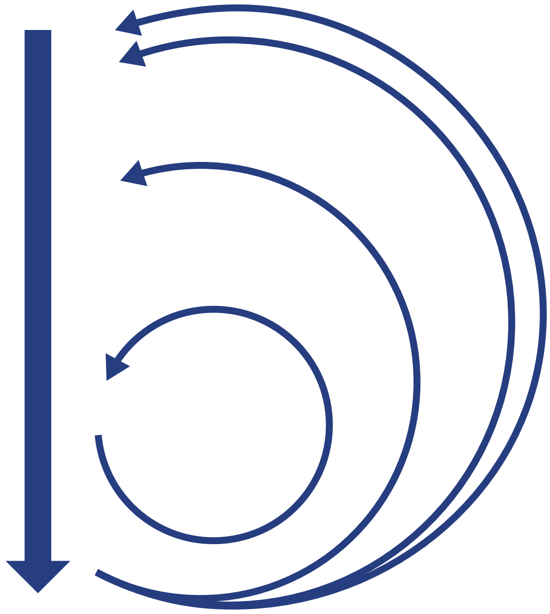

PRODUCT DESIGN FOR A CIRCULAR ECONOMY

A CASE STUDY TOWARDS A CIRCULAR LUMINAIRE

Master Thesis, Integrated Product Design, Delft University of Technology
M.R. van den Berg, July 2014

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EXECUTIVE SUMMARY

In general the majority of the current economy is a linear economy based on a 'take-make-dispose" model that relies on easily accessible resources and energy. This creates huge amounts of waste at end of life impacting nature and society. Furthermore resource scarcity is increasingly becoming an issue impacting price and availability of products. The linear model is increasingly harder to sustain in the current world and therefore a radical change of the system is desired.

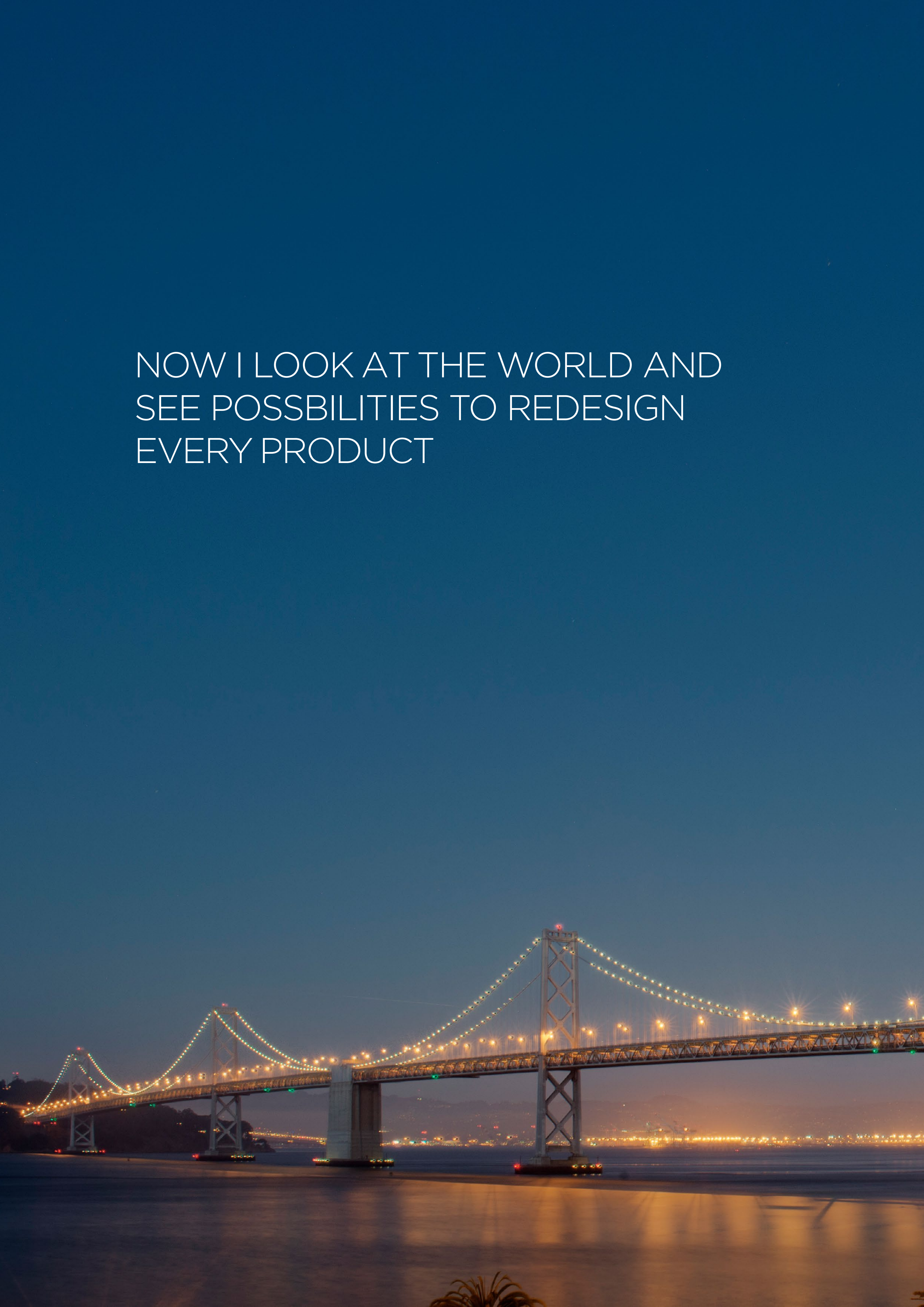
Circular Economy (CE) is a framework focusing on resource and value recovery to systematically design out waste. In contrast to other sustainability frameworks it explicitly includes a business approach. The framework involves decoupling wealth from resource usage by product life extension, using renewable energy and diversity for resilient and productive systems. The framework can be seen as a solution for the end of the age of cheap resources and fossil fuels.

CE is primarily promoted by the Ellen MacArthur Foundation which published three reports that primarily focus on the business case. For circular product design there is little information available. Therefore this thesis looks at what CE means for circular product design and how that can be applied by use of a case study.

A Circular Design Model is proposed that identifies five main characteristics for circular design: future proof, disassembly, service, remake and recycling. Based on these five main characteristics various guidelines from literature were gathered and combined to create a Circular Design Guideline List. The list shows all relevant guidelines that can be taken into account. Based on the guideline list three tools are presented that can be used to apply circular design: a Circular Design Vision, A Circular Design Spider Map and a Circular Design Scorecard. Depending on the situation and user a simpler or a more extensive tool might be more suited.

The tools have been developed by and used in a case study of the design of a circular indoor luminaire. With an understanding of LED developments and products analysis opportunities are identified for a circular indoor luminaire. A concept design has been developed that shows the application of circular design. For the concept luminaire the main characteristics are: ease of access to the LED module and driver, easy disassembly and modularity.

NOW I LOOK AT THE WORLD AND
SEE POSSBILITIES TO REDESIGN
EVERY PRODUCT



1. INTRODUCTION

Before you is a graduation report describing a design project within the circular economy (CE) framework which is completed in cooperation with Philips Research and Philips Lighting. The goal of the project is to extend the Philips recycling guidelines with CE activities based on gained knowledge from a case study. This report completes my master program Integrated Product Design at the faculty of Industrial Design Engineering at the Delft University of Technology.

1.1 Company

Philips is a large multinational organized in three divisions: Consumer Lifestyle, Healthcare and Lighting. Philips is committed to improve people's daily lives with meaningful innovation. The goal is to improve the lives of 3 billion people by 2025, approached by a social and ecological dimension. Philips sees the CE as a necessary boundary condition for a sustainable world. This is supported by Philips' partnerships with the Ellen MacArthur Foundation, Circle Economy Netherlands, the Products That Last consortium, Solve the E-waste Problem (StEP) initiative and GreenElec.

Philips Lighting is the largest manufacturer of lighting in the world measured by applicable revenues and develops lighting for a wide range of applications (Bloomberg, 2013)Philips Lighting is currently focused solely on the development of LED lighting technology, which is expected to drop in price in the coming few years and take a large share of the lighting market. Therefore this project will focus only on LED lighting and will disregard other types of light sources.

1.2 Project scope

Philips Lighting is interested in exploring the opportunities of designing luminaires for a CE. Recently Philips started with a first step towards a circular business model. Architect firm RAU asked Philips if they can lease lux from Philips instead of buying the lighting. In this service model Philips decides on the type, amount and location of lighting that is needed.

Philips is doing research on design for recycling at End of Life (EoL) of luminaires in the GreenElec project. To extend this further Philips is also interested in opportunities for designing for reuse, repair and remanufacturing. Therefore the goal of this project is to use design strategies suited for repair, re-use and remanufacturing in a concept luminaire for the Philips Lighting portfolio. The context will be the business to business (B2B) market where it is easier to implement a service model. A redesigned luminaire could reduce the need for new products and materials and result in an increase of the revenues over product life time. The results of the project are recommendations for expanding the design guidelines of Philips to include CE activities. This project looks at CE from a product design and business perspective. Therefore the focus is towards the technological nutrient cycle that looks at getting the most value out of products in contrast to the biological cycle that mostly deals with getting materials safely into nature.

1.3 Problem definition

In general the majority of the current economy is a linear economy based on a 'take-make-dispose" model that relies on easily accessible resources and energy. This creates huge amounts of waste at end of life impacting nature and society. Furthermore resource scarcity is increasingly becoming an issue impacting price and availability of products. The linear model is increasingly harder to sustain in the current world and therefore a radical change of the system is desired. Circular Economy is a framework for change towards a restorative circular economy, done by redesigning products and rethinking business models.


PHILIPS
innovation you
When Philips LEDs began lighting up the Dragon Bridge in the port of Da Nang Vietnam, it brought more tourism and prosperity to the local community. And great joy to Phan Kho Tudng.

PHILIPS

A circular economy based business puts both challenges and opportunities on the design of products. Products should be built in such a way that they can continue to deliver performance for a long time. However, B2B luminaires of the Philips Lighting portfolio currently are not easy suited for a CE. It is impossible, time consuming and/or not economically attractive to perform any action to the product to upgrade or prolong the lifetime of the product.

1.4 Research questions

The main challenge of this project will be to explore how products can be made suitable for a circular economy and how this can be translated into design guidelines for industrial designers. This will be done by a case study approach using luminaires as an example and applying the guidelines in the design of a luminaire. The core research question of the thesis is:

Q: How to design products for a CE?
The term product is here used to describe the design of physical products exclusive of other types of design such as services or interaction design.

The following sub-questions will be used to answer the main question:

SQ1: What is circular product design?
SQ2: What are the relevant guidelines for circular product design?
SQ3: How to use the guidelines in circular product design?
SQ4: What are the opportunities for luminaire design in a circular economy?

1.5 Sustainability

The interest of companies like Philips in designing products in a different and better way could not have gotten this far without the first report of the Club of Rome that planted the seed for all further research in the area of sustainability.

Since the first report of the Club of Rome, The limits to growth in 1972, the topic sustainability created awareness and has become increasingly more important. It brought the realization that it's not possible to have unlimited exponential growth of the population and economy in a closed system like the Earth. There are limits to food production, the quantity and rate of resources depletion and the pollution of the environment. After the creation of awareness and the message that we cannot continue on the same path forwards comes the question: What can we do about it?

> *"Humanity has the possibility of making development sustainable, that is of ensuring that it meets the needs of the present without compromising the ability of future generations to meet their needs. The concept of sustainable development involves limits, but not absolute ones, since they are imposed on economic resources by the present state of technology and social organization and by the capacity of the biosphere to absorb the effects of human activities. Technology and social organization can, however, be managed and improved to usher in a new era of economic growth."*
>
> ***Our Common Future, UN 1987***

The first response was to minimize everything in order to lower the environmental impact from pollution, waste, energy usage to the amount of products being used. This approach led to design tools such as Eco-Efficiency and Life Cycle Analysis (LCA). Eco-Efficiency focuses on minimization and increased efficiency. LCA is a tool to measure the impact of every part of the product during its lifecycle to identify opportunities for improvement.

Other responses followed later with different approaches. Biomimicry takes inspiration from nature with its 3.6 billion years of trial-and-error evolution to create innovative products. Biomimicry can inspire in thinking from a nature principles and provide fresh solutions. However, (Fish & Beneski, 2014) argue that evolution has its inherent limitations, is not necessarily the perfect solution and "practitioners of biomimicry need to be aware of the limitations of biology for transition to engineered systems,

NASA, 2012

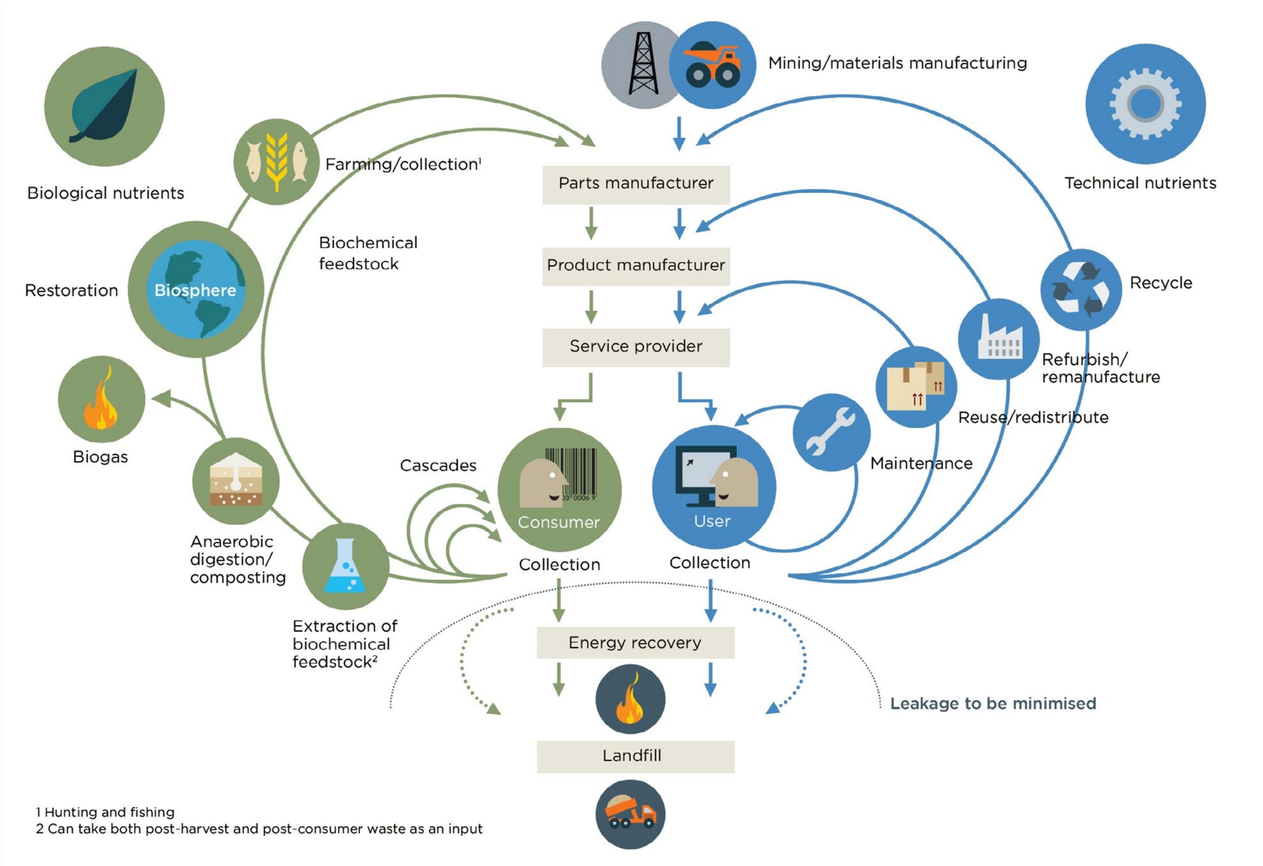


Figure 1 - Circular Economy model (EMF, 2012)

and differences in the culture of biologists and engineers". Cradle to Cradle approaches inspiration from nature in a different way with a regenerative system approach where products are reused over and over. The focus is mainly on closed loops of material streams at EoL via recycling or upcycling and removing toxic elements. Industrial Ecology takes a systemic approach to study material and energy flows through industrial systems and less focused on product design.

1.6 Circular economy

CE takes inspiration from the aforementioned frameworks to present a more economic incentivized framework focusing on resource and value recovery to systematically design out waste. The framework has its roots in biomimicry, industrial ecology and cradle to cradle from a more nature point of perspective and the works of Walter Stahel (Performance Economy) from a more economic point of perspective.

CE describes a model of closing material loops in an economically attractive way. It includes decoupling wealth from resource usage by product life extension, using renewable energy and diversity for resilient and productive systems. The framework can be seen as a solution for the end of the age of cheap resources and fossil fuels.

> *The current economy is "based on a linear 'take, make, dispose' system which relies on large quantities of cheap and easily available materials and energy.*
>
> *The circular economy refers to an industrial economy that is restorative by intention; aims to rely on renewable energy; minimises, tracks, and hopefully eliminates the use of toxic chemicals; and eradicates waste through careful design. The term goes beyond the mechanics of production and consumption of goods and services, in the areas that it seeks to redefine (examples include rebuilding capital including social and natural, and the shift from consumer to user). The concept of the circular economy is grounded in the study of non-linear, particularly living systems.*
>
> ***– Ellen MacArthur Foundation***

In a CE products are designed to get the most value out of the materials by reusing products, components and materials. Products can be made to enter the biological cycle by using organic materials that can safely return to

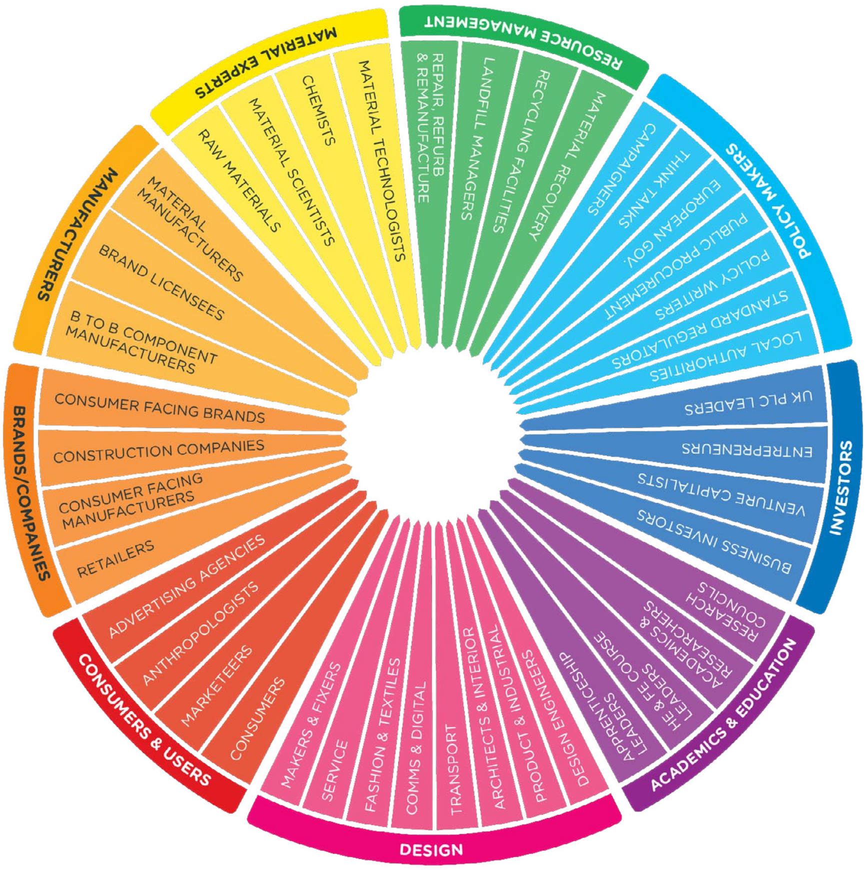


Figure 2 - This circle shows the many different parties involved in a change towards a circular economy. (The Great Recovery)

nature or to enter the technological cycle where synthetic materials are re-used. The Ellen MacArthur Foundation proposes that products in the technological cycle can be maintained, re-used, remanufactured and recycled (see Figure 1). The most value is retained in the more inner circles (maintenance, reuse and remanufacturing) since it are non-destructive processes, in contrast to recycling which is destructive. With non-destructive processes all energy and labor previously added to the parts is retained. In addition CE involves new business models for service systems to incentivize companies to systematically design out waste.

The last few years CE has received a lot of attention mainly due to the successful promotion by the Ellen MacArthur Foundation (EMF). The foundation has support from over 50 companies of which some are very well-known such as Philips, Apple, Cisco, Renault, Ikea, H&M and Coca Cola. At Resource Event in London (world's first CE conference) many big companies were present. From governments and local governments interest is shown for example from the Netherlands, France and China. EMF's success can be explained by working together with McKinsey and Company for their reports (EMF 2012, 2013, 2014) wherein they mainly focus on the business opportunities and offering the reports for free. This focus sets it apart from other schools of thought that find it difficult to get real attention from many companies. The framework gets attention from business and governments for different reasons, but a common rationale is worries about the footprint of human activities. In addition, some businesses experience resource insecurity due to higher raw material prices together with high price volatility. Other companies take interest for finding different business models to deal with changing times. Governments take interest in CE from a job creation and sustainability viewpoint.

1.7 Role of industrial designer

The CE poses a profound change in the fundamental model employed by our current linear economy, which has been very successful for the last century. This requires new and innovative systems of business models and products. Innovation is needed from many different areas like policy, economics, material science, mechanical and electrical engineering and design (see Figure 2). From a product design perspective industrial designers are well equipped to bring different fields of expertise together to design products suitable for a CE.

DESIGNING FOR A CIRCULAR ECONOMY

2. CHANGING BUSINESS MODELS

This chapter describes the interest from Philips in CE and the changes in business models. The description gives a better understanding of the setting in which product design takes place.

> *We believe that customers will increasingly consider natural resources in their buying decisions and will give preference to companies that show responsible behavior—something we are already seeing. Designing products and services for a circular economy can also bring savings to a company. The first impression people always have is that it adds costs, but that's not true. We find that it drives breakthrough thinking and can generate superior margins.*
>
> ***- Frans van Houten, CEO Philips***

2.1 CE motivation

CE gets interest from different parties (governments, businesses and citizens) with different interests (Mentink, 2014). CE is seen by Philips as a way to fulfill their sustainability ambition to "... make the world healthier, more sustainable through innovation and improve the lives of 3 billion people a year by 2025." (Philips, 2014a).

2.2 Circular business model

In a transformation towards CE businesses may need to change their business model (BM) to deal with additional challenges. Closing material loops can be done by the waste collector or the producer. The latter however requires businesses to find ways and develop new competences on how to get the products back from the customer. This leads to new business activities with a whole different set of characteristics (see Table 1). Moving from selling products to selling performance "is the most profitable and most material-efficient" (Stahel, 2006). To capture the greatest value from the products that get reintroduced, reentry loops must be kept small (i.e. maintenance and reuse). Secondly, it is desirable to optimize product design so that the least amount of effort is needed to facilitate those loops. The more effort (transport, labor, energy, material) that is required, the less value a company (profit) can recover.

For the outer loop (recycling) the BM can remain linear when the producer does not take on new responsibilities or activities (for example the Philips Slimstyle,Figure 3). For the inner loops developing a circular business model

BM pillar	Linear / selling products	Circular / selling services
What? – the offer	Cheap, quick, easy, dump	Cheap, quick, easy, reuse or recycle
	Products	Services
	Volume based	Performance based, performance indicators
Who? – customer segments and interface	Transfer ownership	Access over ownership
	Products aren't taken back, especially after warranty	Product take back or service/performance provision
		Increased importance of customer insights and customer relationship with company
How? – activities, processes, resources and capabilities	Take, make, waste	Take, make, remake
	KPIs on production of units (make more = sell more; volume based)	KPIs on performance en service efficiency
		Customers become partners
		Setup of reverse logistics
Why? – revenue model	Pay per product.	Pay per use or performance (hours, km, sheets, etc.)
	Make more = sell more	Make better = sell/gain more

Figure 3 - Differences in businnes model between a linear and a circular economy (Mentink, 2014)

Figure 4 - Philips Slimstyle, a LED bulb that is optimized for recycling that resulted in a cost reduction.

(CBM) can be very complex. It requires looking beyond the company itself by involving all related parties. Is the new CBM profitable, will consumers accept it, will suppliers and partners cooperate, what is the risk, what is the investment?

2.3 CBM complexity

A CBM brings new challenges for businesses such as new competences that are needed and many unknown aspects. A shift to long-term thinking is inevitable. Businesses need to know what and where their product/installed base is and track the lifecycle of every component. There will be more logistics and storage management. It is about predicting the lifetime accurately, what can be reused, how much servicing would be needed, tomorrow's resource prices, if the technology becomes outdated and if the product becomes out of fashion (Boersma, 2013). Businesses need to have a well-established long term strategic view, including roadmaps that include forward and backward compatibility for their portfolio anticipating changing customer needs for the following decades.

A good example of the difficulty of closing material loops are smartphones. Smartphones are highly valuable products and therefore interesting to get back and close the loop, preferably at the reuse or remake level to retain as much value as possible. Some enabling factors for a smartphones in CE are:

- Already service based. Intimate interaction between operator and customer via lease-type of contracts.

However, there are several complicating factors:

- The B2C aspect makes it difficult to get a steady and controlled flow of products (the products are highly decentralized) and to incentivize the consumer to return their old smartphones. Consumers are reluctant and can have an emotional product attachment even though the product is not used anymore.
- Many different actors. The producer gets the components from a myriad of suppliers to make a smartphone that is sold through mobile operators. The producer has little control over the components and little control over the sales with no direct customer contact.
- Smartphones consist of highly condensed and miniaturized components. There is little or no room available to make it modular and enable disassembly.
- Unpredictable reliability of returned smartphones.
- Rapid product development. The smartphone changed a lot in the last few years due to fast changing technology which makes it difficult to make a future proof smartphone in terms of available spare parts and foresee future upgrades. This makes it challenging to design for the inner circles.

- What to do with old smartphones? Recycle and recover the materials, reuse them in developing countries, upgrade or repair? Is the producer responsible and taking their products back or are the mobile operators partly responsible?

