

Improving the repairability & recyclability of an outdoor luminaire

Daniël Ouwehand Master Thesis
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Delft University of Technology
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Master Thesis
MSc. Integrated Product Design
Faculty of Industrial Design Engineering
Delft University of Technology

Author
Daniël Ouwehand

Supervisory Team
Chair
Prof. Dr. A.R. Balkenende
Department of Sustainable Design Engineering

Mentor
MSc. S.M. Persaud
Department of Sustainable Design Engineering

Company Mentor
S.J.M. Kuppens
Signify Netherlands B.V.



Preface

When I started my studies, sustainability and circularity was not a priority in my designs and not one of my strengths, resulting in designs barely showed any circularity benefits.

However, in recent years, my love for sustainability has grown and I found it incredibly interesting to create a design with repairability and recyclability as its focus. It created clear goals to work towards, while presenting challenging obstacles to overcome. This made the design process and design itself more complicated and fun than I expected.

Therefore, I hope that this design research can be an inspiration for students, designers, and anyone else interested.

Acknowledgements

Before we dive into the world of circularity, I would like to thank some people for helping me survive the last few months. First of all, Ruud, for always giving clear and direct feedback on my attempts at academic writing. Stefan, for helping me get through the struggles of the chaotic process we call design.

Furthermore, I would like to thank Simon, for being a great sparring partner and teaching me different views and new design methods. My other colleagues at Signify have also been a great help, being able to use your expertise and knowledge.

Finally, I would like to thank my parents for supporting me in moments of stress, and my friends for accepting me back after months of radio silence.

Abstract

This research aims to improve the balance between repairability and recyclability of an outdoor luminaire. For this, an existing outdoor luminaire, the Luma Gen2, was used as a case study. The product architecture of the Luma was analyzed, as well as its performance in the context of repairability and recyclability.

The repairability analysis showed that certain priority components are easily reachable and require few tools. However, the theoretical repair practices of the GearFlex box were not always experienced in the field and resulted in the need for individual driver replacement. Furthermore, the L2 was difficult to reach as it requires upside down disassembly.

A shredder experiment showed the recyclability of the Luma. Most of the aluminum of the Luma ended up in the non-ferrous fraction and the wires and electronics were mostly liberated. The bolts used for the spigot, glass clamps and ground wires did not liberate and were mostly found in the wrong fraction. Also, certain materials were used that are difficult to recycle, like PC, PMMA, and Silicon rubber.

To determine what an optimized design of an outdoor luminaire could look like, 2 concepts and a full redesign of the Luma Gen2 were made. Experts ranked the concepts and found them to show improvements in both repairability and recyclability. The selected concept was developed further and turned into a functional prototype. This prototype decreased the time of a driver and L2 repair with a factor of 9. The recyclability of the prototype is also assumed to be significantly improved.

Furthermore, existing design guidelines regarding repairability and recyclability were presented and used during the concept development phase. These guidelines were analyzed on their usefulness and application to this specific product group and were adjusted accordingly, resulting in a suggested set of design guidelines on the repairability and recyclability of outdoor luminaires.

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Terminology

L2
A metal core printed circuit board that includes the LED's used to output light.

Spigot
The part that facilitates the interface between the luminaire and the pole.

Driver
An encapsulated module containing a circuit that provides the necessary power and current to operate the L2 and other components in the luminaire. In this report, driver refers to the entire driver module, meaning the electronics and housing of said electronics.
A
Liberation
The coming apart of multi-material parts by physically breaking them loose in the shredder of a recycling plant.

Fragment
The resulting pieces of material after shredding.

Homogeneous
Fragments consisting out of a single material.

Heterogeneous
Fragments consisting out of multiple different materials.

Separation
The mechanical (and sometimes manual) sorting of waste streams of shredded material.

Fraction
The resulting waste stream containing a specific type of material.



Chapter 1.
Introduction

In recent times, there has been a growing emphasis on sustainability and the reduction of our environmental impact. Various methods have been employed to achieve these goals. One area of focus is the creation and production of products that are easier to repair and recycle.

