical investigation. Opt Lasers Eng 2009;
4. Alma E. F. Taylor. Illumination Fundamentals. Lighting Research Center. Rensselaer Polytechnic Institute. 2000. P.
5. Barney, S. Simplifying the sophisticated: LED driver selection made easy. LEDs Magazine. April/ May 2014 Issue.
6. Berman, B. 3-D printing: The new Industrial revolution. Business Horizons (2012) 55, 155—162
7. Boddu M, Musti S, Landers R, Agarwal S, Liou F. Empirical modeling and vision based control for laser aided metal deposition process. In: Proceedings of the twelfth annual international solid freeform fabrication symposium; 2001.p.452-9
8. Buijs, Jan. "Modelling product innovation processes, from linear logic to circular chaos." Creativity and innovation management 12.2 (2003): 76-93.
9. Cheah C M, Chua C K, Lee C W, Feng C, Totong K. Rapid prototyping and tooling techniques: a review of applications for rapid investment casting. International Journal of Advanced Manufacturing Technology, 2005, 25(3–4): 308–320
10. Chowdhury, Ashfaqul I., Gary R. Allen, and Thomas A. Knapp. "Lightweight heat sinks and led lamps employing same." U.S. Patent Application 12/979,476.
11. Chua C K, Leong K F, Lim C S. Rapid Prototyping: Principles and Applications. 3rd ed. Singapore: World Scientific Publishing Company, 2010, 165–171
12. Cormier D, Harrysson O, West H. Characterization of H13 steel produced via electron beam melting. Rapid Prototyping Journal, 2004, 10(1): 35–41
13. Cross, N. Engineering design methods: strategies for product design. John Wiley & Sons, 2008.
14. Crump S S. Fused deposition modeling (FDM): putting rapid back into prototyping. In: The 2nd International Conference on Rapid Prototyping. Dayton, Ohio, 1991: 354–357
15. Diegel, O., Singamneni, S., Huang, B., Gibson, I., Curved Layer Fused

Deposition Modeling in Conductive Polymer Additive Manufacturing, Advanced Materials Research, Trans Tech Publishers, 2011:1984-1987

16. Forcolini G. Illuminazione con i LED. Funzionamento, caratteristiche, prestazioni, applicazioni. Hoepli editore, 2011. P.87
17. Foroozmehr E, Kovacevic R. Effect of path planning on the laser powder deposition process: thermal and structural evaluation. Int J Adv Manuf Technol 2010; 51:659–69.
18. Furian, P. H.. Electromagnetic Spectrum and Visible Light. www.crated.com
19. Gibson, I., Rosen, D.W., Stucker, B., Additive Manufacturing Technologies Rapid Prototyping to Direct Digital Manufacturing. Springer. US. 2010.
20. Gu D. D. Meiners W., Wissenbach K. and Poprawe R. Laser additive manufacturing of metallic components: materials, processes and mechanisms. International Materials Reviews 2012
21. Guo N, Leu M.C. Additive manufacturing: technology, applications and research needs. Review paper. Higher Education Press and Springer-Verlag Berlin Heidelberg.2013
22. Haeckel, Ernst. Kunstformen der Natur. Bibliographisches Institut. 1899-1904 Leipzig und Wien
23. Hague, R., Campbell, I., Dickens, P., 2003. Implications on design of rapid manufacturing. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 217 (1).
24. Hague, R., Mansour, S., Saleh, N.,. Material and design considerations for rapid manufacturing. International Journal of Production Research 2004.
25. Hatsopoulos, M.I. “3D printing speeds design cycle”, Design News. 2000
26. Holmström, J., Partanen, J., Tuomi, J., Walter, M., 2010. Rapid manufacturing in the spare parts supply chain: alternative approaches to capacity deployment.
27. Jiang W. and Schneider K. TIR optics enhance the illuminance on target for directional LED modules. LEDs Magazine. February 2012.
28. Karlen M, Benya JR, Christina S. Lighting Design Basics. John Wiley & Sons, Inc. Hoboken, New Jersey, USA. 2012. P.3,4
29. Khaing M.W., Fuh J.Y.H., Lu L.,; 2001; Direct metal laser sintering for rapid tooling: processing and characterization of EOS parts; Journal of Materials Processing Technology; 113(2001); 269-272
30. Klaft, L. Open-source 3-D printers head to a desktop near you; instantly make a part to replace what’s broken. (2010, October 17). Worcester Telegram and Gazette, B5.
31. Koen, P., et al. “Providing Clarity and a Common Language to the “Fuzzy Front End” Research-Technology Management 44.2 (2001): 46-55.
32. Kruth, J.P. Froyen, L. Rombouts, M. Van Vaerenbergh, J. Mercells, P. New Ferro Powder for Selective Laser Sintering of Dense Parts, CIRP Annals - Manufacturing Technology, Volume 52, Issue 1, 2003