A business model for luminaires is less complicated. However, light as a service is not common. Recently, Philips started testing a service based business. The BM is a performance model named 'pay-per-lux' (Philips, 2011) where illumination and not lighting products is key. Philips owns the products and is responsible for the delivered performance. Why is the BM for this case easier to formulate and implement? It has none of the disadvantages of the smartphones example:

- The B2B aspect gives several advantages. Businesses have no emotional product attachment, prefer to outsource and need large quantities of the products. The product location is well known and more concentrated.
- There are fewer actors. The number of parts manufacturers is limited and products are directly sold to the installer or the end-user.
- Luminaires are not highly miniaturized making it easier to disassemble by hand. Luminaires can even have spare room for future upgrades in some cases.
- Predictable quality of products. Luminaires are high up on the ceiling out of reach of people without any movement making it less prone to damage.
- A relatively low level of integration. Although LED technology will change enormously in the coming years in terms of efficiency and type of LEDs, most of the luminaires could remain the same with only a different PCB with LEDs. Smartphones are highly integrated and miniaturized while LED is in its most basic form just power to a LED. LED is also expected to remain the dominant lighting technology for the next 20 years (U.S. Departmand of Energy, 2013).This makes it easier to design for the inner circles.

3. CE MODEL FOR PRODUCT DESIGN

The CE is a relatively new framework that is not yet fully understood by most people as observed at Resource Event in London and at discussions and workshops within Philips. An example showing the difficulty of the terminology is the replacement of a light bulb. Is the action (see Figure 5):

- Re-use of the luminaire?
- Maintenance?
- Repair?
- Upgrade?
- Refurbishment?
- Remanufacturing?
- Reconditioning?

The answer is different for different situations and people. In all cases a light bulb is screwed out and in. From a product design perspective easy disassembly and standardization might be more useful terms. The first part of understanding the CE framework is to have everyone using the same terminology. Therefore this chapter will define the terminology used to answer the question of what circular design is.

3.1 CE model and terminology

Currently the CE model of the EMF (Figure 1) is not all inclusive (1st circle), not fully applicable to product design (2nd circle) and there are multiple interpretations of the terminology used (2nd and 3rd circle) resulting in a misunderstanding and discussion. Therefore, an alternative CE model (Figure 6) from a product design perspective is proposed based on insights gained during the project. In this alternative model, and later in the guidelines, the goal is to get rid of confusing terminology that does not serve a product designer. The suggested terminology therefore tries to simplify and group aspects together in five main topics. Avoiding any overlap is difficult, as all things are related, but a clearer description of circular design can be given.

Before going to the circles, attention needs to be given to the linear line. The linear line downwards with a take-make-waste process is how most of the current economy operates. In addition to material flows the linear line, and the circles, can also be seen as timelines. Products were made to last for a long time, long enough to last several decades. This changed with the introduction of planned obsolescence, making products in such a way they break down or are discarded sooner than necessary. In 1924 Alfred P. Sloan Jr., head of General Motors, suggested to introduce

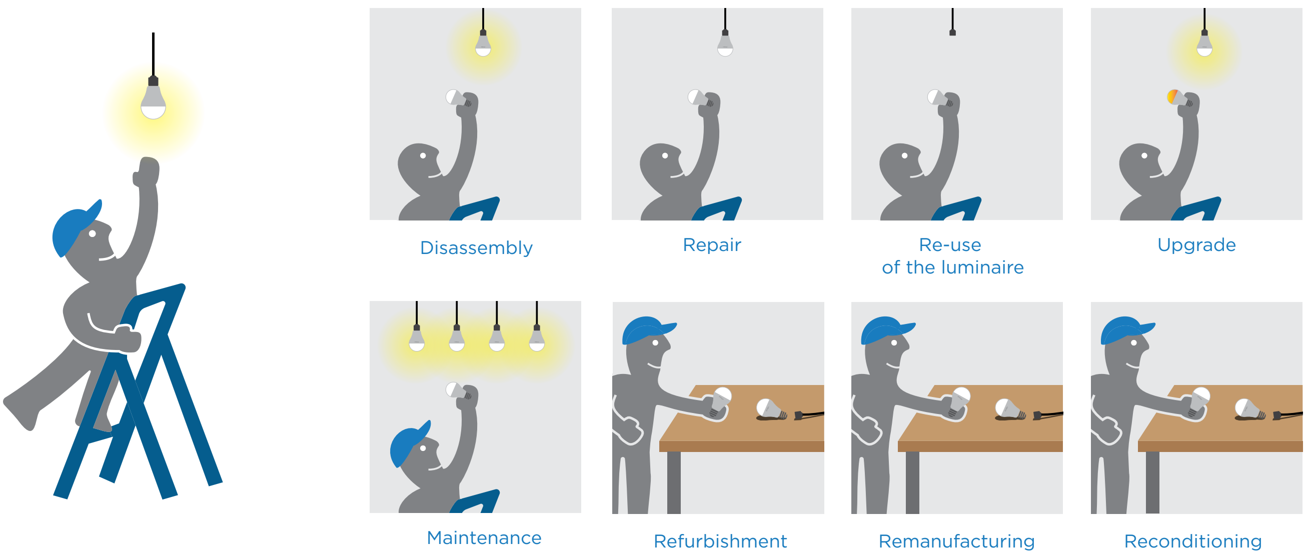


Figure 5 - Different interpretations of terminolgy

Planned obsolescence
Instilling in the buyer the desire to own something a little newer, a little better, a little sooner than is necessary.

– Brooks Stevens

new models with design changes every year to make the consumer want to buy the latest model. This was a new approach at the time that led to GM surpassing sales of Ford in 1931 (Wikipedia, 2014). The term planned obsolescence was eventually popularised by the industrial designer Brooks Stevens at a conference talk in 1954 (Meyers, 2012). In the current economy it has become common practice and logical for many companies to introduce new products every year. Planned obsolescence aided in rapid innovation and has helped companies and the economy to grow. The downside is that it leads to huge amounts of waste of discarded products that are either quickly broken or not desired anymore (but still working fine).

Future proof therefore is about making products that will last long (functional) and used long (desirability). It is the opposite of planned obsolescence and thus slowing down the linear line. This aspect is not clearly mentioned in the EMF model but is relevant to mention explicitly from a product design perspective. CE is about resource efficiency, getting more value from resources in use. The circles are a way to achieve this by closing the material streams. Only focussing on the circles however leaves out the opportunity to also focus on long lasting desirable products as a way to improve resource efficiency. There would be no use for the inner circles when all components last short and when the product is not desired anymore. Future proof thus makes the CE model more complete.

Disassembly is a part of every circle. It is the first step in most actions performed to the product in order to either extend its lifetime or to give a new life to the materials. In general, disassembly needs to be non-destructive if the product or component will be reused. Disassembly can also be destructive in the case of recycling to reuse the materials.

Reuse and 'design for reuse' are often used in CE discussions but ill-defined and thus easily misunderstood. A recycling company and a second-hand shop both can talk about reuse, but will use the word in a completely different way. In the CE model every circle returns to an earlier point in the product life cycle, which is effectively the reuse of a product, component or material. Identifying in every circle what is reused gives more clarity than having its own circle as in Figure 1. Direct reuse by reselling/redistributing (where a product is used for the same purpose without any changes) is part of a business model and not that of product design. Redistribute could be used since a product can be designed to be transported easily (like IKEA's flatpack approach), however this could already be part of standard product design and is not significant to have its own circle in a design perspective.

Service is the reuse or continued use of products and consists of all aspects related to delivering performance for as long as possible in the use phase when the product is at the customer. The word service gives the circle a broader scope than maintenance. Maintenance is about keeping the same performance while it can also be improved with an upgrade.

Remake is the reuse of components and consists of all actions performed when a product returns back from the customer. The goal is to reuse as many components as possible to get a product that can deliver the desired performance. Just a single word 'remake' is used to avoid discussion about the difference between refurbishment and remanufacturing in the EMF model and other terms such as rework, recondition and repurpose. In all cases some level of disassembly is needed and the end result is a working product. The difference is in the amount of effort used, the delivered quality (comparable to as new product or not) and the given warranty. In a service model warranty is not important anymore for the customer, only the guaranteed performance, and becomes an internal risk. The difference of both terms is not always clear, sometimes very small and interpreted different per industrial sector (Appendix C).

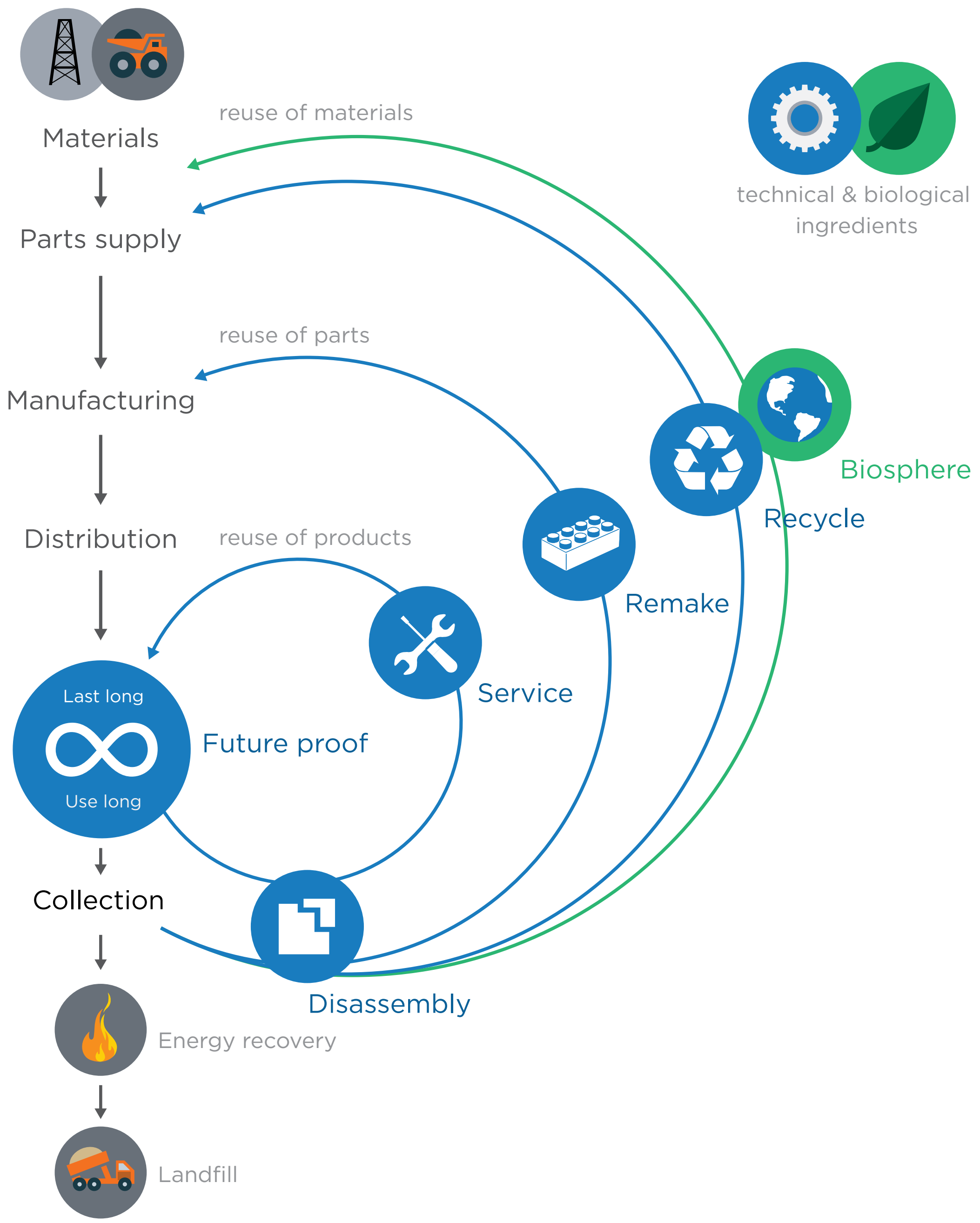


Figure 6 - Adapted CE model

Remake therefore will be used as an umbrella to simplify the model.

Recycling is the reuse of materials and implies material recovery at end-of-life is a necessary condition for resource efficiency that in addition allows recovering any remaining value that a product or component has. This means that, in contrast to all previous aspects, recycling in CE is a mandatory requirement for every product. In recycling disassembly for low-value products is often destructive. Partial non-destructive manual disassembly is also used (Balkenende, 2013) where higher economic yields are achieved due to better material separation. In its essence the word recycling can apply to any circle to recircle. A better word would be material recovery. With material recovery both technological and biological ingredients can be described as the difference in processes is not relevant in the model. The word recycle is still kept since most of the people might have a direct understanding of the meaning, in contrast to material recovery.

The bio cycle with biological ingredients is simplified and placed next to the recycling circle. Figure 1 makes a clear distinction between consumables and durables, with consumables entering the bio cycle. This implies that durable components cannot be made from biomaterials and could lead to discarding them too quickly. Products made from biomaterials could just as well enter the service and remake circle, only at end-of-life the processes are different. From a design perspective the ability to separate and recover materials is important. Just as recycling processes are not shown, all processes biomaterials could go through are not relevant either for product design and therefore left out.

The icons for the service and recycling have been kept almost the same. The future proof icon is the infinitiy symbol to represent the time aspect. In addition it symbolizes the loop of a product that lasts long needs to be used long and if a product is used long it needs to last long. The disassembly icon shows two parts two parts that are disconnected. The remake icon now shows a component instead of a factory to emphasize the product approach. The icon shows a lego block, a component that is a building block to form a product and that shows modularity (see chapter 4.5).

3.2 Defining circular design

As described earlier, the CE model of the EMF can be improved from a product design perspective. The same holds true for the definition of circular design given by the EMF:

Circular design, i.e., improvements in material selection and product design (standardisation/modularisation of components, purer material flows, and design for easier disassembly) are at the heart of a circular economy. (Ellen MacArthur Foundation, 2012)

The EMF definition is not clearly related to the circles, puts the emphasis on the outer circle first (material selection), uses materials twice (material selection and pure material flow) and lacks the long lasting and long in use aspect. With the adapted CE model and the five main topics a better understanding of circular design is given. To answer SQ1 a definition of circular design can be given that is all inclusive, fully applicable to product design, and has a single interpretation of the terminology used:

Circular design, i.e. product design improvements on future proof (long lasting and long in use), disassembly, service (products), remake (components) and recycle (materials) are at the heart of a circular economy.

4. CIRCULAR DESIGN ASPECTS

In the previous chapter a new definition of circular design is proposed with an adapted CE model for product design. The model gives direction on what is important for circular design but remains very general. This chapter lays out the relevant design aspects per topic in more detail and proposes corresponding guidelines.

4.1 Existing CE literature

In the EMF reports some main topics are given on circular design, but those lack detailed information, clarity and are spread throughout the reports. Other CE reports are mostly building the case for a move towards a CE as well, some with more focus on policy change or resources, but a product design focus is missing. The CE toolkit from the University of Cambridge is focused on identifying business opportunities and presents benefits, considerations and case studies. Product design topics are presented as well; however, those can be improved on structure and depth of information. The tool presents a good overview but its actual use in circular design is limited. Further information on how to design for a CE can be found by looking for specific separate topics, for example design for disassembly and design for remanufacturing. The information however is spread out and sometimes overlapping. Modularity can be found in disassembly and remanufacturing literature while disassembly can be found in modularity and remanufacturing literature. Of the several DfX methods remanufacturing is the most encompassing, including disassembly, cleaning, reassembly and testing guidelines. Remanufacturing however is approached from a single product view lacking the system approach thinking of CE. In the following paragraphs all relevant aspects will be explained in detail after which they can be used to put in a cohesive model.

The following paragraphs present all relevant topics and guidelines for circular design, structured according to the five main topics. Criteria are categorized where they belong the most and to prevent a long list of double guidelines later on. For example, a repair can be done by exchanging a module while modules later on are categorized under remake.

4.2 Future proof

As mentioned in chapter 3 future proof is the first step to take into account in circular design. A product that is used for a long time is very resource efficient and keeps the most value that is embedded in the product. All steps that come afterwards are only needed if the product fails to deliver the required performance on either a functional and/or a desirable level. From the very beginning a product should be intrinsically designed to last long and be used long. An intrinsically long lasting design is the step before lifetime extension. For example, maintenance cannot prevent a plastic product to eventually become brittle. Future proof extends the question 'how to design for the circles' with 'how can the circles stay relevant over time'. For example, the heat sink of a LED spot could be reused several times. Although, with improving efficiency of LEDs, the need for a relatively large and heavy heat sink will diminish, making reuse in next generation LED lamps less likely. Designing the heat sink for reuse on a component level that will never be reused would make no sense.

Firstly, to be used long the product needs to last long. The performance on a functional level needs to be delivered for a long time. Functional durability and reliability of the product and its components ensures that failures are less likely to happen. A luminaire needs to keep giving light. In addition a product needs aesthetic durability to keep its appearance over time. A chair that delivers the functional performance seating that easily gets dirty, scratches and discolors fails to deliver performance on an aesthetic level. In the case of energy using products efficiency needs to stay optimal. A luminaire with LEDs can deliver the required amount of light but when the light output degrades over time it might not meet the highest efficiency standards anymore. In that case a functioning product that looks new still might not deliver the desired performance.

Secondly, a long lasting product then needs to be used long. Customer needs and desires are very likely to change over time. Companies can grow, shrink, change their office plan or want a different type of light. Retail for example changes cycle every seven years to improve the customer experience (Matias, 2012). Companies might see the benefit of dynamic lighting to increase employee performance (Philips, 2014c). Office space might be rented by a different company or even the building owner might change. In an increasingly more digital world users might demand to personalize the light with their smartphone. In a CE therefore having a vision about the product portfolio and the world of tomorrow becomes even more important. Roadmaps and strategic plans need to look even further ahead.

Products need to adapt to changing user needs. Adaptability is a step beyond upgrading. Upgrading relates to improving performance or adding performance, e.g. more efficient LEDs or adding sensors. Adaptability also includes changing performance according to the user needs. Maybe the user wants to change from ambient luminescence to a focal glow []. Maybe the luminaires needs to change from a square to rectangular shape.

Timeless design is aesthetic performance on a desirability level. Design classics such as the Barcelona chair do not need to adapt, their aesthetics are still desirable today. Making a product with the latest trend color might be desirable for a shorter time than a black or white version. It can also spark discussion on how to easily change the color in the future when the latest fashionable color really is necessary.

One more factor for a future proof design to take into account is legislation. Legislation will change over time and is likely to become stricter. Since legislation usually takes time before it is passed it is possible to anticipate on it.

> *What is sustainable today might not be sustainable tomorrow.*
>
> ***- Henk de Bruin, Head of Corporate Sustainability Office Philips***

A company can mitigate the risk of not being able to re-use products and components in the future by anticipating future legislation. Some legislation is more obvious such as toxicity of materials. An example is the use of brominated flame retardants (BFR) to reduce flammability. It is possible that in a few years they are banned for use in the EU. An example of less obvious legislation is that of disassembly times for EEE. Currently the EU investigates legislation for removing the PCB from televisions by manual disassembly within 180 seconds (European Commission, 2012). This could be extended later on to include other product categories.

4.3 Disassembly

In a linear economy products are designed for assembly to achieve low manufacturing costs. This can result in difficult to disassemble products or even products that are sealed for life. In a CE this is undesirable. A product that does not fulfill the functional or desirable performance anymore goes to one of the circles where disassembly is needed to allow any actions to recover resources and value. In service and remake it consists of non-destructive disassembly in order to repair, upgrade, adapt or remake the product. In recycling disassembly can be destructive to separate the product in different material streams. In recycling design for disassembly can reduce costs and improve efficiency (Kuo, 2006). In the current linear system recycling is the most common route for electric and electronic equipment (EEE). Non-destructive disassembly therefore is mostly found on a limited scale in products where users often need to disassemble something, for example with removing the battery cover to replace the battery. For the inner loops there is high potential to implement non-destructive disassembly for keeping the most value (Peeters, et al., 2012).

Active disassembly (AD) is a technique that is in development for already several decades, but not widely used. It uses smart materials that respond to an external trigger (heat, vacuum, water or ultrasound waves) to quickly and cleanly break connections. AD could greatly reduce disassembly times in a relatively cheap way and aid in an automated disassembly process. Its use is limited mainly due to a lack of standardization of methods and an infrastructure for a steady flow of products. Another disadvantage is possible damage to electronics. For luminaires AD is less interesting since most of the disassembly would be preferred to take place at the location of the luminaire with limited options for AD tools making it difficult to apply.

Optimizing product disassembly can best be done at the design stage where 80-90% of disassembly gains are determined (Desai & Mital, 2003) in contrast to optimization of the disassembly processes. In literature the design for disassembly guidelines mostly focus on fasteners, product architecture, modularity and material separability.

Connections need to be quickly and easily disconnected, either in a non-destructive way for service and remake or a destructive way for recycling. The literature mostly discusses fasteners (Peeters, et al., 2012) (Mital, et al., 2008) as for keeping a product together. Replacing the word fasteners with the more inclusive term connections removes the restriction in limiting thinking to fasteners. Connections can also be made without fasteners by a form fit or welding. The product architecture facilitates the ease and speed of disconnecting those connections.

Modularity will be discussed later under remake and material separability under recycling.

4.4 Service

Service is the first circle and consists of all aspects related to delivering performance for as long as possible in the use phase when the product is at the customer. The word service gives the circle a broader scope than maintenance. Maintenance is about keeping the same performance while it can also be improved with an upgrade.

Service consists of all actions performed to the product in order to keep it in working condition. This includes cleaning, repair, upgrade and lifetime prognostics. Cleaning can be performed in order to keep a product clean without any dust or dirt. Cleaning can improve the aesthetic performance and increase the efficiency in a product. For example, in luminaires dust can reduce the lumen output by up to 20%. In literature maintenance is usually separated from repair, they can mean different things for different sectors. With maintenance on a bicycle the chain can be lubed, the brakes and tire pressure can be checked to prevent trouble. With repair on a bicycle a part that is not performing well or is broken can be replaced. In other cases such as luminaires however, there are no parts to which an action can be performed to prevent failure other than replacing a part. In those cases maintenance and repair consist of the same actions. Repair as a way of keeping a product in working condition is therefore similar to and grouped together with maintenance. As service is performed in the use phase it is beneficial to be performed at the location where the product is used. On-site servicing avoids the need for logistics of products. Depending on the product and context it can be in the office, outside the office, or even outside the building in a mobile upgrade container. A luminaire that takes 15 minutes to upgrade to newer LEDs next to the office desk could be expensive to upgrade, too obtrusive and cause too much downtime for the customer. The next step in optimizing service is to include monitoring of the performance status and quality of the product. This allows for timely servicing to be scheduled and done in a more effective way. Instead of preventively replacing all luminaires only those that are likely to break down can be repaired at the appropriate time.

Remake

Remake follows after service when the product needs more extensive actions to order to meet functional and desirable needs. While most information is present in literature on remanufacturing, additional information can be found from disassembly and modularity literature is used. The remanufacturing process usually consists of the following eight steps (Sundin, 2004):

- Collection of core
- Inspection and identification of faults
- Disassembly of whole product
- Cleaning of all parts (and storage)
- Reconditioning of parts (and replacement with new parts where required)
- Reassembly of product
- Testing to verify the product functions as a new product

These steps can be translated into the following main product design characteristics: disassembly, cleaning, remanufacture and assembly (Ijomah, et al., 2010).

The term ‘core’ is commonly referred to in remanufacturing (Sundin, 2004) (Gray & Charter, 2008) (Ellen MacArthur Foundation, 2013) as a re-usable product or component that retains significant residual value at end of life and is robust and relatively easy to return. A core could be a

Figure 8 - Example of a remanufactured Engine (Bosch)

single part or an assembly of multiple parts. Core denotes the presence of a single part, the central, innermost, basic or most important part that is the essence of a product. In addition it implies that components other than the core are not to be taken into account for remake. With the aim of CE to be resource efficient the focus could be extended to the reuse of as many components as possible. The term 'module' could be used instead to describe a single component or an assembly of components to perform a single or multiple functions. In a luminaire the reflector could be a module consisting of a single component to shape the beam. The driver could be a module that is a complex assembly of components to convert power and drive the LEDs. The term 'module' implies it to be a part of a product without denoting any importance. The use of modules can easily be translated to modularity, a product design characteristic that is identified as related to the remanufacturing process (Ijomah, et al., 2010).

Modularity has a multitude of potential benefits such as "economy of scale, increased feasibility of product/ component change, increased product variety, decoupling risks, the ease of product diagnosis, maintenance, repair, and disposal, and ease of reuse, reduction of waste, and recycling of products" (Huang, et al., 2011). With modularity obsolescence will relate to the components instead of the whole product. Components could be grouped in separate modules that make sense for the use case. As observed in an outdoor luminaire workshop (Philips, 2014d), the LED engine can be made into a separate module, but in practical use it might never be exchanged. A higher level of modularity could cost more where each module needs its own enclosure and connection. The higher costs could be offset by gains in other areas, for example with lower maintenance costs (Ijomah, 2009).

Modularity also benefits the stock and delivery time. For example, the PowerBalance comes in several lumen packages, color temperatures and housing form factors resulting in a large number of luminaire types. If the LEDs are a separate module to be added at the last moment lower stock would be needed. If one lumen package doesn't sell well there is a lower financial risk if not the whole product but just the separate LED module is obsolete.

For luminaires the modules could be divided in four groups: LED, driver, housing and optics. In some cases the optic is the housing or almost indistinguishable and LED-board and driver can also be integrated.

Figure 9 - Example of modules per fucntion (Sony F55)

4.5 Recycling

Although not the focus of this research, recycling is addressed to give a complete overview. Recycle is the reuse of materials to recover the basic resources and any remaining value. To improve the recycling rate for electronic products and thus successful material recovery, three main areas can be identified (Balkenende, et al., 2011): materials, electronics and connections. The diversity and type of materials influence the achievable recovery rate. Although electronics are actually a complex mixture of materials, they are mentioned separately due to their distinctive characteristics. Electronics are highly complex sub-assemblies with a relatively large amount of valuable materials. This has led to separate recycling processes specifically for electronics. Connections influence the separation of the different materials. When recyclable materials are used there still could be losses if they are connected with dissimilar materials. While guidelines on non-destructive connections also apply for recycle, guidelines for connections in recycle are destructive and therefore only applicable in recycle.

4.6 Guidelines

Figure 11 presents the combined main topics of the guidelines. Appendix B shows the complete list of combined guidelines from (Balkenende, et al., 2011), (Desai & Mital, 2003), (Hata, et al., 2001), (Hultgren, 2012), (Ijomah, et al., 2010), (Mital, et al., 2008), (Mulder, et al., 2014), (Peeters, et al., 2012), (Peeters & Dewulf, 2012) and (Sundin, 2004).

In front of the guidelines the circular design model with a short explantion is mentioned to put the guideline list in the right context. As mentioned earlier, disassembly is applicable to all circles. This is represented in the list by a vertical line dropping down from disassembly spanning service, remake and recycle. A distinction is made at recycle where disassembly could also be destructive.