In the field of lighting, outdoor luminaires are a prevalent product that can have a significant impact on the environment if not designed with repairability and recyclability in mind. Their size, manufacturing materials, and electrical components make them an intriguing product to examine.

1.1 Circular Economy Framework

This design research is based on research by Balkenende et al. (2017) on design for the circular economy, in which multiple design perspectives are presented that focus on either extending or closing the product resource loop (Figure 1).

“Design for durability” focuses on increasing the durability of the product. While not the focus of this research, durability and reliability will be important for the final design. “Design for product-life extension” includes design for repair, upgradability and remanufacturing. While resulting in different product qualifications, these design directions have much in common. Design for repair will be a focus of this design research. The final design perspective is “Design for recycling”. While recycling usually results in a loss of material, it is the final stage for every product, and therefore also a focus of this design research.

Designing products with a focus on prolonged use/reuse and recycling also decreases the use of critical materials needed for new products (Bakker et al., 2019). This is important as the scarcity and economic criticality of these materials is increasing (Balkenende et al., 2017).

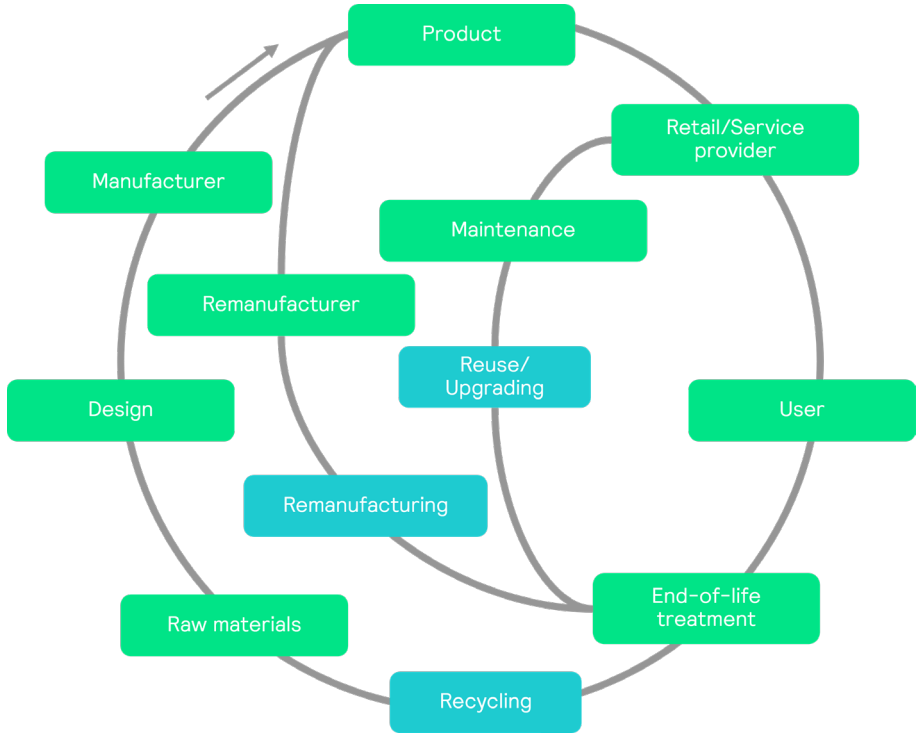


Figure 1: A product lifecycle in a circular economy context (Balkenende et al., 2017)

1.2 Signify

Signify, formerly Philips lighting, is a company of around 30.000 employees with offices all around the world. Their main office is located in Eindhoven, the Netherlands. They are the world leader in lighting design and put great emphasis on the sustainability of their products.

This thesis was done using a specific design case provided by Signify and aims to improve both the repairability and recyclability of the Luma Gen2 luminaire family.

1.3 Luma Gen2 Luminaire

The Philips Luma Gen2 luminaire family is a family of LED luminaires designed by Signify for outdoor use on streets and roads. These luminaires contain valuable materials and are produced in high quantities. They are sold mainly as a B2B product and are expected to survive the outdoor environment for around 50 years, highlighting the importance of their durability and repairability.