33. Kruth, J.P., Levy, G. Klocke, F. Childs, T.H.C. Consolidation phenomena in laser and powder-bed based layered manufacturing, CIRP Annals - Manufacturing Technology, 56: 2, 2007,
34. Lauret J.P. Solving optical problems for LED applications. SPIE International Society for Optics and Photonics. 2015.
35. LEDs-C4. Basic Light Concepts- Binning. Architectural Light Catalogue 2013. P.13
36. Levy, G.N., Schindel, R., Kruth, J.P., Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state-of-the-art and future perspectives,. CIRP Annals – Manufacturing Technology. 2003. 52 (2), 589–609.
37. Lithonia Lighting. White Paper: Binning and LED. 2010. P.1
38. Mansour, S., Hague, R., 2003. Impact of rapid manufacturing on design for manufacture for injection moulding. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 217 (4), 453–461.
39. Mari, E. 25 Modi per piantare un Chiodo. Mondadori, Milano. 2011 p.23
40. Mazumder, J. "A crystal ball view of direct-metal deposition." JOM 52.12 (2000): 28-29.
41. McKinsey & Company. Lighting the way: Perspectives on the global lighting market. 2012
42. Mellor S, Hao L, Zhang D. Additive manufacturing: A framework for implementation. Int. J. Production Economics 149 (2014) p. 194–201
43. MTT Technologies Group. MTT selective laser melting. 2009
44. Mudge R P, Wald N R. Laser engineered net shaping advances additive manufacturing and repair. Welding Journal-New York, 2007, 86(1): 44–48.
45. Onuh S O, Yusuf Y Y. Rapid prototyping technology: applications and benefits for rapid product development. Journal of Intelligent Manufacturing, 1999, 10(3/4): 301–311
46. Otubo J, Antunes A S. Characterization of 150 mm in diameter NiTi SMA ingot produced by electron beam melting. Materials Science Forum, 2010, 643: 55–59
47. Pahl, G., et al. Engineering design: a systematic approach. Vol. 157. Springer Science & Business Media, 2007.
48. Palladino P, Spotti P. Illuminare con i LED. Principi e Applicazioni della Luce Elettronica. Techniche Nuove. 2012, Milano, Italia.
49. Pham D T, Dimov S S. Rapid prototyping and rapid tooling – the key enablers for rapid manufacturing. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2003, 217(1): 1–23
50. Ponche R, Kerbrat O, Mognol P, Hascoet JY. A novel methodology of design for Additive Manufacturing applied to Additive Laser Manufacturing process. Robotics and Computer-Integrated Manufacturing. Elsevier Ltd. 2014

51. Poprawe R. Loosen, P. Hoffmann, H. D.: 'The future of high power laser techniques', Proc. 16th Int. Symp. on 'Gas flow, chemical lasers, and high-power lasers', Gmunden, Austria (ed. D. Schuo¨ cker), 634602; 2007, SPIE.
52. Ramchandra P., Boucar D., Solar Lighting. Springer-Verlag London Limited. 2011. P. 77
53. Rudd, M. (2011, January 16). Next, we'll print out a curly iPhone. The Sunday Times Review, p. 7.
54. Sedacca, B. Hand built by lasers. Engineering and Technology, (2011). 6(1), 58—60.
55. Sherman, L. M. (2009). Additive manufacturing: New capabilities for rapid prototypes and production parts. Plastics Technology, 55(3), 35—45.
56. Simchi, A., F. Petzoldt, and H. Pohl. "On the development of direct metal laser sintering for rapid tooling." Journal of Materials Processing Technology 141.3 (2003): 319-328.Kruth, J. P. Levy, G. Klocke, F. and Childs, T. H. C.: CIRP Ann., 2007, 56, 730–759.
57. Stemp-Morlock, G. (2010). Personal fabrication. Communications of the ACM, 53(10), 14—15
58. Strategic Directions, The next frontier: New technologies will enable cost-effective customization. 2008. Strategic Directions 24 (8)
59. Strondl A, Palm M, Gnauk J, Frommeyer G. Microstructure and mechanical properties of nickel based superalloy IN718 produced by rapid prototyping with electron beam melting (EBM). Materials Science and Technology, 2011, 27(5): 876–883
60. The Economist, Print me a Stradivarius: How a new manufacturing technology will change the world. (2011, February 17). p. 7
61. Thilmany, J. (2001), "Printing in three dimensions" Mechanical Engineering, May.
62. Ulrich, K.T., and Eppinger S. D.. Product design and development. McGraw- Hill Education. 2004.
63. Vayrne, B. Vignata F., Villeneuvea, F. Designing for Additive Manufacturing. Proceedings of the 45th CIRP Conference on Manufacturing Systems. 2012.
64. Ventola, Luigi, et al. "Heat Transfer Enhancement by Finned Heat Sinks with Micro-structured Roughness." Journal of Physics: Conference Series. Vol. 494. No. 1. IOP Publishing, 2014.
65. Wendel B, Rietzel D, Kühnlein F, Feulner R, Hülder G, Schmachtenberg E. Additive Processing of Polymers. Macromolecular Materials and Engineering. 2008
66. Willis, Karl, et al. "Printed optics: 3d printing of embedded optical elements for interactive devices." Proceedings of the 25th annual ACM symposium on User interface software and technology. ACM, 2012.
67. Wohlers, T. Wohlers Report 2005, Worldwide progress report on the rapid prototyping, tooling, and manufacturing state of the industry, Wohlers Associates, 2005