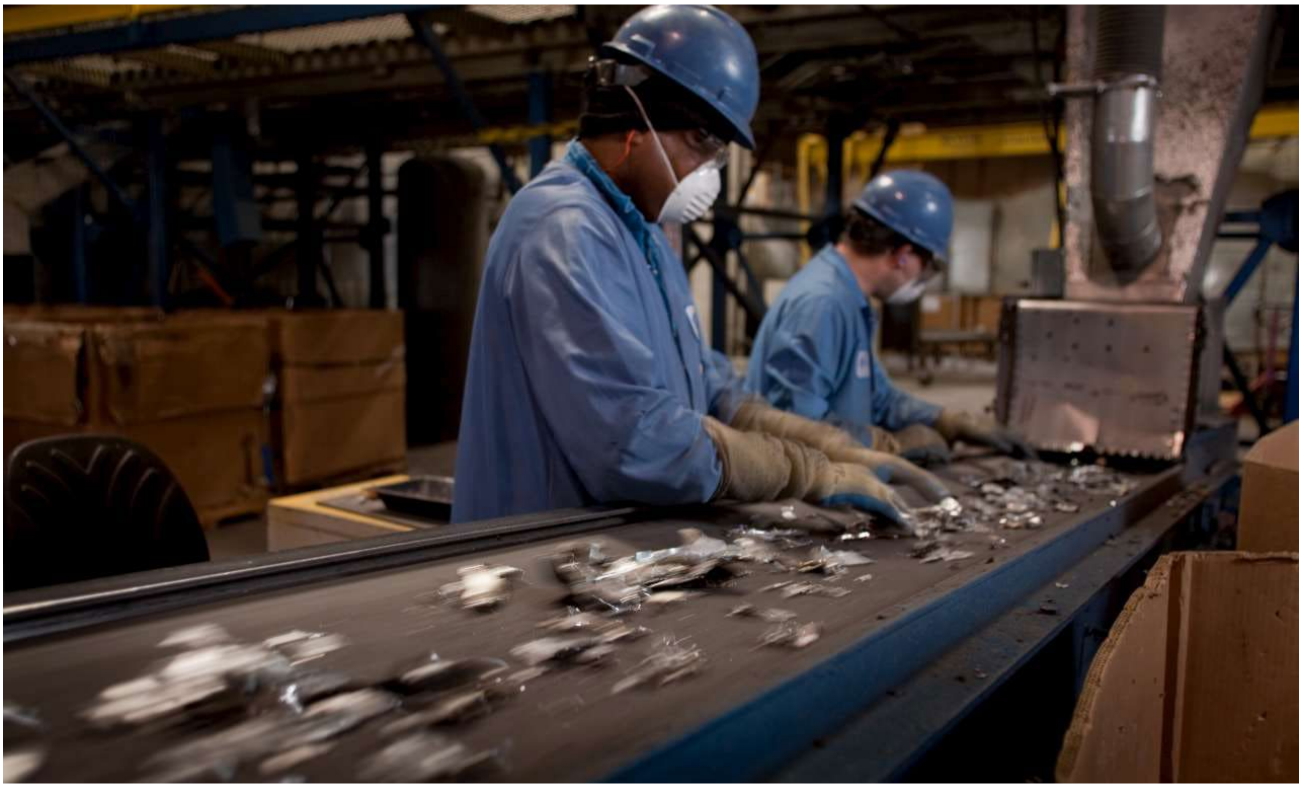


Figure 10 - Workers sift through chopped up smartphones and computers at an e-waste recycling plant. (Dell)

Circular Economy

Design systems and products to recover resources and value

Strategy	Scope	Aspect	Guideline
Futureproof – Last long, use long		Last long	Performance
			Reliability
			Durability
		Use long	Roadmap fit
			Upgradability
			Adapatability
			Timeless design
			Anticipate legislation (e.g. toxicity, recyclability, disassembly time)
Disassembly – allow to service, remake and recycle		Connections	Quick and easy disconnect
			Limit use and diversity of fasteners
			Limit use and diversity tools
		Product architecture	Simplify product architecture
			Allow ease of acces to components
			Clarity of disassembly sequence
Service – Reuse of products	only non-destructive	Maintenance	Ease of cleaning
			Ease of repair / upgrade
			Allow onsite repair and upgrade
		Lifetime prognostics	Online monitoring for quality, testing, maintenance and billing
Remake – Reuse of parts	only non-destructive	Modularity	Use modular components
			Standardize interfaces
			Back- & Forwards compatability
		Reliability assesment	Allow for easy read out of components
		(Reverse) Logistics	Product can easily be returned
			Spare part harvesting
			Local production
Recycle – Reuse of materials	destructive & non-destructive	Materials	Avoid the use of (non-compliant) coatings
			Limit the number of different materials
			Only use materials that can be recycled
			Use preferred/pure materials
		Electronics	Get PCB out in one piece
			Easy/fast detection of materials
			Use SMD components
		Connections	Avoid fixed connections
			Break down by (shredding/disassembly) to
			Pieces of uniform composition
			Pieces of relatively large size (>1cm)

Figure 11 - Circular Design Guideline List

5. DESIGN TOOLS

The guideline list groups and orders all relevant topics for circular design with corresponding guidelines. The guideline list is a tool that can be used in the design process; however, it has its limitations. The list is extensive and thus might not be inspiring for designers in the idea generation phase, does not show a way towards fully circular design and lacks a way of comparing products on circular design. The guideline list is suited to be used as the reference on which other tools can be based upon. This chapter shows how the guideline list can be translated to other tools that might be easier or more useful to use depending on their application in order to answer SQ3.

5.1 Other CE tools

As described earlier, the CE is a relatively new framework with a limited amount of information on circular design.

The Closed Loop Calculator from Kingfisher asks 10 questions to calculate in four categories (production, use, end of use, reduce waste) how closed the loop is. The tool can be used to evaluate existing products and business practices and is intended as a simple approach to be used by anyone. As only four questions relate to an aspect which a designer has influence on, are not ordered next to each other, and their connection to the CE model is unclear, its use for circular design is limited.

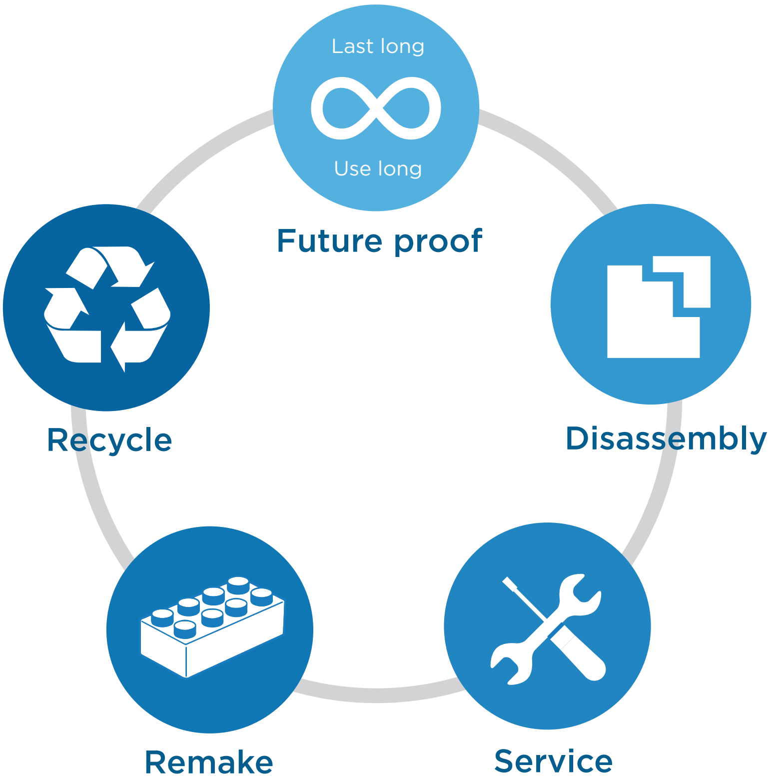
The CE toolkit is very detailed, presenting an introduction, benefits, considerations, product design guidelines and case studies. The toolkit also has an assessment tool that asks 33 questions, with a 3 point scale for answering, and shows the potential for improvement in seven categories from low, medium to high. The tool uses the same terminology as the EMF and thus has the same limitations. The assessment tool asks both business and product questions next to each other, has no clear connections to the guidelines and the guidelines could be improved on ordering. The depth of information makes the toolkit a valuable tool, but could be improved for circular design and use in the design process.

5.2 Circular Design Vision

The circular design approach described in chapter 3 and 4 can be represented in a quick overview, the Circular Design Vision (Figure 12). It consists of two parts, the five main topics and a corresponding design vision. The five main topics with their icon have the same order as the Circular Design guideline list and positioned in a clock wise direction. The same order and colour usage is used in the design vision. The design vision puts the five main points in context. The tool could be used as a quick introduction, a discussion tool, a tool used in a workshop for a short design exercise or as a memory aid during the design process.

5.2.1 Testing

The tool has been used by an intern at Philips Lighting and in this project at the beginning of the luminaire design process. In both cases the tool was viewed as a useful overview to use during the design process. The intern mentioned she viewed this tool as more useful than the other tools. At the start of the luminaire design process this tool and the guideline list were the only tools. The Circular Design Vision not used anymore in a later phase when the Circular Design Spider Map was developed. Further research needs to be done to test the usefulness of this tool in the proposed applications.



make it	future proof	for endless performance and adaptability
with design for	disassembly	to allow
easy	servicing	for optimal performance
modular design to	remake	products
and optimizing for	recycling	at end of life

Figure 12 - Circular Design Vision

5.3 Spider Map

For a nice compromise between the guideline list and the Circular Design Vision a spider map (also known as radar chart) can be used (Figure 13). Words are placed along the axis, instead of a multitude of data as input, to show a general direction. This allows for the tool to be used in the first phases of the design process where no detailed information is available yet. The Circular Design Spider Map could be used to discuss the ambition of the project, show a way towards circular design and to compare with other products. The tool allows for users of different backgrounds to use the same terminology.

5.3.1 Ordinal axis

The Circular Design Spider Map uses the five main topics from the guidelines list as the axis and follows the same ordering as the Circular Design Vision in a clockwise direction. Each axis has the same amount (four) of criteria for a good balance. The circular design spider map uses an ordinal scale. For the Circular Design spider map the ordinal scale is more applicable and used on purpose to present a way towards the future with a circular economy. The ordinal scale allows for the ranking of current and new products with respect to how well they are suited for a circular economy. Using a nominal scale would assume a ranking in circularity is not needed and is more applicable in a future where everything is circular. The axis in the ordinal spider map start at the inside with a linear economy and gradually go to a circular economy at the outer circle. The ordinal scale of the axes ranks the criteria but does not show the relative degree of difference.

5.3.2 Criteria

Criteria near the centre of the spider map are related to linear products and are undesired; criteria in the middle and outer circle are desired and can be cumulative. Efforts are made to define the criteria such that they and their axis are self-contained and distinct, allowing to rank high on one dimension while ranking low on another (Garvin, 1984). For example, on the service axis the criterion repair and upgrade does not include the word easy. Easy repair and upgrade would put the focus on the action of easy disassembly instead of the ability of repair and upgrade. Self-contained axes thus aid in thinking per axis and prevent overlooking some aspects. Although one axis can benefit the other, this does not necessarily mean that is always the case. Modularity can benefit the ease and speed of disassembly, however, in the case of the PowerBalance (see chapter 7.1) this does not apply.

5.3.3 Testing

The Circular Design Spider map has been discussed with several people (designers, engineers, sustainability manager, project manager and a scientist) within Philips to get feedback for improvements. In addition the spider map has been used at Philips in one workshop where I was present and two workshops where I was not present. In the first workshop with eight participants the spider map was used to discuss the ambition of a new product. The tool made all participants use the same terminology and worked as a discussion tool and memory aid to which the participants referred back to. For a cradle-to-cradle customer the recycle axis is the most important axis while for a product manager in some cases future proof is more important. In another workshop, with engineers in a factory setting that used it to evaluate products, showed that the spider map is not applicable for every setting. Engineers are more used to numbers and precise data and thus found the spider map too abstract. They preferred a measurable way of scoring products so results across factories can objectively and consistently be compared.

5.3.4 Alternative spider map

Based on the first workshop an alternative spider map with an extra axis was explored (Appendix C). The extra axis ‘Energy Use’ allows the spider map to be used more from a marketing perspective and received positive feedback from several people within Philips Lighting. In lighting energy use has the most environmental impact during its total lifetime and is the main selling point for LED lighting. Including it in the spider map can show that customer demand in relation to other aspects of sustainability. Energy use is used as ‘use renewable energy’ as one of the five main topics of the EMF view on CE and could be considered as a resource. It is therefore not strange to include in a CE spider map, however, from a circular design perspective it is less applicable. Energy usage cannot aid in closing material loops, only reducing resource use of energy. Influence of

© 2014 Philips Design Lighting

Figure 13 - Circular Design Spider Map

the designer is limited to the efficiency of the product and cannot decide if renewable energy is used (or only by applying solar panels to every product). Only efficiency would be eco efficiency, not CE. Concluding, the energy axis is not preferred in a CE spider map.

A second alternative was explored with all of the sub categories of the five main categories (Appendix D). This alternative was explored to see whether or not the five axis spider is a too simplified representation of the Circular Design guideline list. In the end this alternative is not fully developed as it is expected it will be too detailed to be useful in the intended application of a workshop setting.

5.4 Scorecard

A scorecard is another approach that is explored for use in circular design. The developed scorecard is an excel file based on the guidelines list with dropdown lists for scoring every topic. For all five main topics an average score is weighted and represented in a spider map as well. Some topics have an objective scale (e.g. the amount of tools needed) while most have a subjective 5 -point Likert scale. The scores are not absolute and thus can only be used for a qualitative comparison between products. The scorecard has more detail to score products and the final scores can be justified more objectively. Compared to the CE spider map this tool is more suitable for scoring existing products or final developed products and to create awareness for several improvement opportunities for those products. That makes the tool perfect for managers and engineers to measure, track and communicate results. As a design tool it is however less suited.

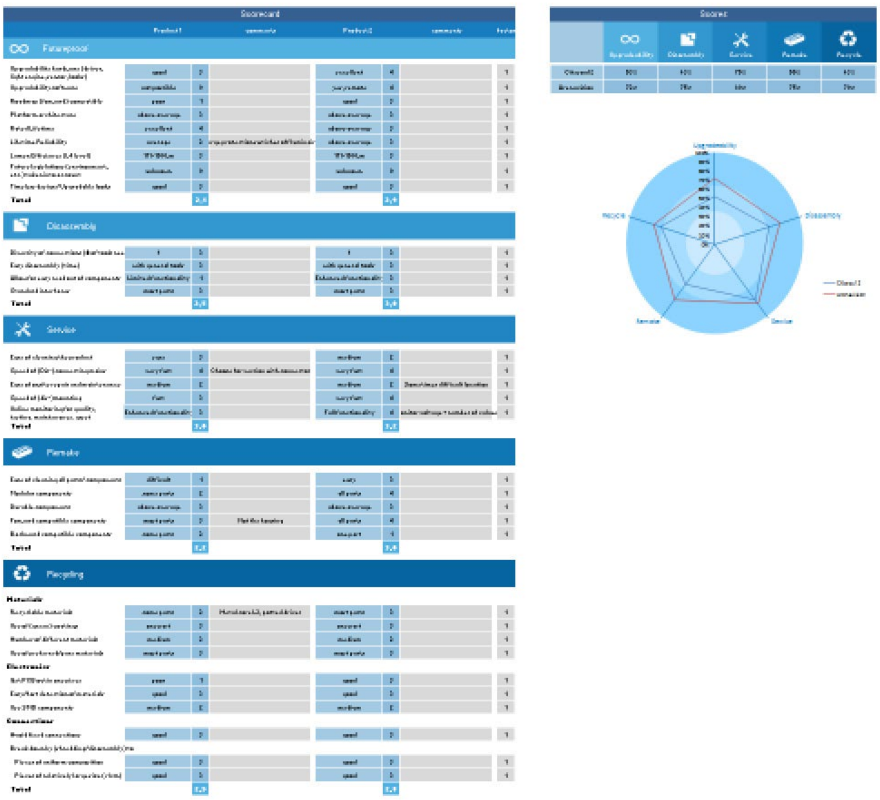


Figure 14 - Circular Design Scorecard

LIGHTING AND CIRCULAR DESIGN

6. UNDERSTANDING LIGHTING

For developing and testing the circular design approach, LED luminaires are used as a case study product. This chapter describes the LED technology and developments in order to understand opportunities and barriers for a circular luminaire.

6.1 Luminaire

A luminaire is the whole product that holds a light source. This includes the housing, electronics (driver and wiring) and optics (reflector, lens). LED luminaires usually are sold as one product, including a non-removable light source. Professional luminaires are luminaires used in office, retail, industry and outdoor applications. The term luminaire will be further used to refer to professional luminaires.

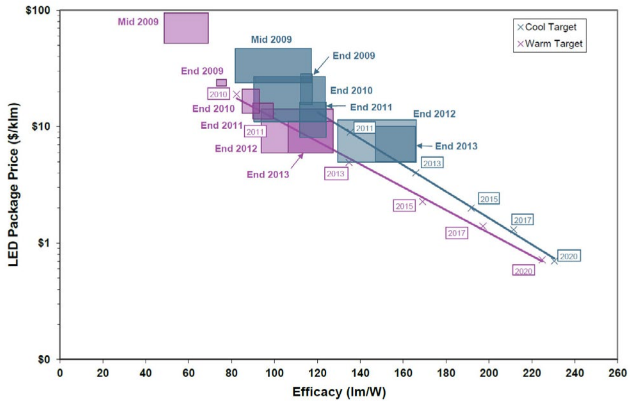


Figure 15 - Price-efficacy developments for LED packages (U.S. Departmand of Energy, 2014)

Light Emitting Diodes (LEDs) are very energy efficient low voltage light sources that require DC power. LED luminaires have an additional benefit of LEDs emitting light in one direction leading to a lower loss of light. LEDs have a very long useful lifetime, in professional luminaires often up to 50.000 hours. LEDs rarely break down, only their lumen output will decrease over time. The useful lifetime is defined as a percentage of remaining light output. For example, a luminaire can be specified at L80B50 for 50.000 hours. L80 refers to 80% of remaining lumen output, B50 refers to a maximum of 50% that will not meet the L target. LEDs are smaller, generate less heat and are more energy efficient than other lighting technologies. Furthermore, LEDs have the potential to create any color of light and desired color quality. A single or multiple LEDs together with wiring is also referred to as a LED module (Zhaga, 2014).

The driver is the electronic part that controls the LEDs. It converts AC power to DC power, regulates the power delivered to the LEDs and protects the LEDs from voltage fluctuations. The AC to DC conversion part could be omitted when a DC power source is used, for example with solar power, power over Ethernet, power over USB and batteries. Fully electronic drivers can also handle information from a range of different inputs to dim the LEDs or change colors. Drivers are available in several form factors. The form factor used most in indoor luminaires is a linear form factor. The height and width are fixed while the length varies depending on functionality and specifications.

6.2 Critical Raw Materials and LED

One of the drivers for a CE is resource scarcity. Due to globally increasing levels of GDP and a lower availability of resources this is expected to become a major threat for businesses. The main issue for lighting products is not the physical scarcity of materials but economical and geopolitical criticality (Balkenende & Beasjou, 2009). Short-term mismatches between supply and demand result in high price volatility. As an example, China produces up to 97% of global production of rare earth elements and increasingly needs it for domestic use. Especially in electronic products many different rare earth elements are used, often with medium or low substitutability.

For LED luminaires of Philips these issues are not critical (Balkenende, 2013) as the amount of rare earth elements used in LED technology is very low, a factor 100 lower compared to CFL (Balkenende, 2013). The phosphors then contribute insignificantly to the costs of a luminaire.

6.3 LED development

The development of LED lighting goes much faster than any of the previous lighting technologies. LEDs are

Figure 17 - Zhaga specifications are grouped in 'Books'

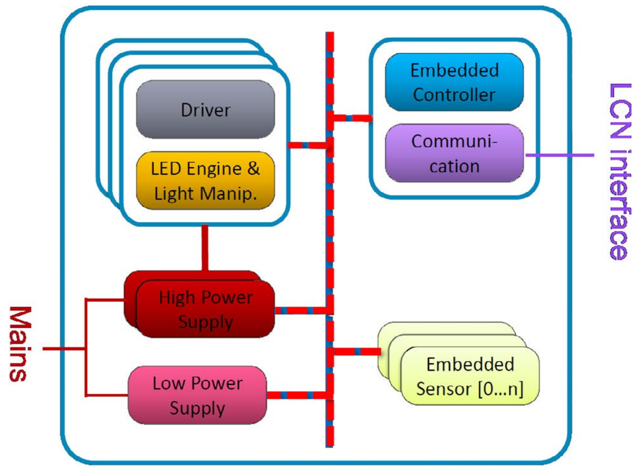


Figure 16 - EnLight: Intelligent Lighting Architecture

semiconductor based and can develop at a speed typical for the semiconductor industry (doubling of all kind of performance parameters every few years). The change and progress in the last five years has gone faster than anticipated (Product Architect, 2014). Innovation goes so fast that there is low standardization in the product architecture. An example is the Slimstyle (Figure 4) released in January 2014 at the US market, wherein the LEDs and electronics are differently configured and the design strongly deviates from the usual bulb shape, allowing more efficient heat dissipation and thus making an aluminum heat sink obsolete. This results in reduced material usage and lower costs, while recyclability improved as disassembly (in shredder) was taken into account in the design. Another change over time is the type of LEDs used on a PCB that changed from high-power to medium-power. The size of the PCB might remain the same, while containing more, lower power LEDs and thus requiring the driver to use a different voltage. The fast changing technology creates much shorter product development cycles while at the same time the product life is has increased significantly. With a LED light source that has a long useful lifetime of up to 20 years it is not as important anymore to be able to change the light source. This has resulted in many luminaires with LEDs that are not easy to replace (if a replacement is available at all in 10-20 years) and some even being sealed for life.

Prices of LED have dropped significantl in the last few years and will continue to drop further (Figure 15) while effiencies have increased. This allows for an upgrade to tuneable color recipes to become more affordable. For two different color temperatures twice the amount of LEDs are needed (warm and cool white), three times as many LEDs for full color. In five years LEDs are expected to reach their maximum of commercially achievable efficiency. From then on offering an upgrade to even more efficient LEDs is not that significant anymore. Replacing already very energy efficient LEDs with 10% more efficient LEDs does not have a significant impact and might not be paid back in energy savings.

6.4 Standardization

For a working CE model it is important to have replacement parts available for a long time. If a LED module needs to be replaced in 10 years there has to be a LED module with the same interface and a form factor that will fit. When this is standardized there is no need to keep replacement parts in stock for 10 year old technology.

Zhaga is an industry consortium that develops specifications for professional LED light sources to enable interchangeability (Figure 17). The specifications define the interface between the LED module, the electronic control gear and the luminaire and are divided in 'books' for different applications. An interface consists of a mechanical, thermal, photometric, electrical and control component. Although specifications are now standardized there still are many different standardized sizes. For example in book 7 there are seven different sizes. EnLight is a consortium that develops specifications for lighting electronics, drivers and controls (Figure 16).

6.5 Digitalization

The digitalization of light opens up endless possibilities. Luminaires can be connected to the internet for remote monitoring, controlling and sending software updates. With an intelligent lighting system users can control the luminance and temperature with their smartphone while the building manager gets detailed information of occupancy and temperature at every location (Philips, 2013). Adding sensors to every luminaire creates a higher resolution of possible data. The occupancy cannot only show if there are people, but also the amount of people that are present. The building manager could decide for example to turn off the lights at a low occupied area to create higher occupied areas. This can result in savings on lighting and heating and as a way to stimulate interaction between people. The luminaires can even be controlled by an app on the smartphone by the employee to tune the light to their personal preferences. The Philips Hue range is another example where the lights at home are controlled by the smartphone. Developers can even create apps for Hue to use it in new ways that extend the functionality beyond what was available in the beginning. Coded lighting is another technology where information is send with light by variations in invisible high frequency light changes.

Figure 18 - Philips Fortimo Driver and LED module

7. PRODUCT ANALYSIS

In this chapter, a set of five indoor luminaires is evaluated. The luminaires are disassembled to understand current luminaire design and to identify opportunities for a circular luminaire. The luminaires cover a range of different applications to get a broad perspective of different product architectures.

7.1 Products

The Powerbalance is a recessed luminaire for use in offices. With 115lm/W and a UGR rating of 19 it is the most efficient office luminaire on the market. The unified glare rating (UGR) is an important factor for office luminaires. The UGR number indicates how much discomfort is perceived by a person.

The Powerbalance can be disassembled by removing 4 screws, the rest can be done by hand. The product is designed as part of a product family and therefore has some modular properties. The luminaire consists of 4 modules that can form a square or rectangular shape. In each module are 2 LED boards, 2 pairs of cups and 4 diffuser plates. Disassembly is straightforward and for most part easy. Getting the modules out of the metal frame is difficult and takes some time. The use of snap fits make assembly very quick and easy, but not disassembly.

15 minutes to disassemble, replace LED modules and reassemble.

The StyliD is a spot. A key characteristic of a spot compared to other luminaires is that it is a point light source. Light comes from a very small area forming a focused beam. This requires LEDs to be positioned next to each other at close distances and thereby generating enough heat to require a relative large heat sink. In addition it requires the use of a thermal paste/pad for good thermal conductivity to the heat sink. In the foreseeable future a heat sink will remain necessary for spots. With more efficient LEDs the size of the heat sink can be reduced. However, it is difficult to predict how the thermal management of a spot will develop. Other solutions for heat dissipation might also be used as shown by the Slimstyle. The heat sink in the StyliD is made from aluminum and can be reused several times, but it is undesirable to transport and reuse heat sinks that are expected to become over dimensioned or obsolete over time. This makes recycling likely the only and most suited option for the heat sink.

Modularity is limited to changing the beam angle reflector, which can be done easily without tools. The complete head cannot be removed from the box (that contains the driver) and the bottom side of the box that is available in multiple colors is time consuming to change.

The TTX Led industry is a LED replacement for use in the Maxos and TTX trunking systems. Its applications are industry and retail. For this luminaire different light distributions are available (narrow, wide and double asymmetric). The double asymmetric beam for example is used in supermarkets aisles for uniform lighting of the products.

The Pacific LED is a waterproof luminaire for use in indoor and outdoor applications such as parking garages. Like the TTX LED Industry, Fortimo LED boards are screwed to a metal base. The whole metal base with LEDs and driver is encased by polycarbonate housing. Getting the inside assembly out of its encasing is easy and quickly done without tools. Further disassembly requires a tool and time.