10.2 Websites

- Andy Gilmore website: http://crowquills.com/
- Arcam A B. http://www.arcam.com
- BAG Electronics website. http://www.bagelectronics.com/
- COB LED vs SMD. Posted On: Monday, 30 June 2014 05:49:49 Europe/London by Focus LED UK Ltd. http://www.focusledltd.co.uk/blog/cob-led-vs-smd-led/
- http://2bora.com/en/technologie/dioda-led
- http://2bora.com/en/technologie/natezenie-swiatla
- http://en.wikipedia.org/wiki/Creative_problem-solving
- http://gantlights.de/
- http://nemolighting.com/
- http://n-e-r-v-o-u-s.com/shop/search_tags.php?search=lighting
- http://oliviervanherpt.com/
- http://oliviervanherpt.com/functional-3d-printed-ceramics/
- http://pct.cree.com/dt/index.html
- http://theenergycollective.com/todayinenergy/356546/led-bulb-efficiency-expected-continue-improving-cost-declines
- http://www.3dlac.com
- http://www.alibaba.com/product-detail/LED-Kafuter-K-5202-Silver-Insulation_1246850542.html
- http://www.benjaminhubert.co.uk/works/lighting/heavy/
- http://www.creativeeducationfoundation.org/our-process/what-is-cps
- http://www.disneyresearch.com/project/printed-optics/
- http://www.electronicsweekly.com/news/wp-content/uploads/sites/16/2008/03/ itemid-52190-getasset.jpg
- http://www.exnovo-italia.com/
- http://www.innermost.net/wp/portland-2
- http://www.ledil.com/node/2/p/13522
- http://www.ledil.com/node/2/p/8548
- http://www.makexyz.com/
- http://www.mgxbymaterialise.com/
- http://www.mgxbymaterialise.com/webshop/order/family/detail/shopdetail/27?product=118
- http://www.personalfab.it/en/products/deltawasp-40x60-2/
- http://www.personalfab.it/shop/powerwasp-evo/
- http://www.piulab.it/
- http://www.piulab.it/1/ceramici_ceramic_848801.html
- http://www.soddu.it/design/GA_soddu_e.htm
- http://www.theverge.com/2013/8/13/4617076/andy-gilmore-ghostly-

international-video
- https://ultimaker.com/
- https://ultimaker.com/en/products/software
- https://www.educate-sustainability.eu/portal/content/photometry
- Light Fixture (Luminaire) Types. http://www.archtoolbox.com/materials-systems/electrical/lightfixtures.html
- Lighting Language. Light Logic for the 21st Century. http://ieslightlogic.org/lighting-language/
- Types of Lighting Fixtures. http://www.hgtv.com/remodel/mechanical-systems/types-of-lighting-fixtures Retrieved March 28, 2015.

11. Acknowledgements

The following people have contributed to the realization of this project. I would like to express them my sincere gratitude for their efforts, support, guidance and collaborative attitude:
Marinella Levi
Valentina Folli
+Lab Politecnico di Milano: Chiara Capuzzo, Erica Contran, Maria Luisa Miotti, Francesco Pacelli, Sara Ridolfi.
Rocío Gambín
Miguel Melo
Benni Li Volsi and Claudio Lostaglio at Nemo Lighting
Blaster Diseño: Juan Felipe Pérez, Luis Bernardo Pérez, Alan Sepúlveda
My family