The Modular SL mini poly is a suspended luminaire for use in offices and homes. Suspended luminaires are often located at eye height making aesthetics very important. Getting to the LEDs is easy by clicking out the diffuse plate. This can be done with a sucker, a screwdriver is possible as well but has the risk of damaging the aluminum. The Zhaga standard is used but replacing LED modules is difficult. Four fortimo LED PCBs are screwed to a metal plated that itself is screwed to 3 cables that connect to the housing for grounding. On the bottom there is a glue strip to keep the cables to the LEDs in place. The cables to the driver can be detached by hand easily but the driver itself is attached to the housing with two screws.

Figure 19 - Philips Powerbalance

Figure 22 - Philips StylId Compact

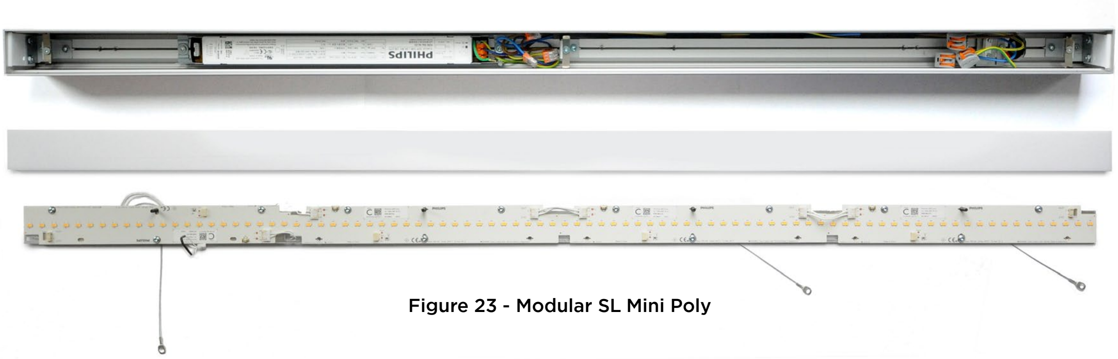


Figure 23 - Modular SL Mini Poly

Figure 20 - Philips TTX LED Industry

Figure 21 - Philips Pacific LED

7.2 Value

Figure 24 shows the average value of different components in luminaires. It indicates which modules are most interesting to keep and what value can be kept when replacing one module instead of the whole luminaire.

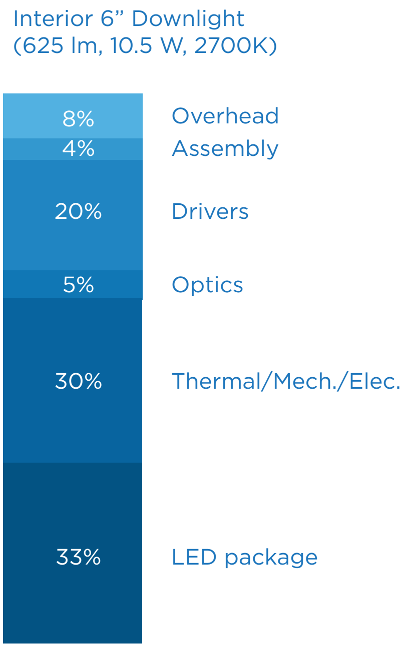


Figure 24 - Cost breakdown of indoor luminaire (U.S. Departmand of Energy, 2014)

7.3 Observations and learnings

Disassembly of the products gives a good insight in how they are made. Several key learning points:

- In all luminaires the LED and driver were difficult to access or unclear how to acces
- All luminaires used the Zhaga standard
- Some drivers had fixed wires, some had removable wires
- Modularity does not imply quick disassembly
- No screws does not imply quick disassembly
- Driver was placed with a form fit in the stylid
- LED module does not have to be screwed to metal
- Heatsink is not always required (PowerBalance)
- JST connection for LED module is sometimes used
- Not all luminaires completely non-destructive to disassemble

8. CE OPPORTUNITIES

Based on the LED developments and product analysis opportunities for a circular luminaire can be determined.

8.1 Service model

A service model could be beneficial for a circular product. When ownership remains with the company there is a strong incentive to reduce total lifetime costs. As described in chapter 2.1 the conditions for a B2B luminaire in a service model are favourable. In the service model long performance with low maintenance cost is desired.

8.2 Design

In the case of luminaires the emphasis is on the functional performance of giving light. If there is no light the product is not a luminaire anymore. A luminaire in its most basic components can be divided in four main parts:

- Driver to power the LEDs
- LEDs to create light
- Optics to spread light
- Housing to connect everything together

The first two parts are the key ingredients to generate light. To keep, guarantee or improve the functional performance they need to be replaced easily. The LEDs need to be replaceable for changing to more energy efficient LEDs, when light output has depreciated too much or for a different color or quality of light. The driver needs to be replaceable mainly due to possible failure and to a lesser extent with a change of LEDs requiring a different voltage or a change of energy source (AC or DC). These actions are repair and upgrade and fit in the service circle. Other upgrades could be the addition of sensors for intelligence.

8.3 Program of requirements

A program of requirements is a common tool used in the product development process. A list of requirements is made based on user and market insights to ensure a successful final product. The requirements are objectively measurable and are either met or not met. For the development of a CE luminaire no specific user or market segment was chosen. This allowed for exploring a wide range of opportunities for indoor luminaires to identify an optimal CE solution. The Circular Design Vision was used as an alternative to the program of requirements.

DESIGN OF A CIRCULAR LUMINAIRE

9. CONCEPT DEVELOPMENT

This chapter shows the application of circular design on the design of a luminaire.

9.1 Ideation 1

Several of the evaluated luminaires were explored for a circular redesign. The presented ideas show the application of some of the previously mentioned opportunities applied in a product. Additional sketches can be found in Appendix G.

As described earlier the StylID does not have the best potential for a CE. Besides service or remake the heat sink, some ideas were explored to see what is possible:

- As a non-recessed luminaire the appearance matters, the bottom plate of the driver housing needs to be easily changed
- Make the head removable for a quick change to a small or large head
- Reduce the size of the driver housing such that the driver is not encase anymore. The driver then is clicked in.

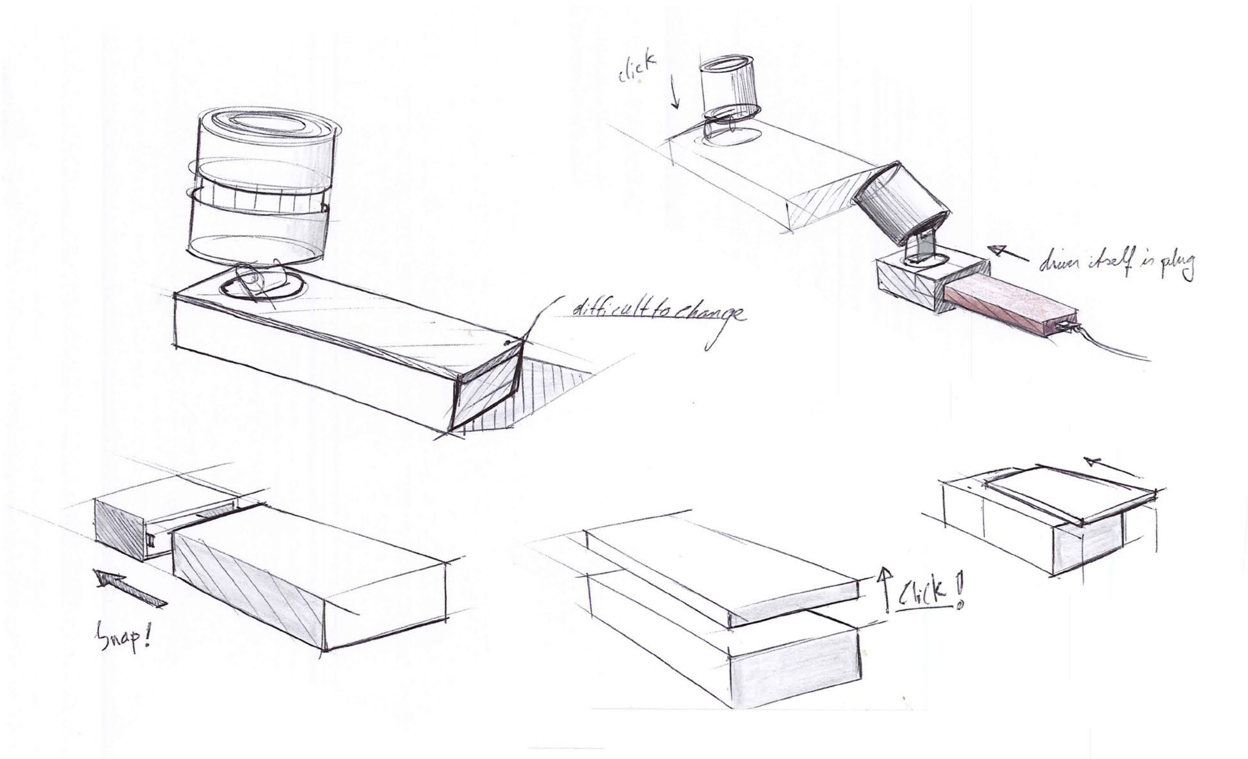


Figure 25 - Ideas on a spot

The PowerBalance is already designed with modularity in mind, however the LEDs and driver are time consuming to access. Some ideas for increased modularity are shown in Figure 26.

Some of the ideas shown:

- Access LEDs from the back
- Slide out the LEDs
- Making each cup a single module, increasing form freedom and thus extend the amount of possible light applications.
- Changing looks on the front, square to circle
- Limitations:
- Cups make it difficult to access LEDs from underneath. Replacing the LEDs from the front of each cup remain difficult and time consuming (16 cups in one PowerBalance).
- The cups still take a lot of space

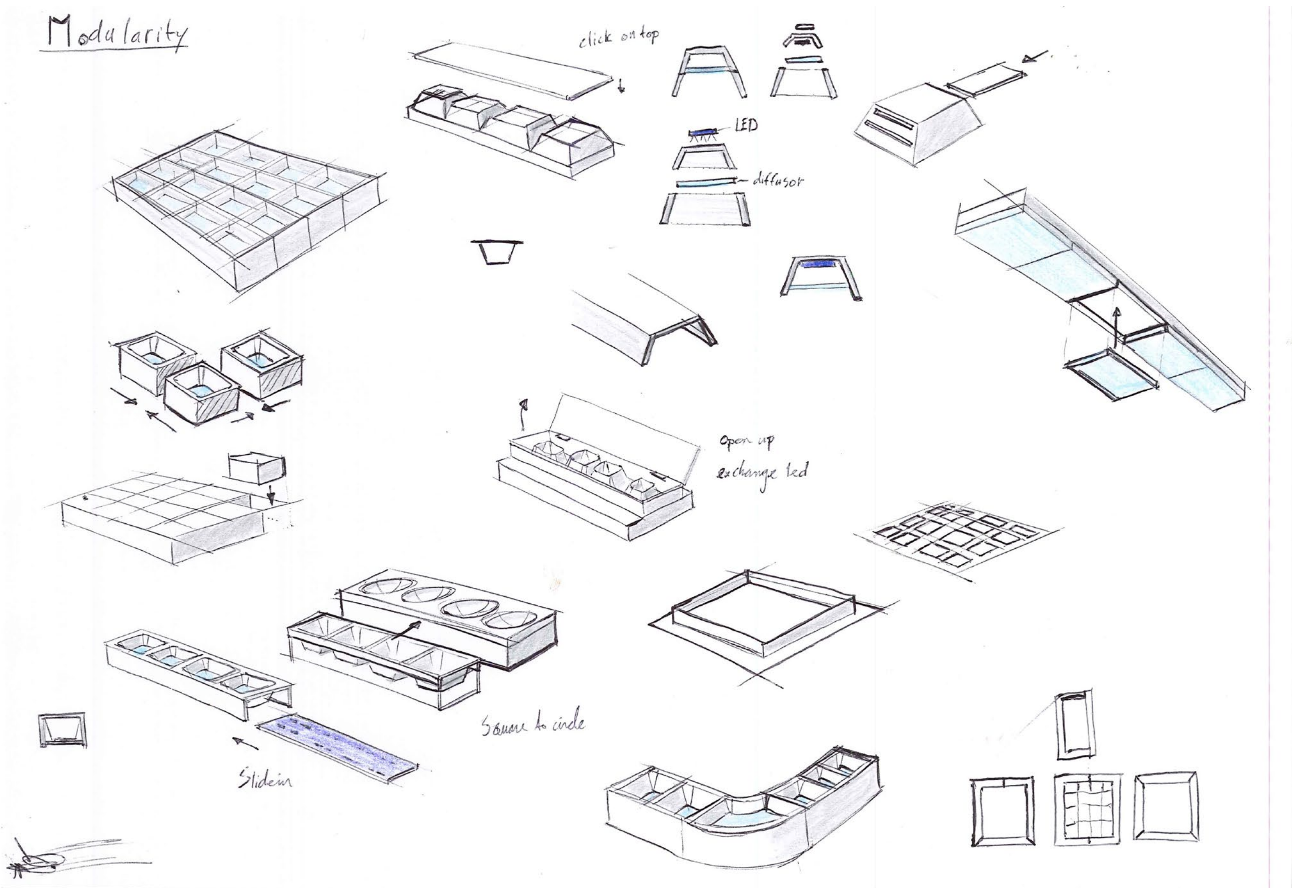


Figure 26 - Ideas on modularity

A suspended luminaire has some other challenges. As it is in direct view its appearance is more important. In the Modular SL Mini Poly and SmartBalance the driver is responsible for half of the total height and does not use the full length (creating unused space).

Some of the ideas shown:

- Place driver on the outside of the luminaire. This allows for a slimmer luminaire and easier access to the driver.
- External driver consists of two parts. The second part could be the power conversion part, controls or smart sensors.
- Removable end caps. Different material or finish allows for changing looks. The luminaire could also be extended with an extra middle part while keeping the end caps.
- Housing and end caps with non-vertical walls allowing stacking during transport.

Limitations:

- External driver might require a custom driver with a different housing that looks acceptable or a stock driver with an extra housing is needed.
- Vertically placed external driver might be too much in view

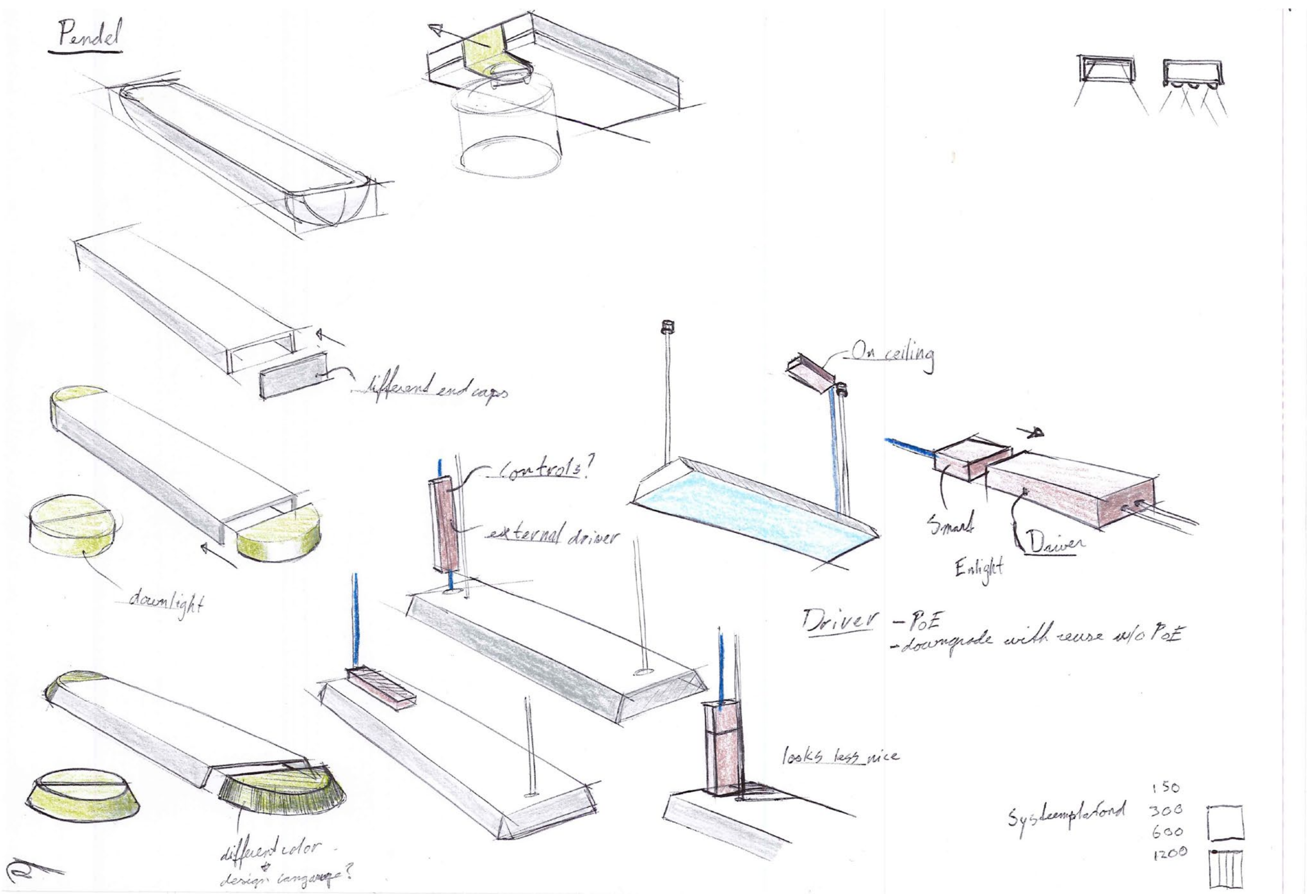


Figure 27 - Ideas on a suspended luminaire

9.2 Ideation 2

The presented ideas show some possible applications of the five main points and some of the limitations. The ideas are based on existing luminaires and lead to the following main limitations:

- Due to the optical principle of downward facing LEDs, access to LEDs remains difficult
- Improving an existing design leads to limited thinking in that product category

While the second limitation is not necessarily a problem, for the design of an optimal circular luminaire a more innovative approach could be taken. As CE is a ‘coherent framework for systems level redesign’ (Ellen MacArthur Foundation, 2012) the ideas are viewed as limited. Therefore a new approach, a system level approach, is further used to tackle the mentioned limitations.

A system level approach is broader than that of a single product. A product family allows for more variation but could still be limited to a product category. The TTX trunking system is an example of a product family existing of different modules attached to a back frame. The available options however are limited, allowing to only creating light lines. Lego with a big ecosystem of standardised modules is a good example of a system approach. The broad variety of possible creations increases the possibilities of reusing products and components in the future.

The second ideation phase therefore explores, in addition to the Circular Design Vision, how easy access to the LEDs and driver could be achieved (1) and how that can be done in a system approach (2). An overview of the idea is seen in Figure 29 and further explained in the next chapter.

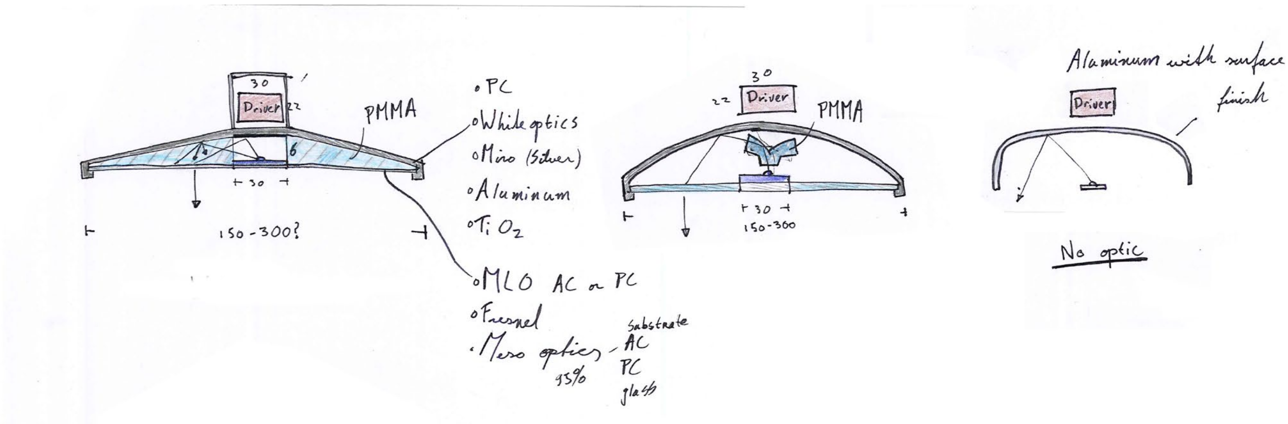
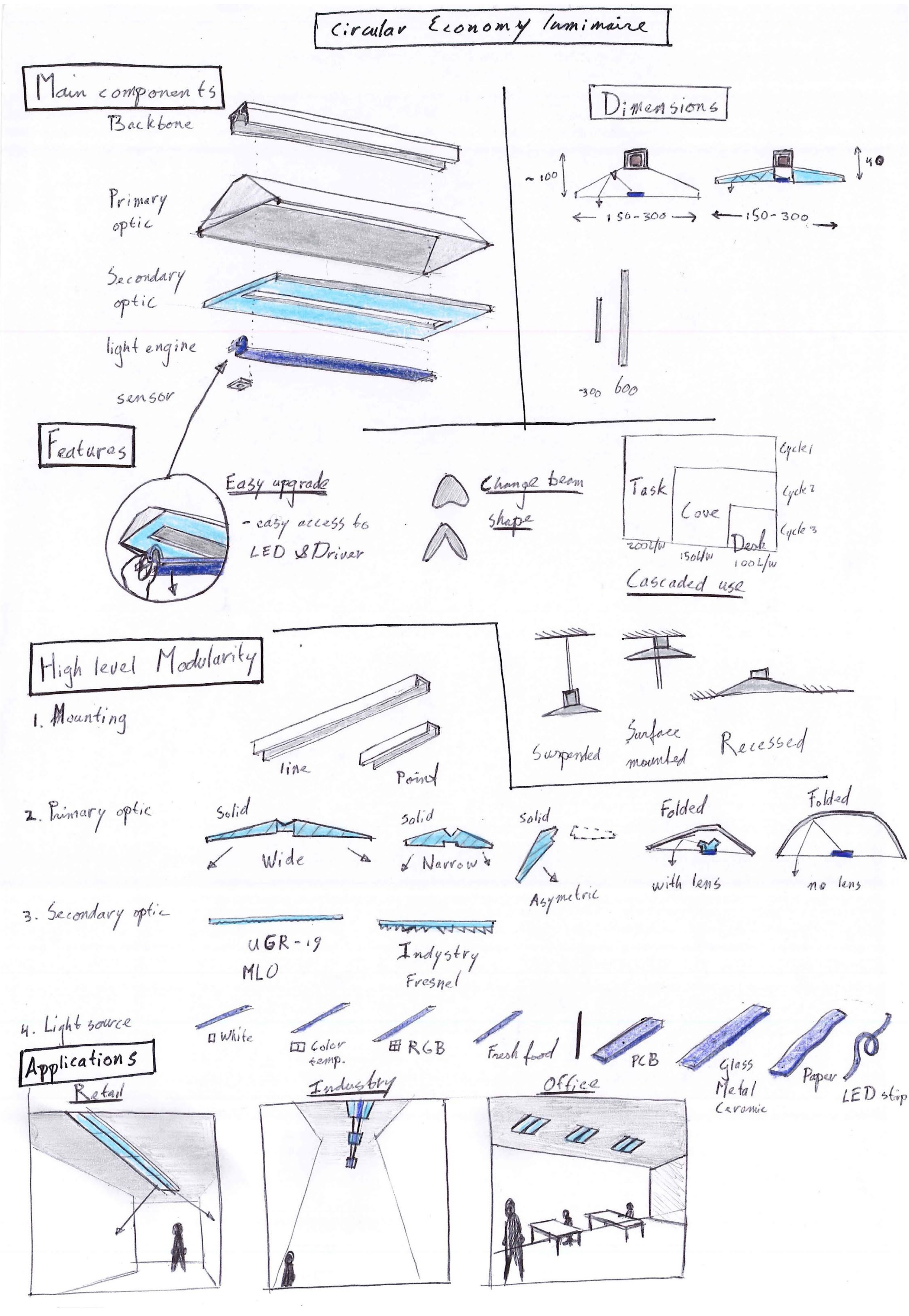


Figure 28 - Different optical principles (top)
Figure 29 - Overview of condept luminaire (right)


Circular Economy luminaire
Main components
Backbone
Primary optic
Secondary optic
light engine
sensor
Dimensions
~100
40
150-300
150-300
300
600
Features
Easy upgrade
- easy access to LED & Driver
Change beam shape
Task
Cove
Desk
Cycle 1
Cycle 2
Cycle 3
200L/W
150L/W
100L/W
Cascaded use
High level Modularity
1. Mounting
line
Point
Suspended
Surface mounted
Recessed
2. Primary optic
Solid
Wide
Solid
Narrow
Solid
Asymetric
Folded
with lens
Folded
no lens
3. Secondary optic
UGR-19
MLO
Indystry
Fresnel
4. Light source
White
Color temp.
RGB
Fresh food
PCB
Glass
Metal
Ceramic
Paper
LED strip
Applications
Retail
Industry
Office

9.3 Concept

The proposed concept is a highly modular platform allowing a wide range of configurations and applications. The adaptable platform approach tries to be future proof by creating an ecosystem of modules that is more likely to be used and produced for a longer period of time. The LEDs and driver are quick and easy to disassemble and access to allow servicing. The driver includes PoE to allow read out of life time prognostics. The modular approach benefits remake with the ease of access to all modules allowing for reliability assessment. For recycling the same type of material could be chosen for the backbone and rest of housing, preferably aluminium for its high recyclability and, based on a quick estimation, low impact (see Appendix E). This all leads to high scores high on the spider map. To score higher on future proof further exploration on the aesthetics would be needed. For remake more research is needed to identify best practice for determining component condition.

9.3.1 Backbone

An aluminium extrusion profile is chosen as the backbone. Appendix F shows different types of profiles explored.The top and side of the backbone have the same profile for various possible uses such as placing optics on the side or suspending it to the side on wall. On the inside a there is a profile on which the driver can click and an Ethernet cable can be pressed into.

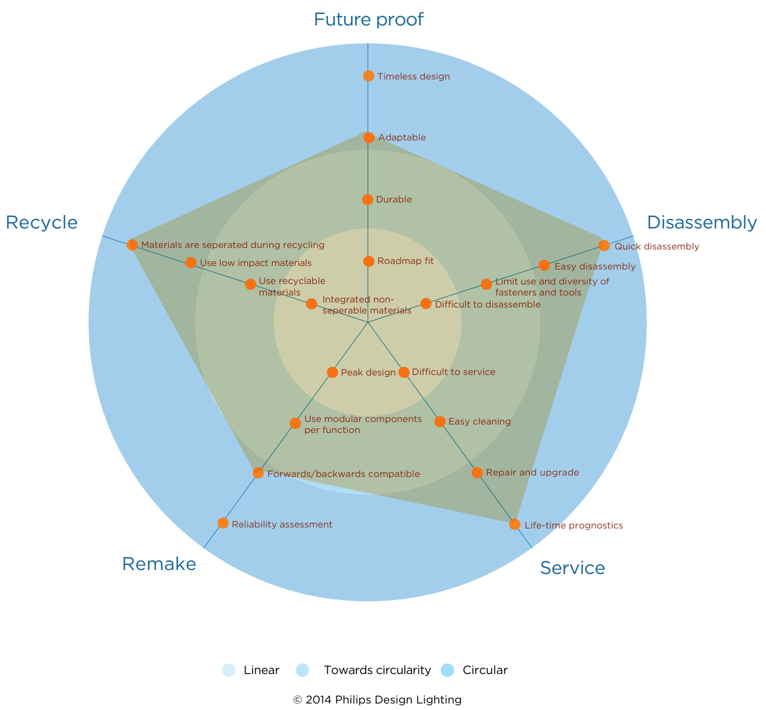


Figure 31 - Assesment of concept luminaire

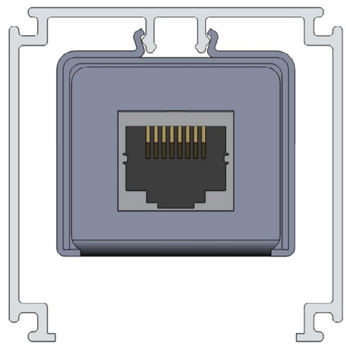


Figure 30 - Backbone extrusion profile

9.3.2 Optics

Different optical solutions are explored to find a solution for easy access to the LED module (Appendix H). The chosen solution is to place LEDs on the bottom of the luminaire, the upward facing LEDs are then reflected down. There are three optical solutions to achieve this (see figure 27 and 32):

- Light guide: create a wide and very thin luminaire, uses more material but could be preferred for a suspended luminaire at eye height.
- Lens optic: uses less material than the light guide but results in a thicker luminaire
- No optic: uses even less material but results in an even thicker luminaire, could be preferred in recessed luminaires for cost savings.

This optical solution creates several benefits. Firstly, the LEDs and driver could be easily accessed from underneath. Secondly, the width of the luminaire is now independent to that of the LEDs. This allows standardzing the LED module while making narrow luminaires (e.g. TTX LED Industry), medium width (SmartBalance) and wide (PowerBalance) luminaires. In addition it allows for different types of LED modules with different placement of the LEDs (see TTX LED Industry). Depending on its application the optic can include a MLOdiffuser or Fresnel plate for a different light disitribution.

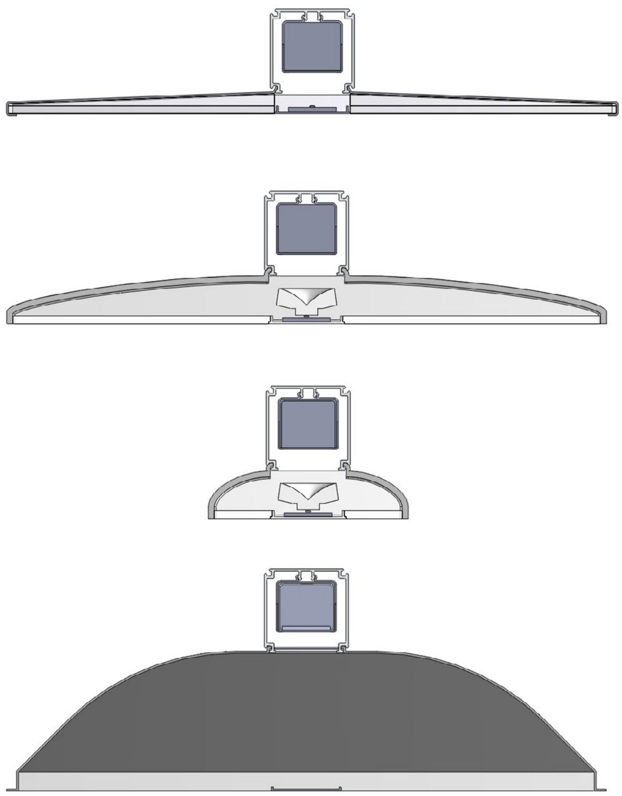


Figure 33 - Several optical principles with different thicknesses and widths

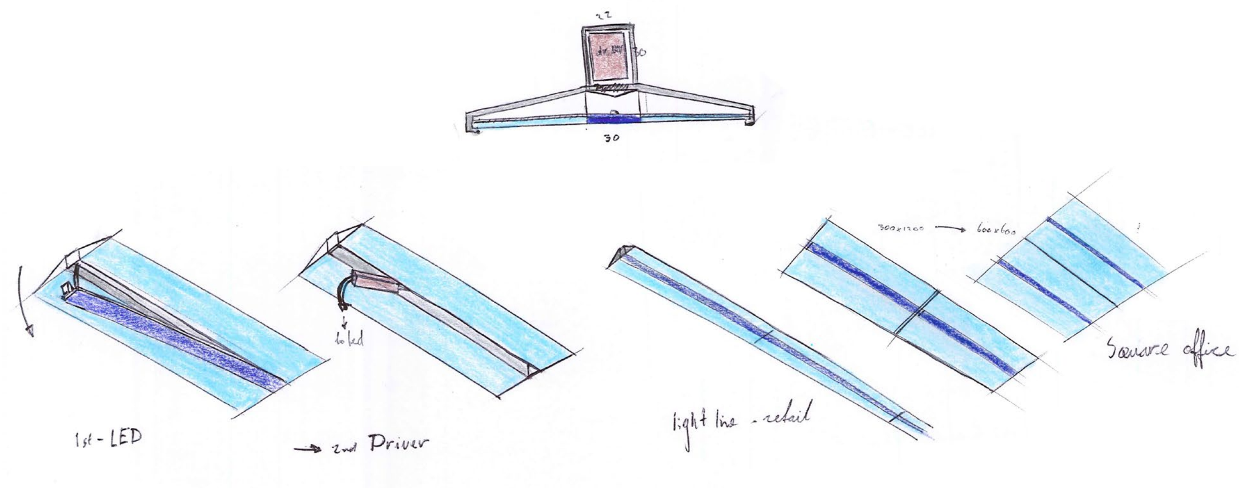


Figure 32 - Disassembly and configurations

9.3.3 Driver

The driver will be separated in its two parts, the power conversion part and the control part. The materials used in the power conversion part are distinctively different from the control part. Separating both parts will get higher recovery rates in recycling (Balkenende, 2013). Secondly, the separation allows for increased flexibility of the power source. When the power source changes, for example AC to DC, only the power conversion part needs to be taken out. Thirdly, if the driver fails only one of the two parts needs to be replaced. The separation thus aids in the reuse of components and benefits recycling.

The connection to and from the driver needs to be easy to disconnect. In this concept PoE is chosen. The connector is standardized, easy to disconnect and transfers information and power in one cable. This connector is preferred above the push pin connector option. The push pin is a bit more difficult to connect and needs more time since each cable needs to be connected separately. For the cable connecting to the LED module a JST connector (Figure 34) is used which is also standardized and easy to disconnect.

9.3.4 Visualization

An exploded view with the light guide optic is shown in figure 35. On the right page the concept luminaire is shown in an office and retail application with different widths. The retail environment also shows the versatility of using a backbone by in this case including a spot.

Figure 34 - JST connector

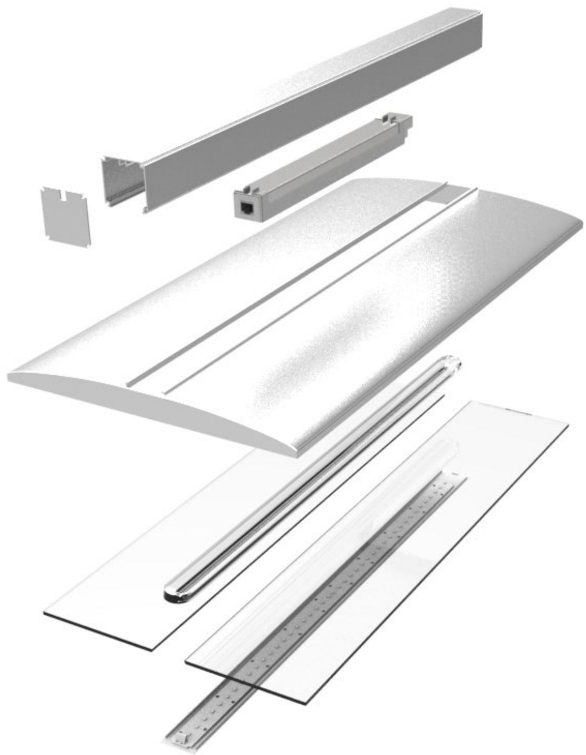


Figure 35 - Exploded view of the luminaire with light optic.
Figure 36 - Retail environment (top right)
Figure 37 - Office envrionment with 4 luminaires (bottom right)


Milch
Brot
Käse

10. CE AND SUSTAINABILITY

The CE framework from the EMF draws inspiration from several sustainability frameworks to present a new framework that explicitly adds a business approach. The approach of systematically designing out waste by recovering resources and value via several circles does not focus on sustainability explicitly. Sustainability is implicitly present as resource efficiency and recovery is clearly linked to sustainability. In addition, the use of a performance model which internalizes waste and liability costs is likely to support sustainability even further (Stahel, 2010). The EMF does not use the word sustainability on purpose for the framework to get more accepted (Webster, 2014) but does mention efficiency gains and carbon emission, material and energy savings throughout their reports. In the EMF CE model these sustainability aspects are not present, thus focussing on the system showing several circles for resource and value recovery. This research took the same approach to explore what that, the essence of CE of closing material loops in an economic attractive way, could mean for circular design. As a result the sustainability aspects remain implicit. On its own circular design gives an unbalanced view if used for sustainability by focusing primarily on designing out waste. In that case circular design cannot be seen as a complete separate framework but as an addition to other sustainability frameworks.

For a more balanced and complete framework for sustainability that includes a business approach, circular design could be extended with aspects from other sustainability frameworks. EcoDesign would be a framework that can be easily incorporated as it presents a clear design method that shares several aspects (e.g. reduce waste, reuse of products, maintenance, repair). The Life's principles from biomimicry at first sight would be more difficult to integrate as it presents more abstract strategies which are not all self-explanatory and could be difficult to interpret for designers (e.g. evolve to survive, integrate development with growth, reshuffle information). Appendix I proposes an EcoCircular model, an adapted Circular Design Model that includes six out of the eight EcoDesign strategies used in the Life-Cycle Design Stragies wheel (LiDS) (Brezet & van Hemel, 1997). Reduction of material could be seen as a part of low impact materials (Sustainable Minds, 2014) and new concept development as part of the whole framework. For sustainability purposes this model could bring more balance wherein circular design is implemented in an efficient optimized way with low environmental impact. The LiDs wheel then could be used next to the Circular Design spider map from the scorecard. Further research needs to be done to create a coherent EcoCircular framework as some definitions and strategies currently overlap.

11. CONCLUSIONS

In this thesis the results of the project on product design for a CE have been presented. An adapted CE model for product design is proposed that identifies five main topics: future proof, disassembly, service, remake and recycle. Based on the five main topics a CE guideline list has been developed to support circular design. The individual guidelines themselves are not new, however, the contribution is in the representation that combines several areas of expertise in a CE framework. The guideline list has been used to develop several tools to aid in circular design: the vision circle, a spider map and a score card. The adapted CE model, the guideline list and the tools are each a different representation and useful in a wide range of applications. Each representation has its own usefulness in different situations. A concept luminaire has been developed to test and develop the tools. The luminaire presents how circular design can be applied with a system approach.

This thesis is a first step towards understanding product design in a CE. Feedback from Philips on the guideline list and tools is positive. The guidelines and tools need to be further tested to see what elements work well, need to be adjusted, are not as relevant or are missing. Although the focus has been on luminaires, effort is made to make the guidelines and tools in a general way. They need to be tested in different contexts to examine if their use is limited to lighting, to EEE/technological ingredients or are widely applicable.

The next step for the guidelines is developing them into requirements. The requirements then can be put into milestones to meet. Especially engineers need hard requirements to meet in order to pay real attention to.

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APPENDICES

Appendix A. Sector use of terms (Parker, 2007)

Table 5.2.6a: Sector Use of Term 'Remanufacturing'

Sector	Conformance to 5.1.1 Remanufacturing Spec.	Other use
Aircraft	Almost exclusively in practice	Safety/legal enforces high quality. Also known as rotables.
Automotive	Largely in practice	Large operators more conforming. Smaller operators tending to recondition.
Consumer Electronics	No	Reconditioned/Refurbished is the more common parlance.
Domestic White Goods	No	Generally recycled or reconditioned.
Furniture	No	Almost exclusively refurbished.
Food Processing Equip	Yes	Differences over matching or exceeding OEM specification.
Office IT	Yes	High standards set by majors such as Xerox.
Vending Machines	Yes	

Table 5.2.6b: Sector Use of Term 'Reconditioning'

Sector	Conformance to 5.1.2 Reconditioning Spec.	Other use
Aircraft	Reconditioned	Often the term 'overhaul' is used.
Automotive	Reconditioned	Typical of medium to small operators as alternative to remanufactured. Also rebuilding.
Consumer Electronics	Refurbished	Covers entire range from remarketing of returns with fully warranty, to ex-service with 3 month guarantee.
Domestic White Goods	Refurbished	Disparity of testing standards. Sometimes no repair, just cleaning. 3 month warranty typical.
Furniture	Refurbished	Almost exclusively refurbished in this sector. Guarantees < 1 year typically.
Food Processing Equip	Reconditioned/refurbished both used	Sometimes described 'as new' but betrayed by short warranty.
Office IT	Reconditioned/refurbished both used	Refurb = new with cosmetic damage. Full warranty. Recon = fully tested but not dismantled.
Vending Machines	Refurbished	Limited guarantee.

Table 5.2.6c: Sector Use of Term 'Repair'

Sector	Conformance to 5.1.3 Remanufacturing Spec.	Other use
Aircraft	Yes	
Automotive	Yes	Guaranteed for 30 days-1 year upwards for the replacement part outside of vehicle warranty.
Consumer Electronics	Yes	Term used within warranty. Otherwise described as refurbished.
Domestic White Goods	Yes	Term used within warranty. Otherwise described as refurbished, with 1-3 month warranty.
Furniture	Rarely used	Refurbishment is much more common, reflecting cosmetic nature of defects.
Food Processing Equip	Yes	
Office IT	Yes	Term used usually within warranty. Otherwise described as refurb/recon'ed.
Vending Machines	Yes	

Appendix B. Full Circular Design Guideline list

Category	Sub-category	Goal	Means
Futureproof last long and use long	Long lasting	Performance	
		Reliability	- Design out moving parts
			- Design for understressed use
			- Provide redundancy
			- Overdimension critical components
		Durability	- Wear resistance
			- Use assembly methods that allow disassembly without dam
			- Do not use coated, painted or plated components
			- Prevent discoloring
			- Ensure that fasteners' material are similar or compatible to disassembly.
			- Aging and corrosive material combinations need to be avoic corrode, spread corrosion, and break off inside the product) ofter
			- Protect subassemblies from corrosion, the reasons being the
	Long in use	Roadmap fit	- Ensure a long -term roadmap is available
		Upgradability	- Use materials and assembly methods that do not prevent up
			- Structure to facilitate ease of upgrade of product.
		Adaptability	- Ensure a long -term roadmap is available
			- Prevent product obsolescence (user needs)
		Timeless design	- Emotional durable design (user desire)
		Anticipate legislation (e.g. toxicity, recyclability, disassembly time)	
Disassembly non-destructive	Connections	Quick and easy disconnect	- Use easy to disassemble connections
			- Apply loose fits for internal components
			- Avoid welding and adhesive between sub-assemblies
			- Use joining methods that allow disassembly at least to the po testing before and after refurbishment.
		Limit use and diversity of fasteners	- Minimize the number of fasteners used in an assembly
			- Minimize the types of fasteners used in an assembly and sta
			- Fasteners need to be easy to remove or destroy.
			- Allow easy access and identification of the fasteners
			- Consider the use of fasteners incorporating an active disasse
		Limit use and diversity of tools	- Limit the number of tools needed and tool changes
			- Make it possible to use simple tools for disassembly
	Product architecture	Simplify product architecture	- Minimize the complexity of the product structure
			- Select a product structure which allows a sequence indepen
			- Minimize the number of components used in an assembly
			- Optimizing the spatial alignment between various compone
			- At least one surface needs to be left available for grasping.
			- Simplify and standardize component fits
		Ease of acces to components	- Arrange components for ease of disassembly
			- Consider making the plane of access to components the sam
			- Avoid the need to turn the product in the disassembly proce
			- Metal inserts in plastic parts should be avoided, since this in and complex movements in disassembly. Applicable if meant for o
			- Use assembly methods that would allow disassembly at leas accessed.
		Clarity of disassembly sequence	- Identify components assembly sequence.
			- Identify components requiring similar assembly tools and te
			- Reduce complexity of reassembly

	Source			
	(Mulder, et al. 2014)			
	(Mulder, et al. 2014)			
	(Mulder, et al. 2014)			
	(Mulder, et al. 2014)			
	(Sundin, 2004)			
age to **(reusable)** components.	(Ijomah, et al., 2010)			
	(Mulder, et al. 2014)			
	Maarten			
that of base material thus limiting opportunity of damage to parts during	(Ijomah, et al., 2010)			
led, since disassembling them cleanly and efficiently (due to their tendency to n is difficult.	(Mital, et al., 2008)			
e same	(Mital, et al., 2008)			
ograde and rebuilding of the product.	(Ijomah, et al., 2010)			
	(Ijomah, et al., 2010)			
	Maarten			
	Maarten			
	Maarten			
	Maarten			
	(Peeters, et al., 2012)			
	(Ijomah, et al., 2010)			
oint that internal components and subsystems requiring it can be accessed for	(Ijomah, et al., 2010)			
	(Mital, et al., 2008)	(Peeters, et al., 2012)	(Ijomah, et al., 2010)	(Balkenende, et al., 2011)
ndardize the fasteners used	(Peeters, et al., 2012)	(Ijomah, et al., 2010)	(Balkenende, et al., 2011)	
	(Mital, et al., 2008)			
	(Mital, et al., 2008)	(Sundin, 2004)	(Ijomah, et al., 2010)	(Balkenende, et al., 2011)
embly or embedded disassembly functionality.	(Balkenende, et al., 2011)			
	(Balkenende, et al., 2011)			
	(Balkenende, et al., 2011)			
	(Desai & Mital, 2003)	(Ijomah, et al., 2010)		
dent disassembly	(Balkenende, et al., 2011)			
	(Mital, et al., 2008)	(Desai & Mital, 2003)	(Ijomah, et al., 2010)	(Balkenende, et al., 2011)
nts to facilitate disassembly without jeopardizing assemblability,	(Desai & Mital, 2003)			
	(Mital, et al., 2008)	(Sundin, 2004)		
	(Ijomah, et al., 2010)			
	(Ijomah, et al., 2010)	(Balkenende, et al., 2011)		
ne for all components	(Mital, et al., 2008)	(Sundin, 2004)	(Balkenende, et al., 2011)	
ss	(Mital, et al., 2008)	(Sundin, 2004)	(Balkenende, et al., 2011)	
creases material variety and part complexity and necessitates multiple directions vermoulding	(Mital, et al., 2008)			
t to the point that internal components and subsystems requiring work can be	(Ijomah, et al., 2010)			
	(Ijomah, et al., 2010)	(Sundin, 2004)		
chniques.	(Ijomah, et al., 2010)	(Sundin, 2004)		
	(Ijomah, et al., 2010)			

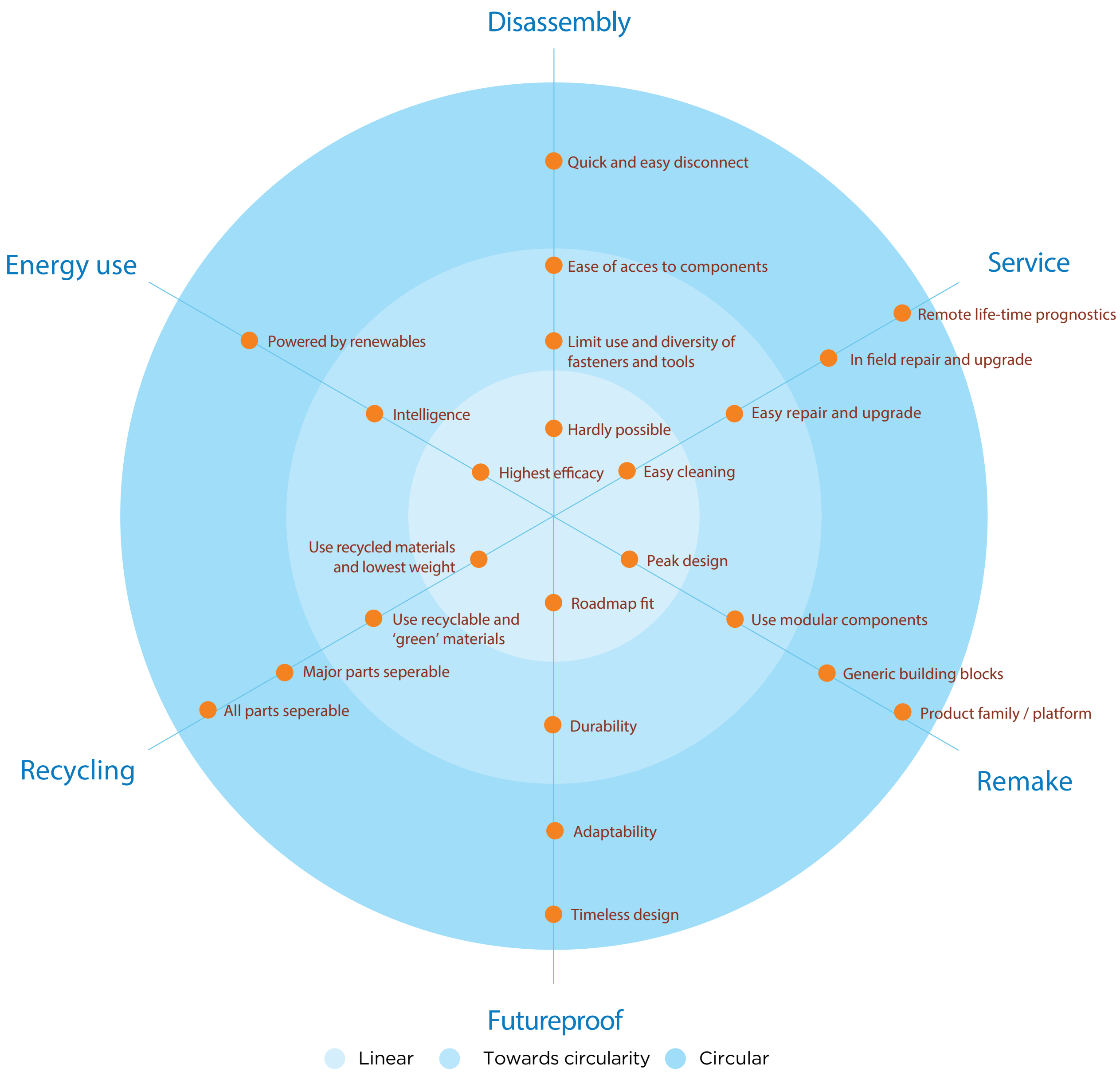
Service Reuse of products	Maintainability	Ease of cleaning	- Ensure product surfaces are smooth and wear resistant.
			- Ensure that all parts to be cleaned are easily accessed.
			- Use material that would survive cleaning process e.g. ensure
			- Limit the number of material types per part.
			- Identify components requiring similar cleaning procedures a
		Ease of repair	- Allow for easy and quick access to parts prone to failure
			- Avoid assembling components with a different life duration
		Allow onsite repair and upgrade	- Allow on site maintenance
	Lifetime prognostics	(Online) monitoring for quality, testing, maintenance and billing	
Remake Reuse of components	Modularity	Use modular components	- Use modular structure so that obsolescence occurs with cor
			- Do not combine components that have different physical lif
			- Do not combine components that have different intervals fo
			- Group components in sub-assemblies according to reuse, re
			- Concentrate compatible material groups in separate subass
			- Allow customization by grouping components in liberally
			- Combinable subassemblies
		Use standard interfaces	- Standardize parts
			- Standardize interfaces
		Back- & forwards compatability	
	Reliability assesment	Allow for easy testing of components	- Standardize test procedures
			- Structure for ease in determining component condition
			- Structure so testing is sequential, mirroring reassembly orde
			- Minimize the disassembly level required to effectively test c
			- Clearly identify component load limits, tolerances and adjus
	(Reverse) logistics	Product can easily be returned	- Ensure products can be stacked
			- Ensure products can safely be transported
			- Minimize product volume
		Allow for spare part harvesting	-
		Local production	
Recycling of material Reuse (from GreenElec)	Materials	Avoid the use of (non-compliant) coatings	- Any secondary coating processes, such as painting, are to be
		Limit the number of different materials	- Minimize the number of material types used in an assembly
		Only use recyclable materials	
		Use preferred/pure materials	- Increase the use of common materials
		Allow material seperability (not from GreenE	- Consider the material compatibilities to eliminate the need
			- Allow easy material identification
			- Add non-contamination markings for the ease of sorting and
			- Any harmful materials, if functionally important, should be g
			- Do not use fasteners that are not compatible with the conne therefore choose plastic fasteners for plastic and metal fasteners f fraction
	Electronics	Get PCB out in one piece	
		Easy/fast detection of materials	
		Use SMD components	
	Connections	Avoid fixed connections	- Prefer snap-fits for plastic components (particularly housing
			- Use a detachable power cord instead of a permanently fixed
		Break down by (shredding/disassembly) to	- If connections are applied that enclose materials permanent during shredding
		Pieces of uniform composition	
		Pieces of relatively large size (>1cm)	

non-destructive & destructive

	(Ijomah, et al., 2010)		
	(Ijomah, et al., 2010)	(Peeters, et al., 2012)	(Sundin, 2004)
e that material melting point is higher than clean process temperature.	(Ijomah, et al., 2010)		
	(Ijomah, et al., 2010)		
nd cleaning agents.	(Ijomah, et al., 2010)	(Sundin, 2004)	
	(Peeters, et al., 2012)	(Ijomah, et al., 2010)	(Sundin, 2004)
	(Balkenende, et al., 2011)		
	Maarten		
	Allard Pheifer		
mponents rather than with entire product.	(Ijomah, et al., 2010)	(Mital, et al., 2008)	(Ijomah, et al., 2010)
e.	(Hata, et al., 2001)		
r maintenance and upgrade.	(Hata, et al., 2001)		
conditioning or remanufacturing potential	(Balkenende, et al., 2011)		
emblies of a product	(Mital, et al., 2008)	(Balkenende, et al., 2011	(Hata, et al., 2001)
	(Balkenende, et al., 2011)		
	(Balkenende, et al., 2011)		
	(Ijomah, et al., 2010)		
	Maarten		
	Nestor Palma		
	(Ijomah, et al., 2010)		
	(Ijomah, et al., 2010)	(Sundin, 2004)	
er	(Ijomah, et al., 2010)		
omponents	(Ijomah, et al., 2010)		
tments	(Ijomah, et al., 2010)	(Sundin, 2004)	
	Maarten		
	Maarten		
	Maarten		
	Maarten		
e avoided, since they inhibit access to and removal of components	(Balkenende, et al., 2011)	(Mital, et al., 2008)	
	(Balkenende, et al., 2011)	(Ijomah, et al., 2010)	
	(Balkenende, et al., 2011)	(Desai & Mital, 2003)	
of separation for recycling	(Balkenende, et al., 2011)		
	(Balkenende, et al., 2011)	(Mital, et al., 2008)	(Sundin, 2004)
d recycling	(Balkenende, et al., 2011)	(Mital, et al., 2008)	
grouped together into subassemblies for fast disposal.	(Balkenende, et al., 2011)	(Mital, et al., 2008)	
ecting components. Fasteners are recycled together with the host component; for metal to avoid polluting other material streams or end up in the waste	(Hultgren, 2012)		
	(Balkenende, et al., 2011)		
	(Balkenende, et al., 2011)		
	(Balkenende, et al., 2011)		
), to allow easy liberation of materials	(Balkenende, et al., 2011)		
d one			
tly, apply gaps and or break-lines to the enclosing material to enable liberation	(Balkenende, et al., 2011)	(Hultgren, 2012)	
	(Balkenende, et al., 2011)		
	(Balkenende, et al., 2011)		

Appendix C. Circular Design Spider Map with energy axis

This is an older version of the spider map, therefore some criteria are outdated.



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Appendix D. Circular Design Spider Map with all categories

This is an older version of the spider map, therefore some criteria are outdated.

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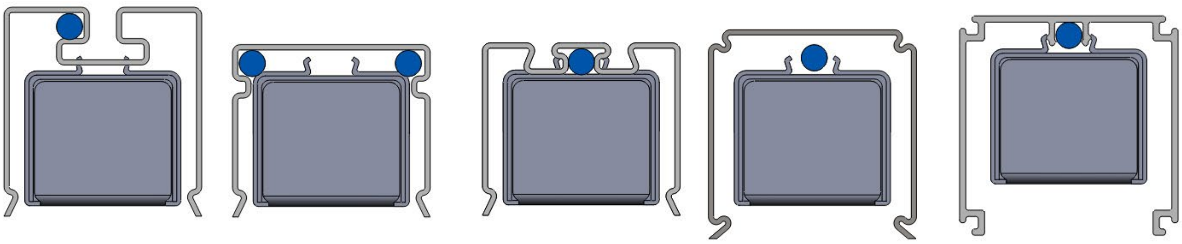
Appendix E. Environmental impact of different material choices

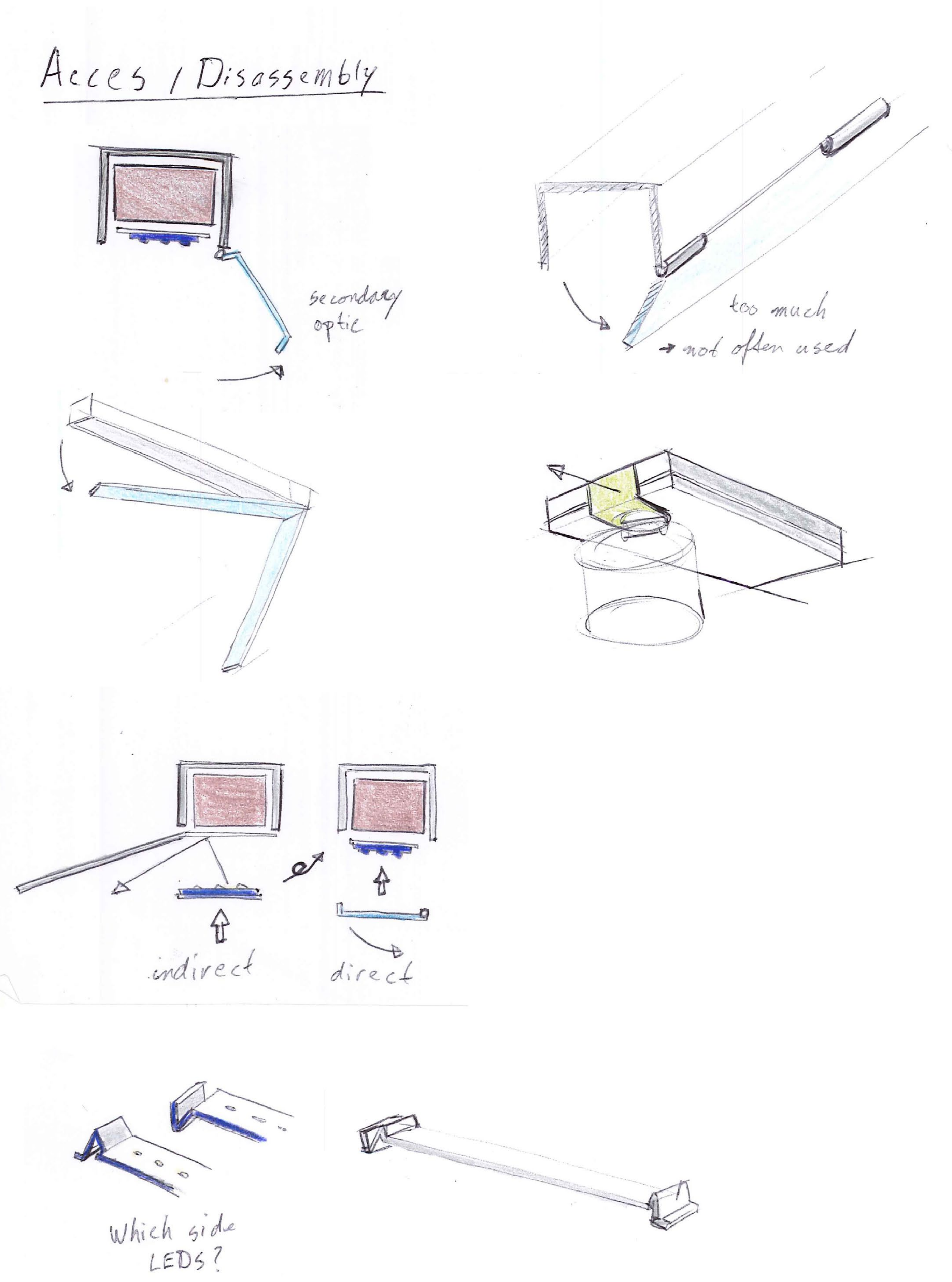
Description			Weight (g)			mPt	mPt not known (but proably smaller than MCPET)				mPt				mPt
profile		Steel (304)	2820	€	8,43	1460,76									
	or	Aluminum (6000 series)	1030	€	1,93	1010,43									
lid		ABS	30	€	0,06	14,85									
	or	PC	30	€	0,08	21,3									
housing (used for internal reflection)		ABS	800	€	1,60	396	+white filler (=TiO2)								
	or	PC	730	€	1,83	518,3	+white filler								
	or	Steel (304)	1440	€	4,31	745,92	+Ti2O coating	or	sheet MCPET	400	146	or	sheet MC PC	430	305,3
	or	Aluminum (6000 series)	500	€	0,94	490,5	+Ti2O coating	or	sheet MCPET	400	146	or	sheet MC PC	430	305,3
optics	option 1	PMMA	660	€	1,98	476,52									
	+	PC (MLO)	760	€	1,90	539,6									
	option 2	PMMA	150	€	0,45	108,3									
	+	PC (MLO)	760	€	1,90	539,6									

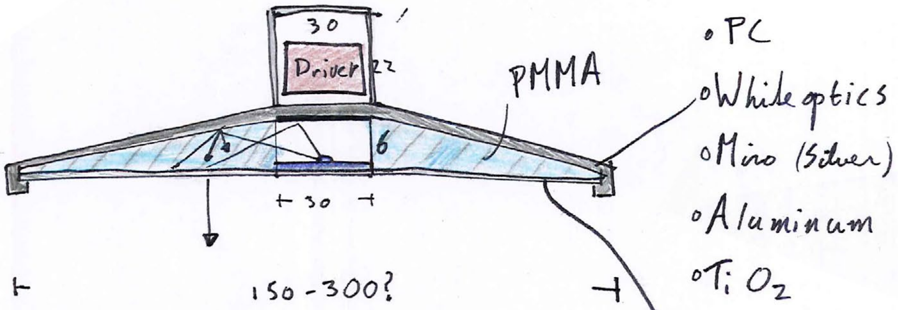
green choices

Appendix F. Backbone profile exploration



Appendix G. Sketches for circular luminaires

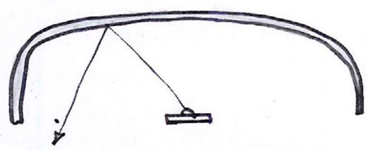


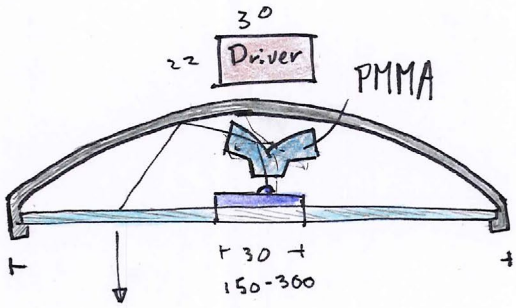


Wide optic

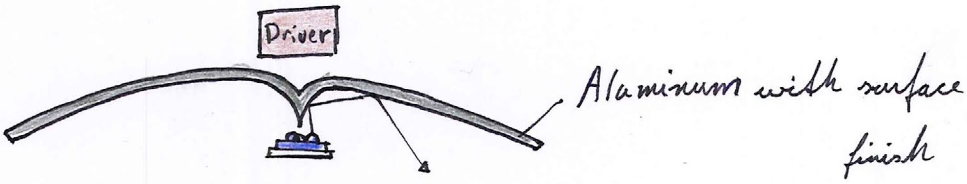
- MLO AC or PC
- Fresnel
- Meso optics 95% – Substrate: AC, PC, glass

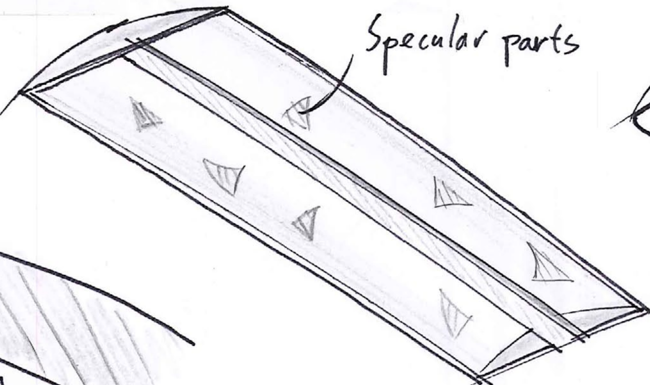
No optic

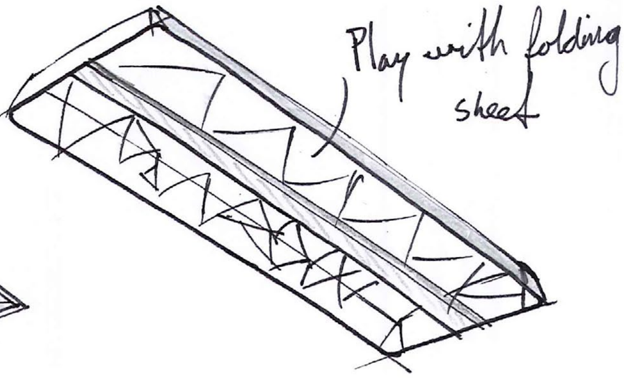


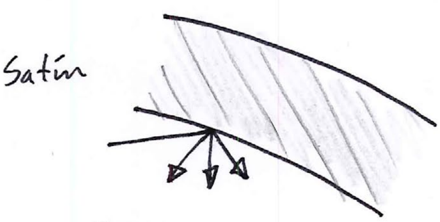


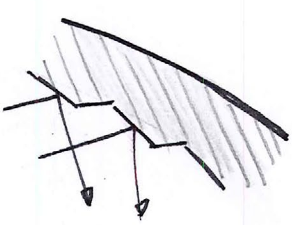
Smaller optic

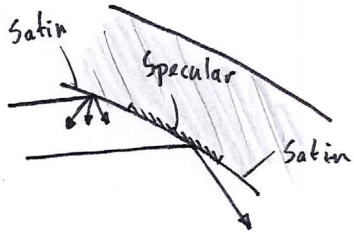








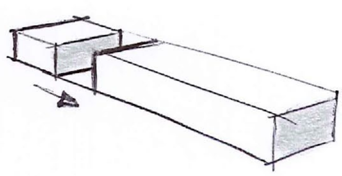


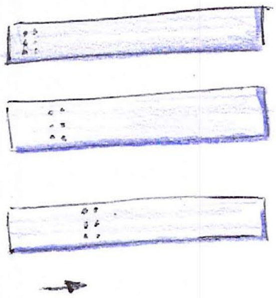


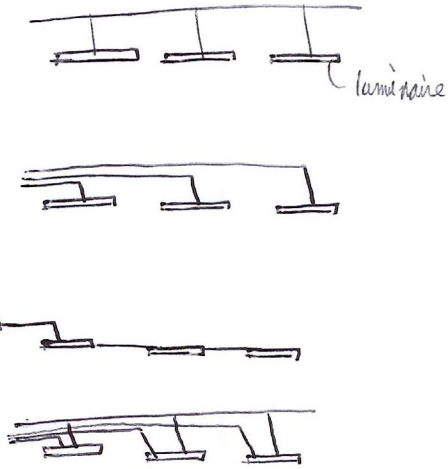
Driver

- which modules?

  - AC/DC power conversion
  - controls
  - buck/boost
  - condensator

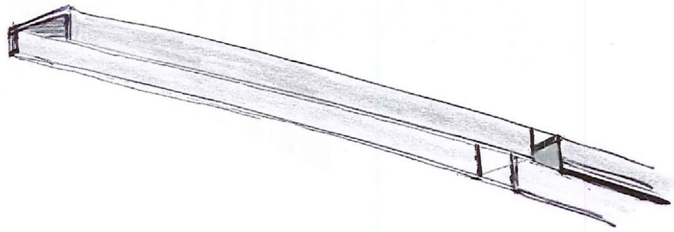


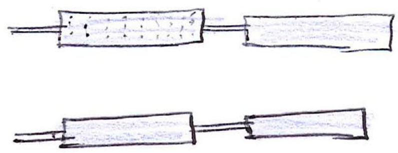


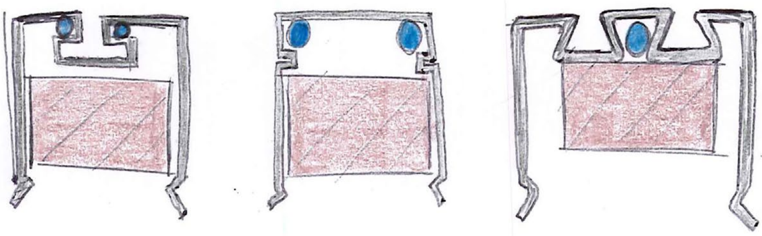


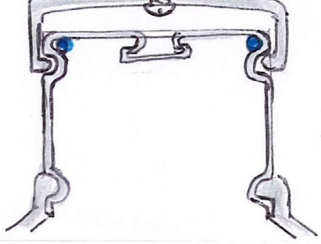
- spot

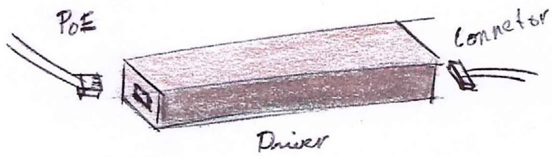
- rail



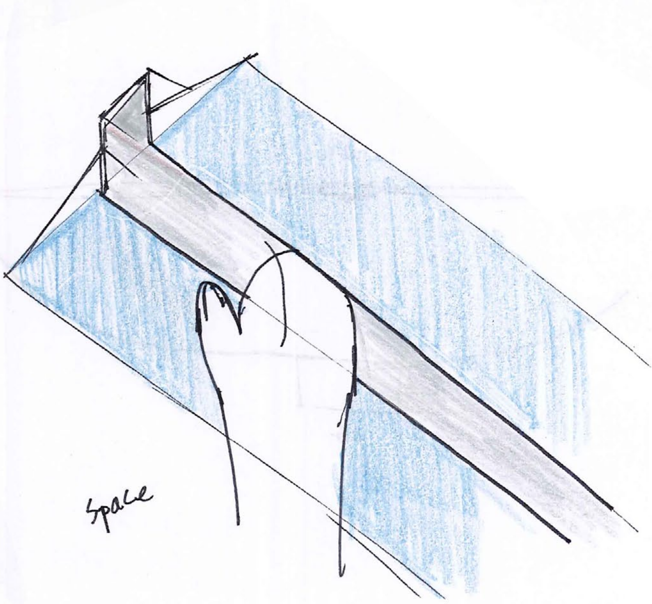


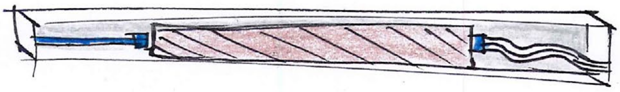


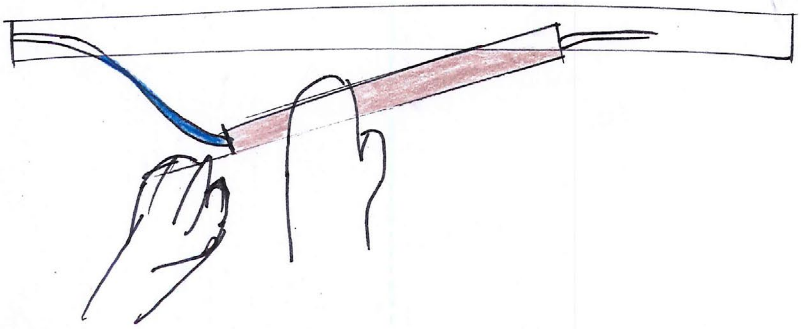


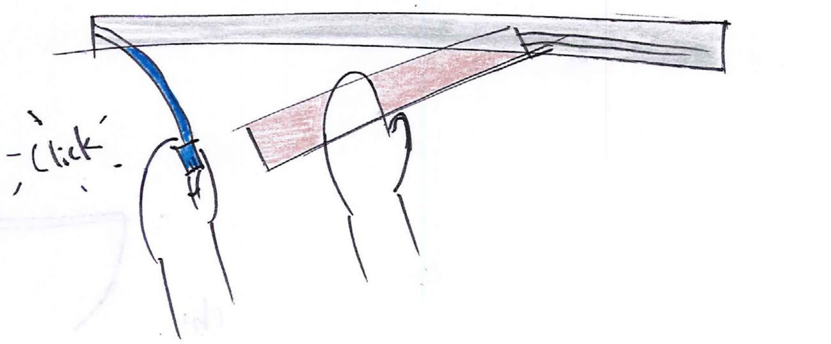


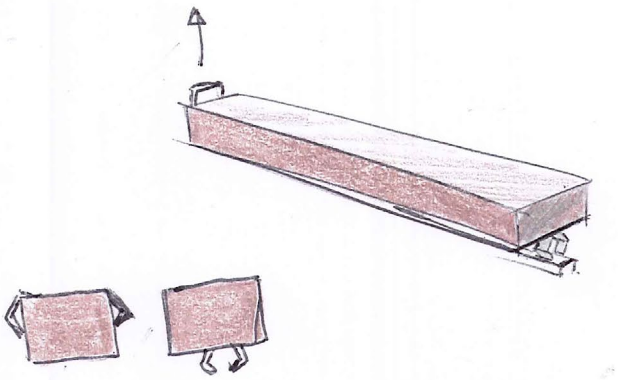
Driver

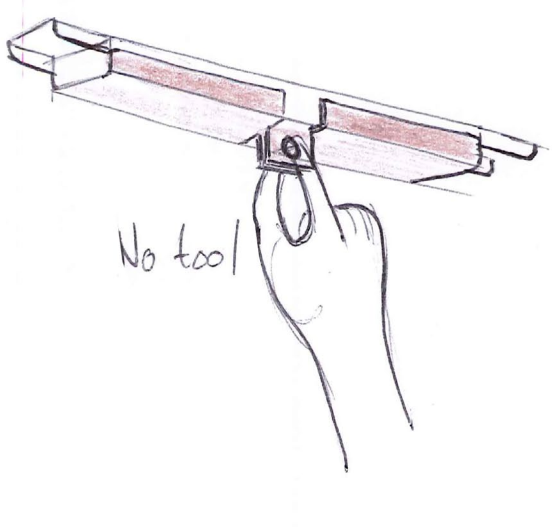


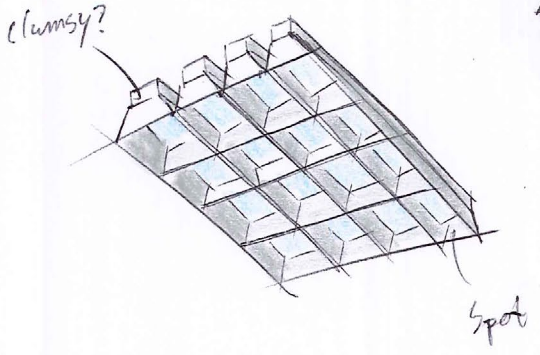


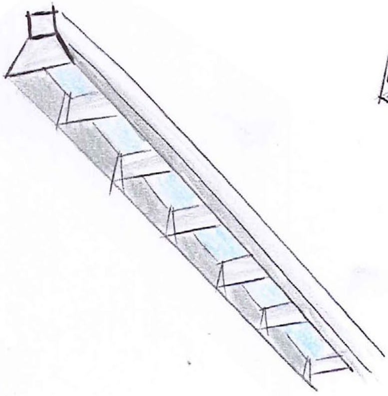


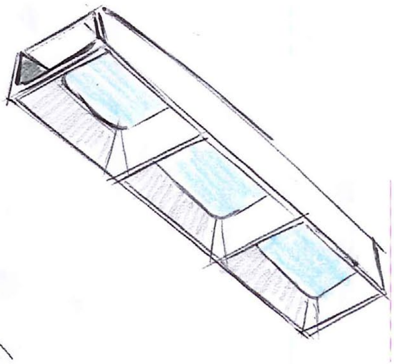


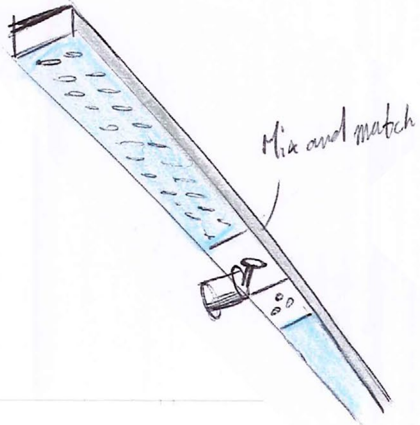


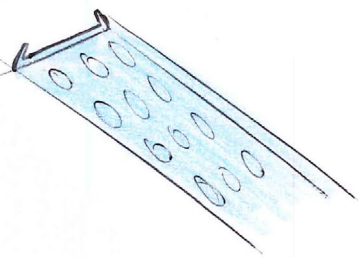


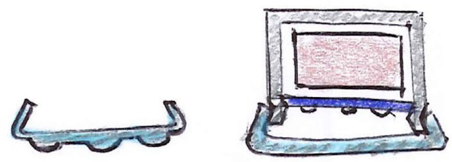

clumsy?
Spot

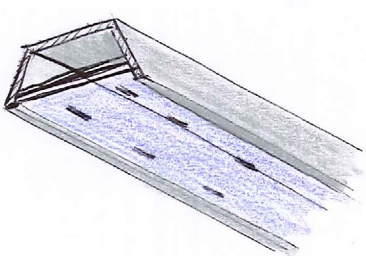


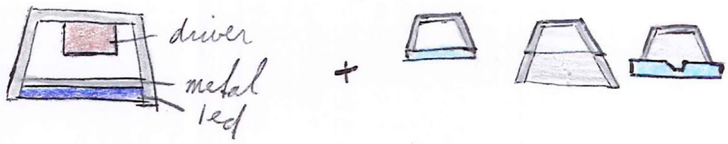


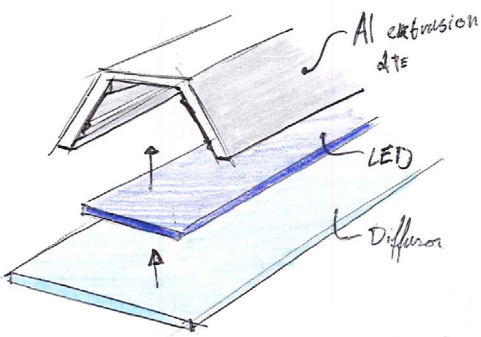

Mix and match

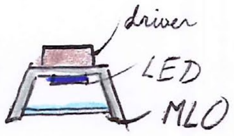


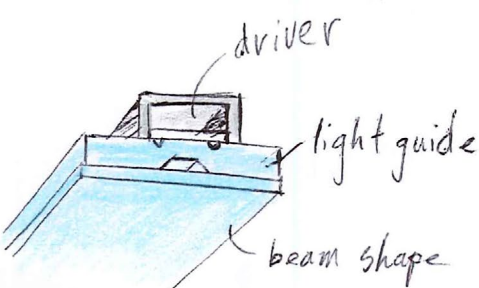


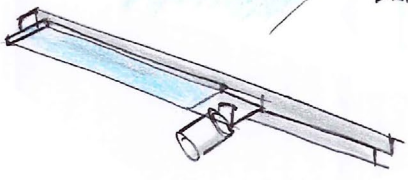


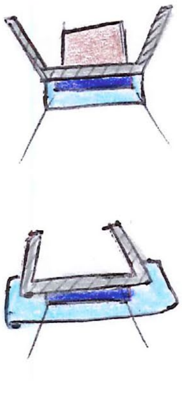

driver
metal
led
+

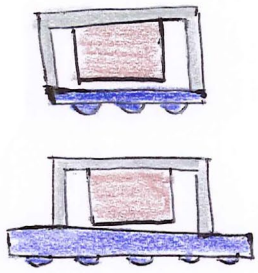

Al extrusion
LED
Diffusor


driver
LED
MLO

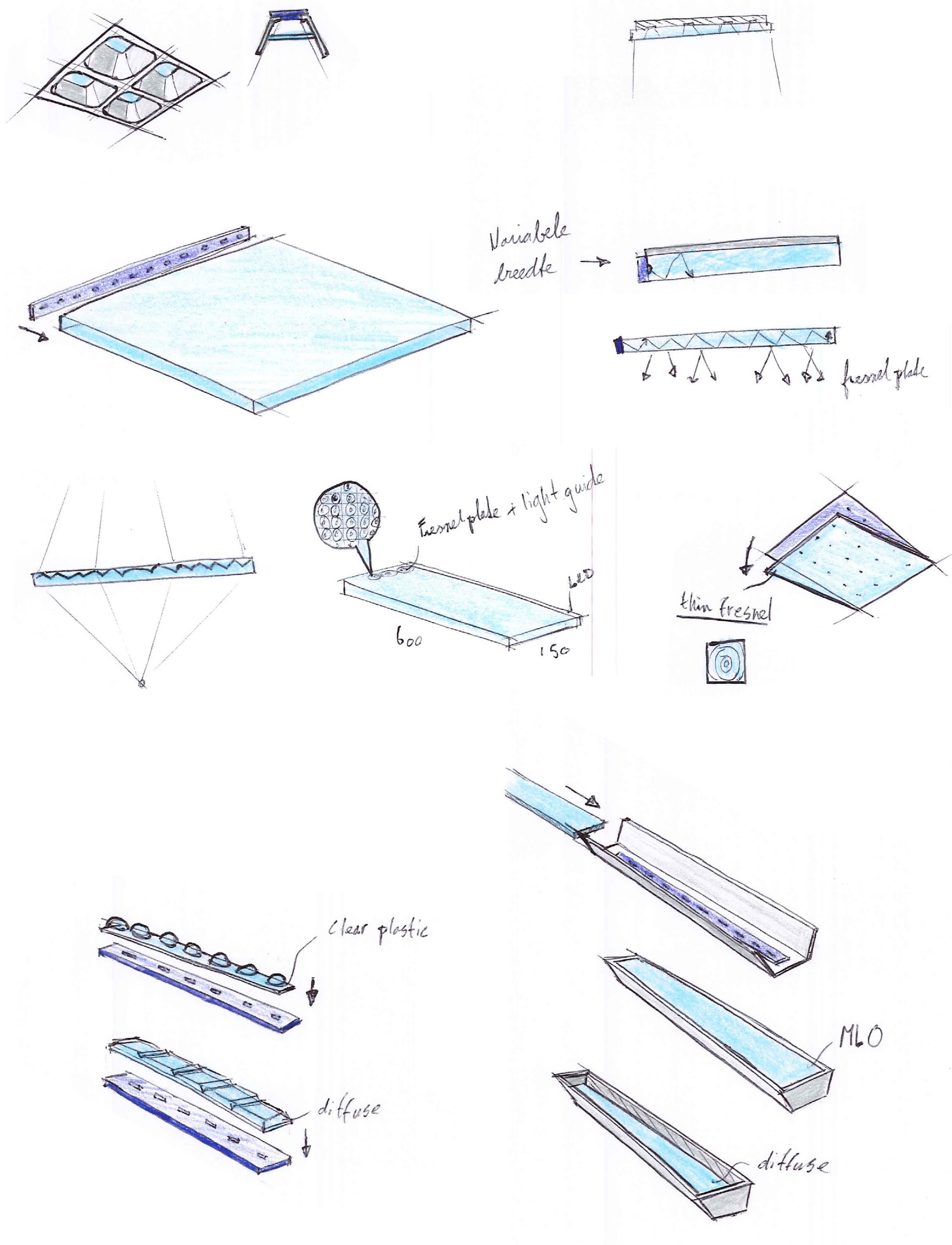

driver
light guide
beam shape



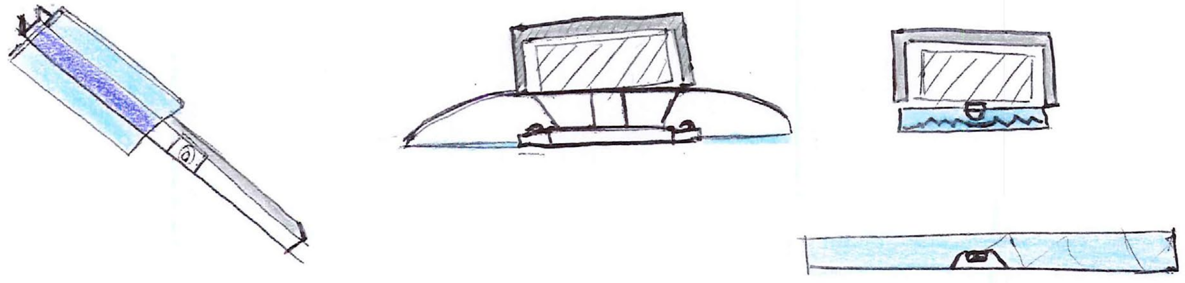


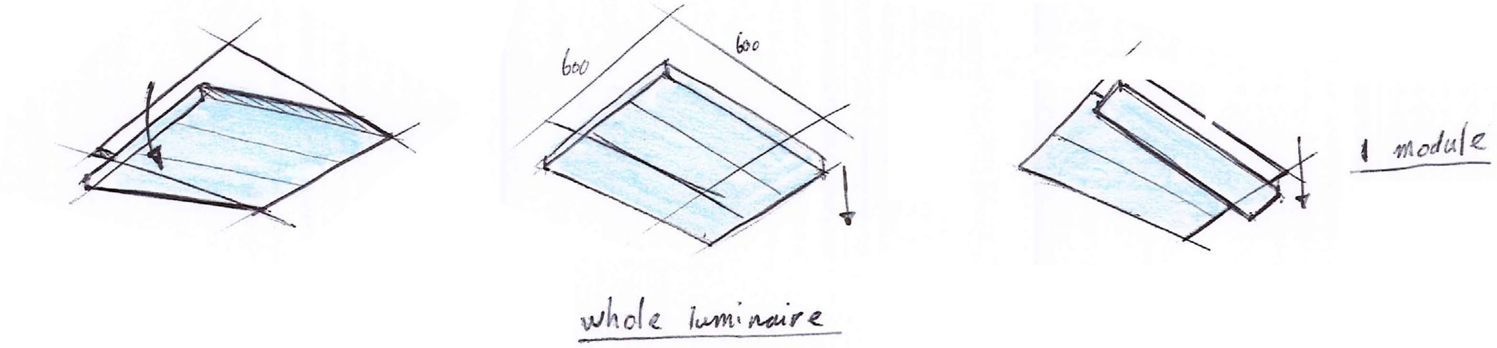


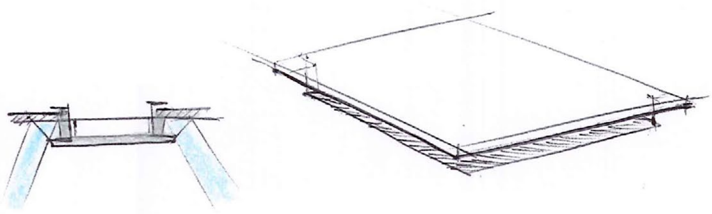
Making light

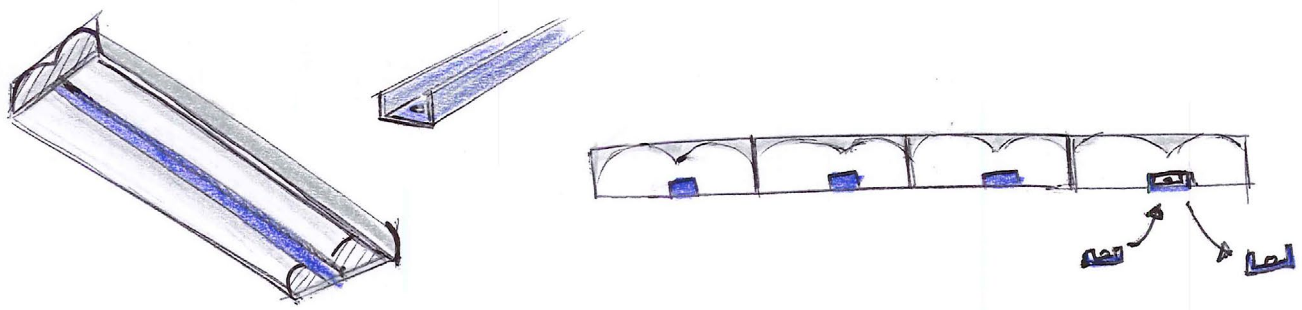


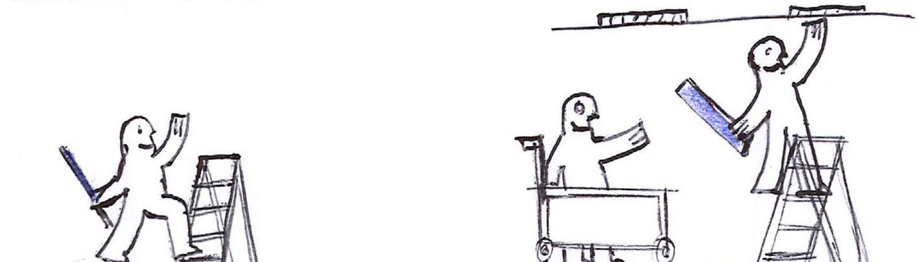
Making light



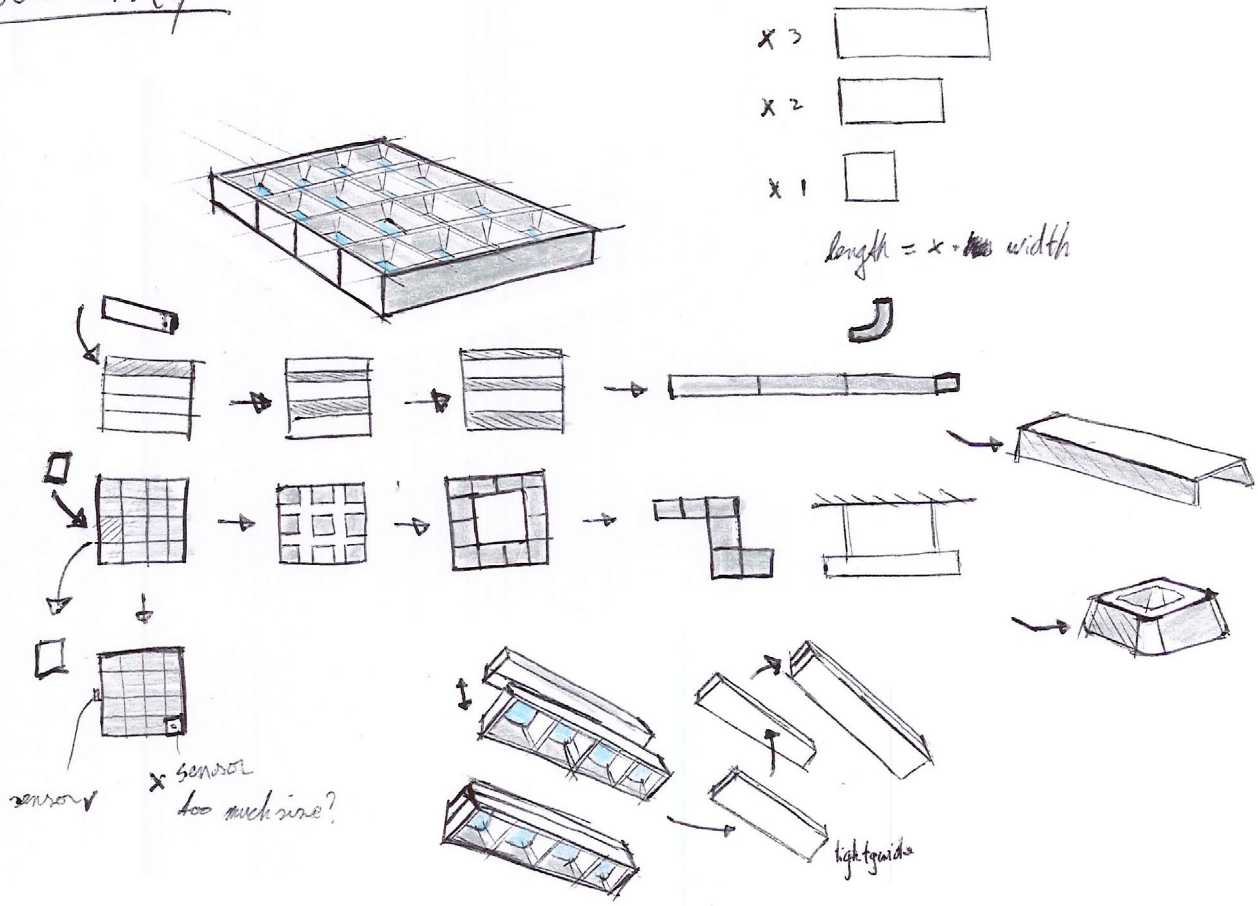


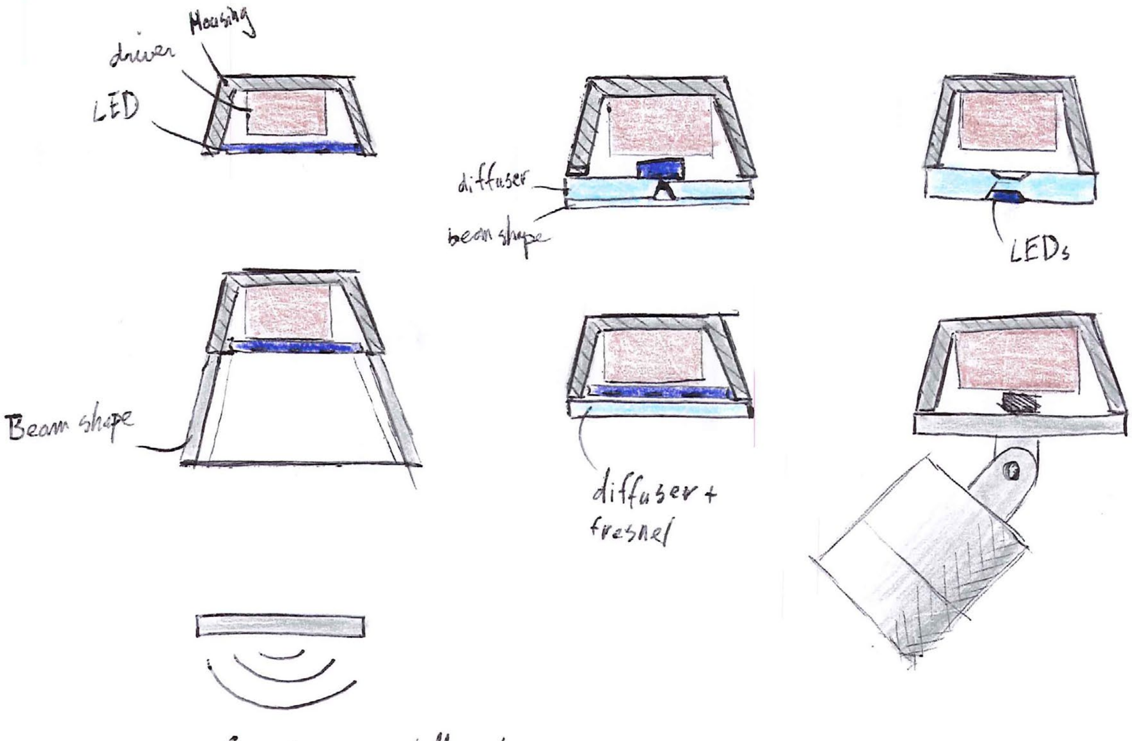






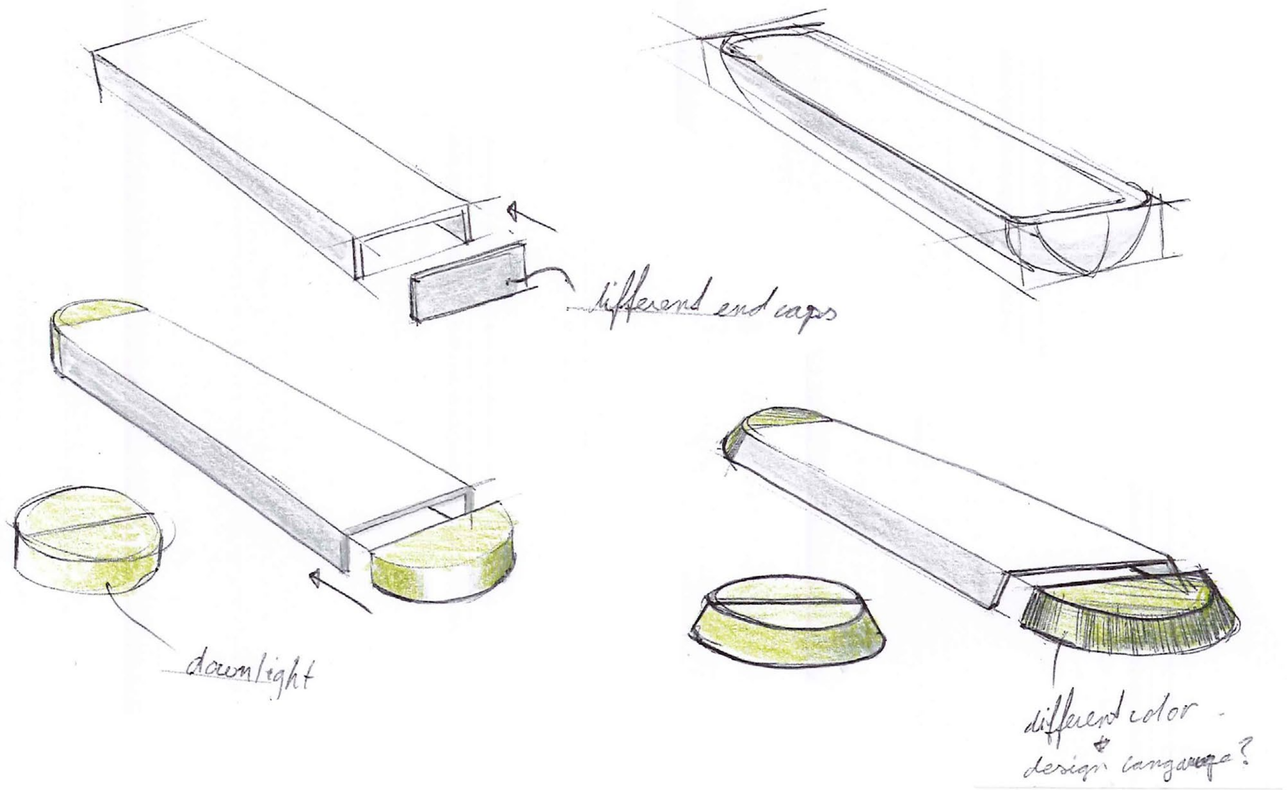
Modularity

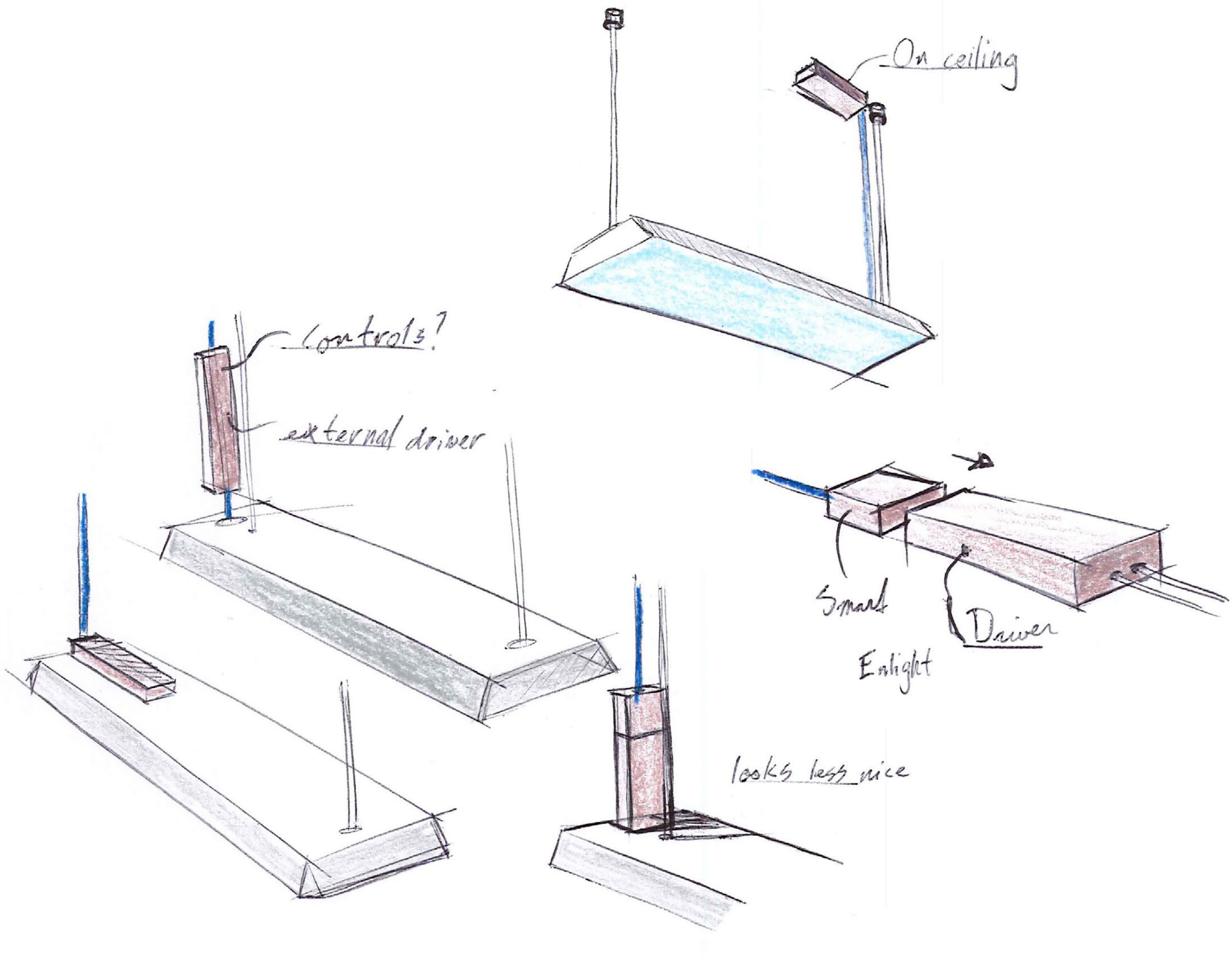




- Sound
- Wifi
- Sensors
- power cord
- on/off cord
- pendel
- beam refocus
- emergency sign

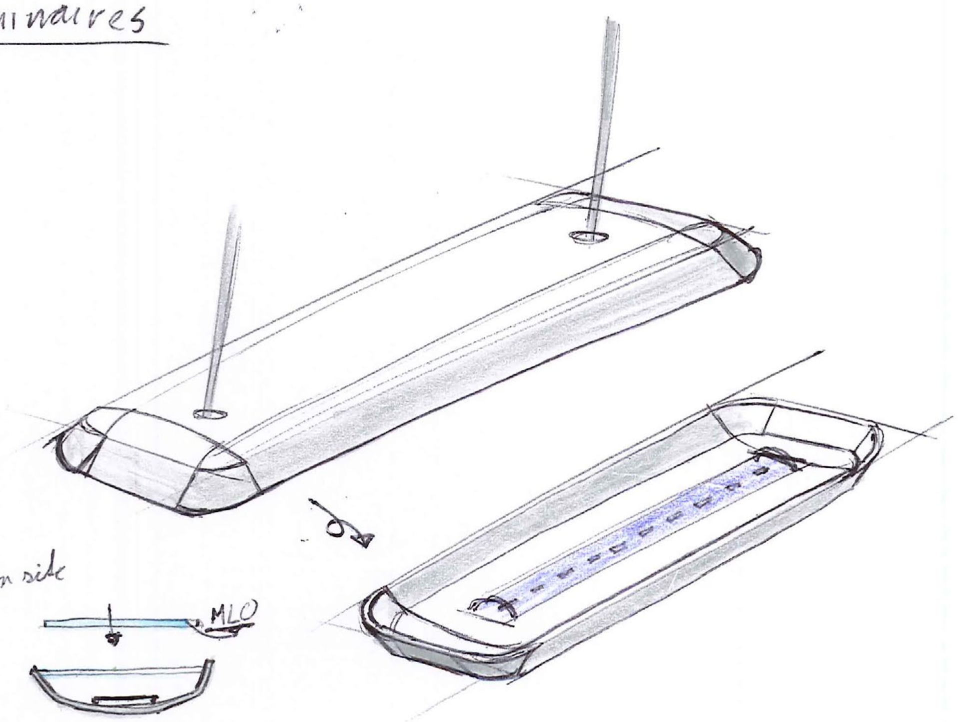
Pendel


differend end caps
downlight
differend color
+
design language?

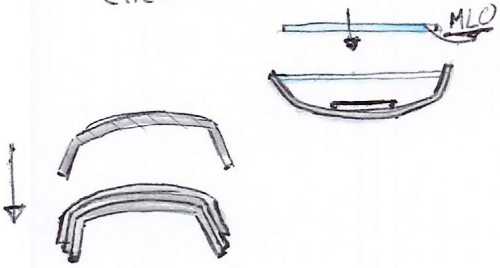

On ceiling
controls?
external driver
Smart
Enlight
Driver
looks less nice

Stack luminaires

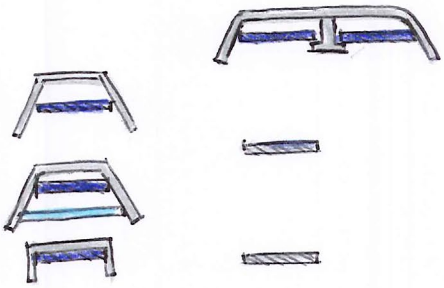
- reduce volume
-



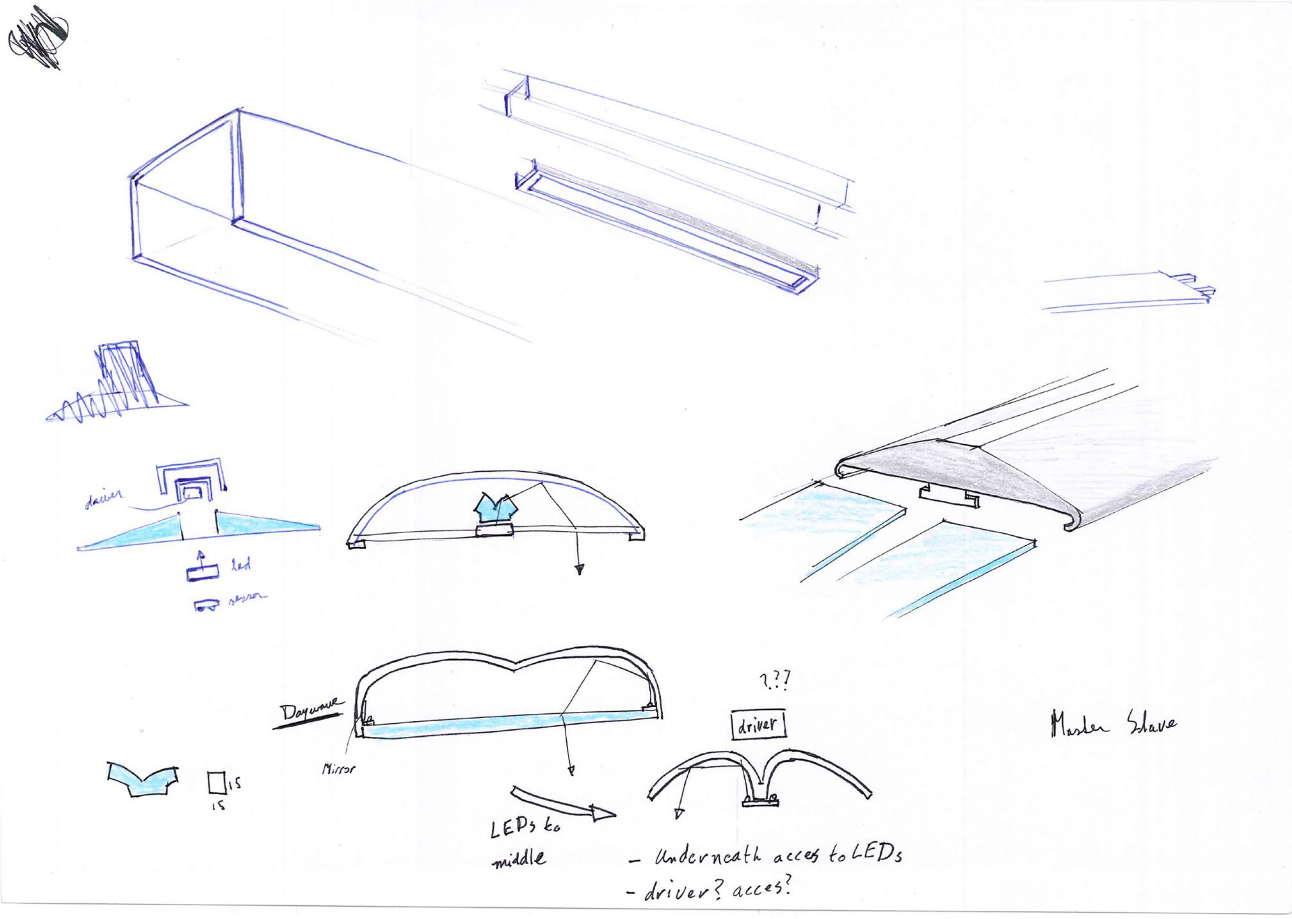
diffuser
click in on site



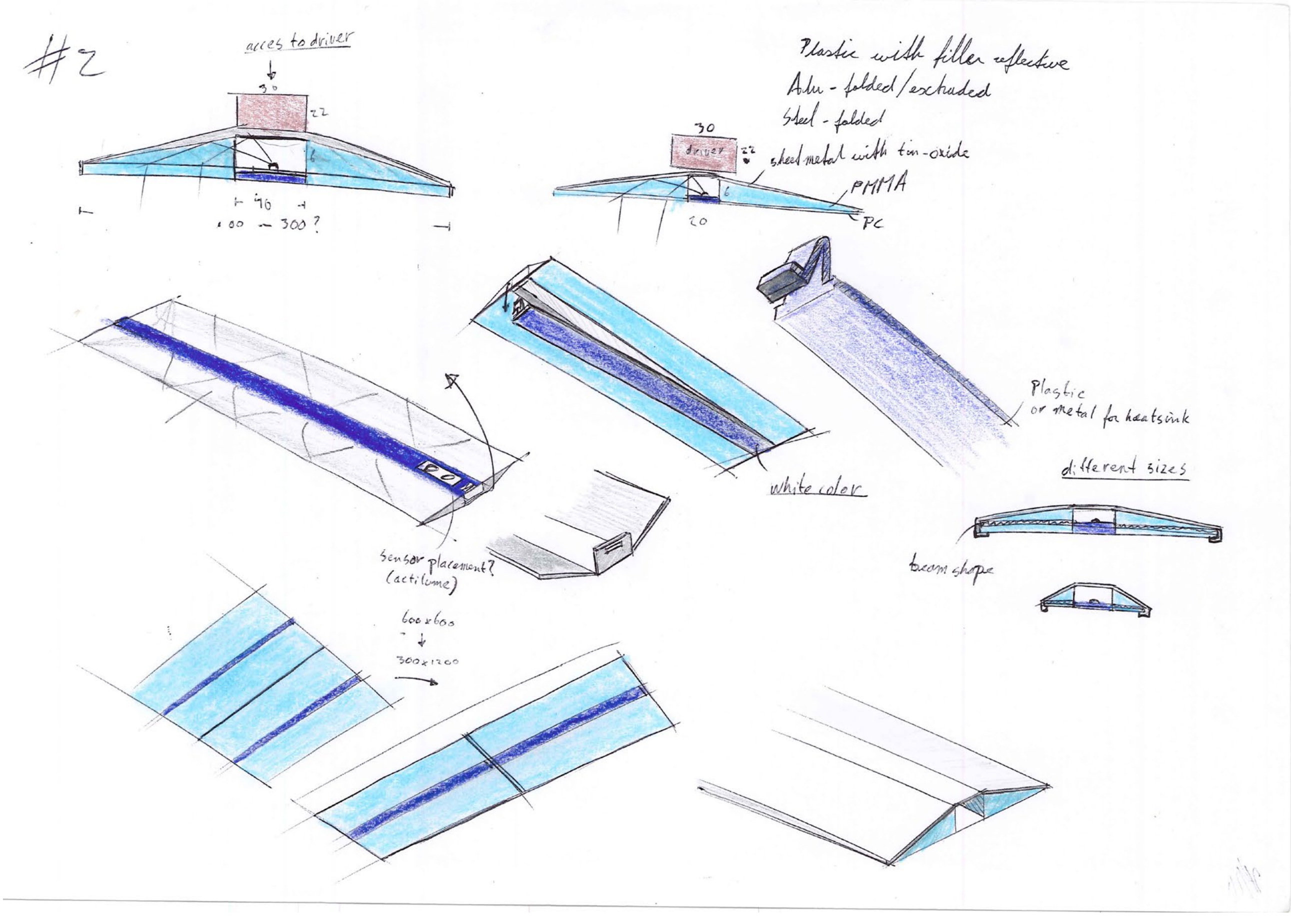
Standardize LED Board



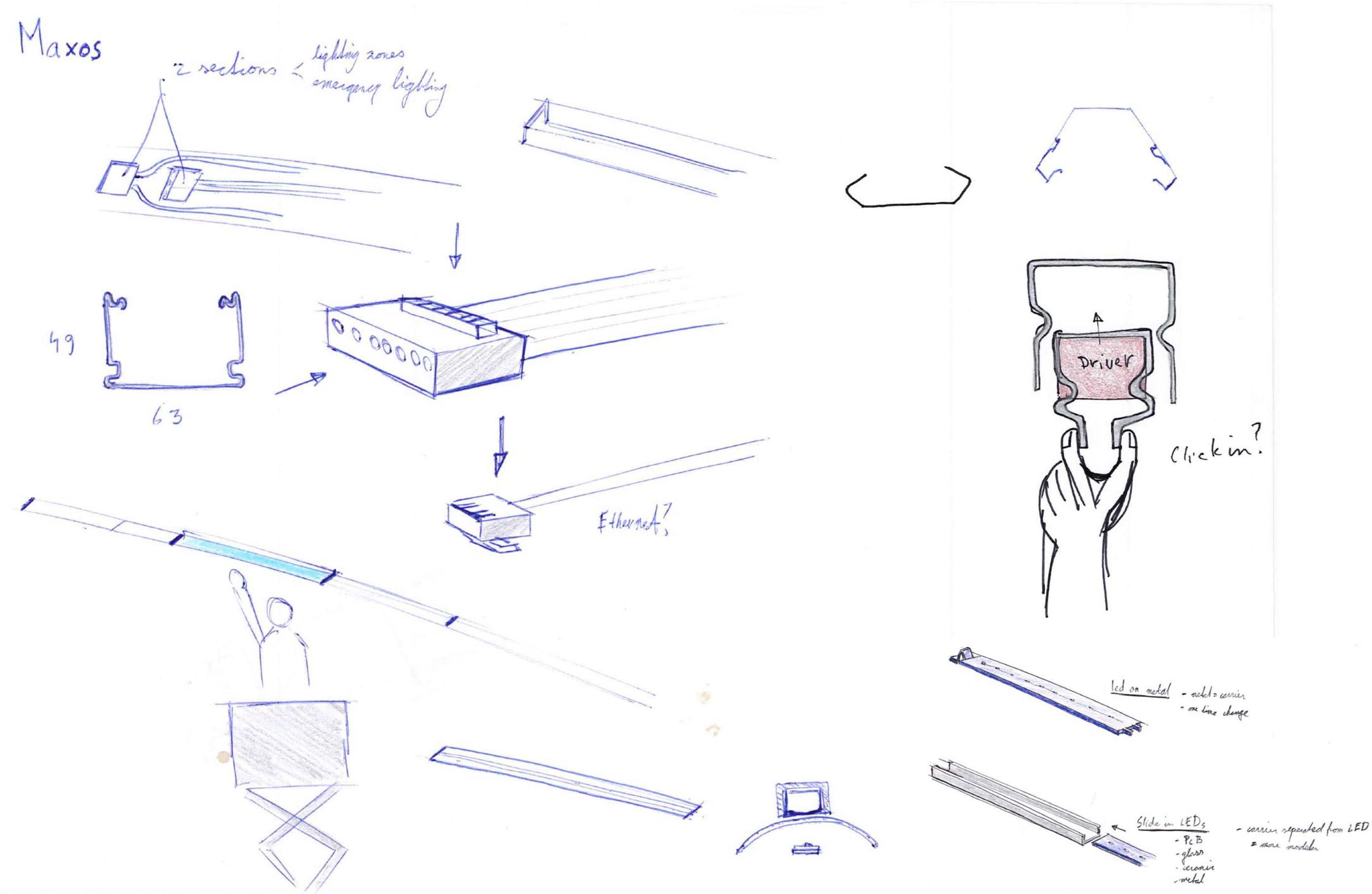
During transport be able to transport more in the office

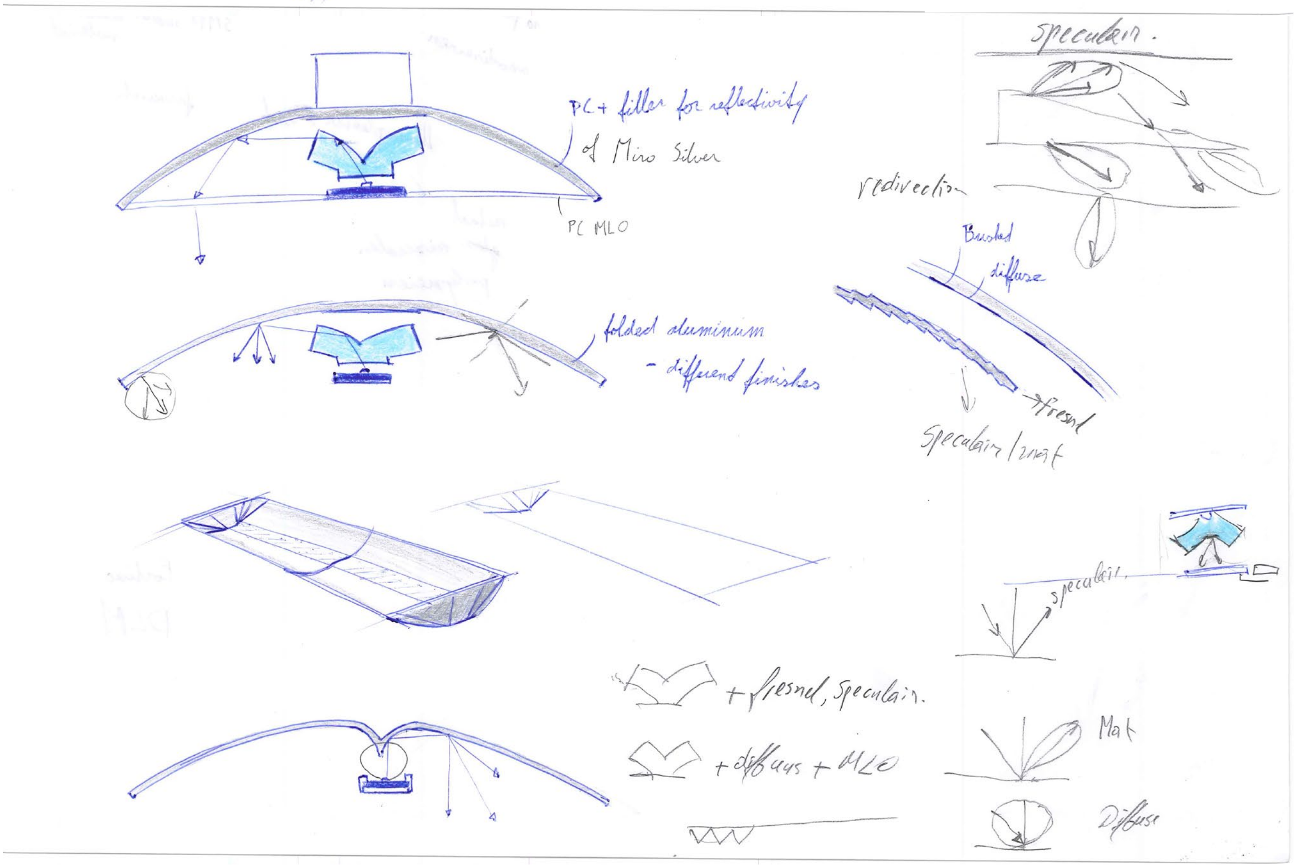


driver
led
sensor
Daywave
Mirror
???
driver
Master Shave
LEDs to middle
- Underneath acces to LEDs
- driver? acces?



#2
acces to driver
30
22
90
100 — 300?
Plastic with filler reflective
Alu - folded/extruded
Steel - folded
30
driver
22
sheet metal with tin-oxide
PMMA
PC
20
Plastic
or metal for heatsink
white color
different sizes
Sensor placement? (actilume)
beam shape
600x600
300x1200


Maxos
2 sections
lighting zones
emergency lighting
49
63
Ethernet?
Driver
Click in?
led on metal
Slide in LEDs
- PCB
- glass
- ceramic
- metal


PC + filler for reflectivity
of Miro Silver
PC MLO
folded aluminum
- different finishes
speculair.
redirection
Brushed
diffuse
fresnel
Speculair / mat
speculair
+ fresnel, speculair.
+ diffuus + MLO
Mat
Diffuse

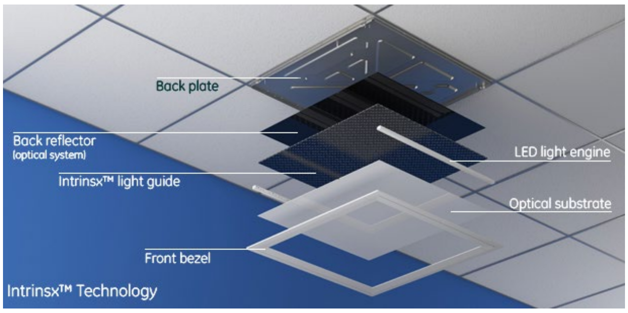
Appendix H. Optics

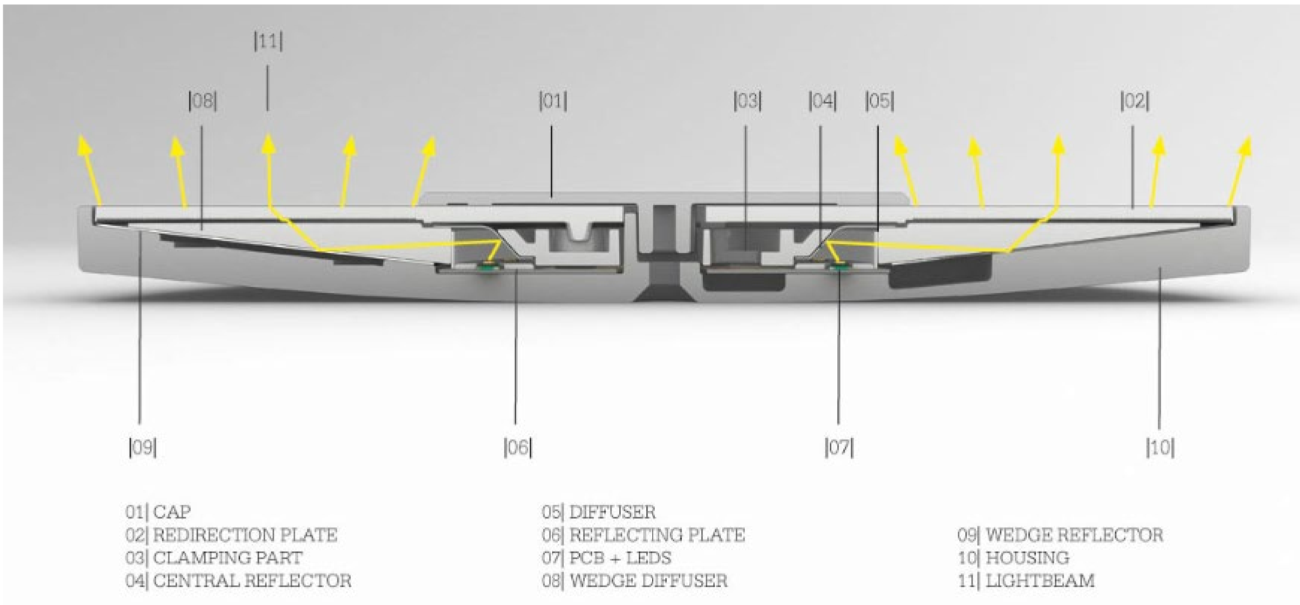
LEDs are very small bright light sources that need optics to deliver light in a desired form. There are multiple options, each with advantages and disadvantages.

Light guide - edge lit

LEDs can be placed on the edge of a transparent plate that acts as a light guide such as in a LCD monitor. It creates a large thin evenly lit surface. The downside is that the LEDs are difficult to acces.

In a variation the LEDs are place next to the edge of a transparent plate. In this case they do not emit light directly to the light guide.





Cup

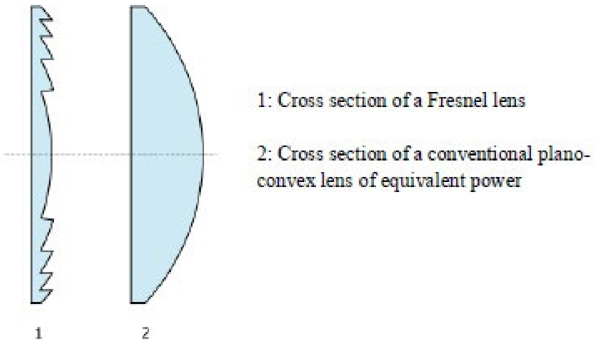
A cup form can be used to distribute and shape the light beam in an efficient way while reducing glare. Cups are used in the PowerBalance and the Lumistone. The downside is that it is difficult to replace the LEDs. When they would be accessible from underneath it could be time consuming to replace every cup, 16 times in a PowerBalance. Accessing the LEDs from the back could be time consuming as well for recessed luminaires.

Lens optic
Lens optics are used to control the distribution of light. It is usually applied in luminaires where glare is not an issue or to distribute light inside a luminaire. For example, in supermarkets a lens optic that creates a double asymmetric light bundle can be used to evenly light the vertical store displays.

Micro Lens Optic (MLO)
A MLO is a transparent plate of AC or PMMA with on one side a micro lens structure for control of distribution and uniformity of light. It is usually applied in office lighting to hide the LEDs and reduce glare.

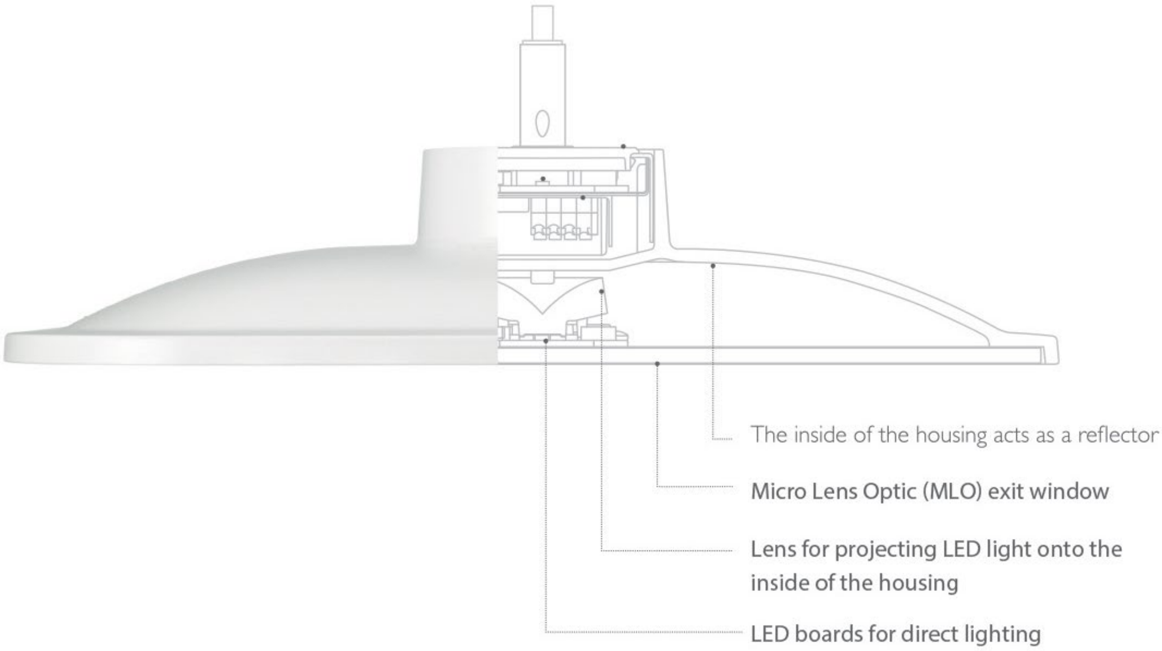
Fresnel

A transparent plate or foil with a fresnel structure to control the distribution of light. It is similar to a MLO but can be thinner when used as a foil.



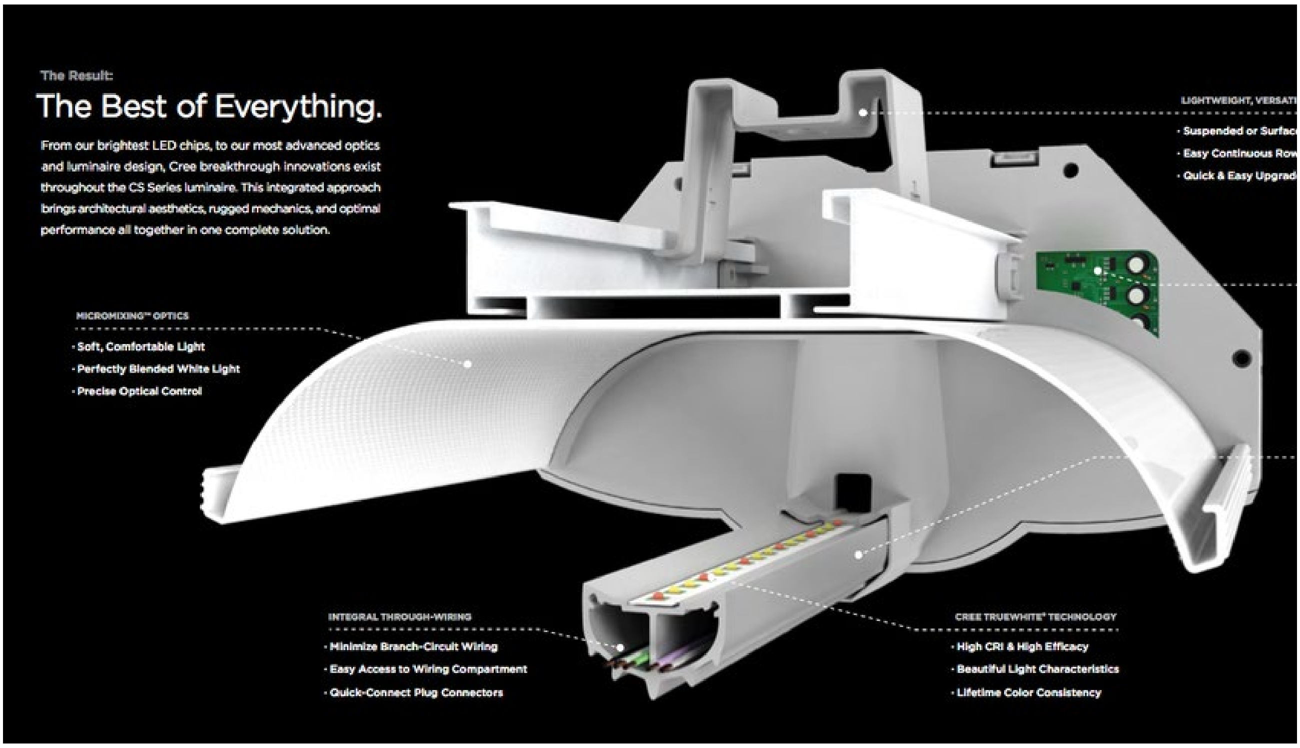
Reflector with optic

Light is distributed by reflection on a surface and then diffused by a plate.



Reflector without optic

Light is distributed by reflection on a surface. The shape and surface finish of the surface can control the distribution of light.



Appendix I. EcoCircular model