1.4 Design Assignment

Due to the long lifetime expectancy of the luminaires, the Luma has been designed with a focus on durability and repairability (Product Architect at Signify, personal communication, 21 May 2024). Signify is interested how this design focus has influenced the recyclability of the Luma, which is currently unknown. Therefore, the aim of this design research is to understand the tensions, opportunities, and challenges related to the repairability and recyclability of the Luma outdoor luminaire.

To determine this, we need to understand the current repairability and recyclability of the Luma Gen2 and how the existing design and product architecture influence these attributes.

Furthermore, Signify would like to have dedicated guidelines for their design team to use during a possible redesign of the Luma. To test these guidelines, a redesign of the Luma will be made, including a demonstrator to validate the (improved) functionality of the concept.

1.5 Research Questions

The goal of this design research is to get a better understanding of important requirements for the design an outdoor luminaire with regards to repairability and recyclability. Furthermore, as part of the design assignment, improvements regarding the repairability and recyclability of an existing outdoor luminaire must be developed into a concept.

To reach this outcome, we need to gain a better understanding of the requirements for the current and future (re)design, leading to the main research question:

Which design requirements are important for the redesign of an outdoor luminaire with regards to repairability and recyclability?

To be able to answer the main research question, three sub-questions must be answered first. The product needs to be analyzed in its current form, resulting in RQ1 & 2:

RQ1: How does the current product architecture determine the repairability of the Luma?

RQ2: How does the current product architecture determine the recyclability of the Luma?

Furthermore, to generate valuable design guidelines for Signify, it is important to know which guidelines already exist and how they can be used in the design process. For this, we need to determine:

RQ3: Which existing design guidelines are important for the design of an outdoor luminaire with regards to repairability and recyclability?

An overview of the research questions, methods, and expected results can be found in Table 1.

Main RQ	Which design requirements are important for the redesign of an outdoor luminaire with regards to repairability and recyclability?		
#	**Research Question**	**Method**	**Expected Results**
RQ1	How does the current product architecture determine the repairability of the Luma?	Hotspot Map & Disassembly Map.	A better understanding of the priority components, time to reach these, pain points
RQ2	How does the current product architecture determine the recyclability of the Luma?	Shredding experiment & Recyclability Map.	Insights into connection liberation, priority components, pain points.
RQ3	Which existing design guidelines are important for the design of an outdoor luminaire with regards to repairability and recyclability?	Literature research into, and analyses of, current guidelines.	A table with relevant guidelines, whether they complement or contradict each other, & how that influences the (re)design of the Luma

Table 1: Research Questions and Approach.

1.6 Research Approach

This design research follows the structure of the double diamond method (Figure 2) developed by Design Counsil (2005).

This method contains four distinctive phases. During the “Discover” phase information was gathered on the subjects of repairability and recyclability. This was done with the use of literature research, conducting interviews with experts, and visiting repair and recycle locations. To gain insights into component liberation of the Luma during shredding, an experiment was carried out.

Furthermore, the Luma luminaire was taken apart to study its architecture and research into existing guidelines regarding repairability and recyclability was conducted.

During the “Define” phase the gathered information was analyzed with the use of a Disassembly Map, Recyclability Map, and Product Journey Map. The pain points and triggers that came out of the initial research and the aforementioned methods were clustered and structured.

During the “Develop” phase a brainstorm session was organized with an interdisciplinary team of Signify employees. During this session, the pain points and triggers were ideated on using the “How-To” method to find interesting ideas to and perspectives to explore the solution space.

To refine the solution space and determine the problems to be solved, the ideas from the How-To method were structured using multiple C-boxes. This resulted in 7 solution directions, tying into 4 overarching problems. During a second, more extensive brainstorm, multiple ideas were generated to solve these 4 problems.

During the “Deliver” phase, the compatibility of the ideas was assessed with the use of a morphological chart. Using the guidelines mentioned before, 2 concepts were chosen. 1 from a repairability perspective and 1 from a recyclability perspective. These 2 concepts were then ranked by experts using a Pugh matrix, both on concept and function-level. The selected concept was further developed, prototyped, and tested to demonstrate is improved repairability and recyclability.

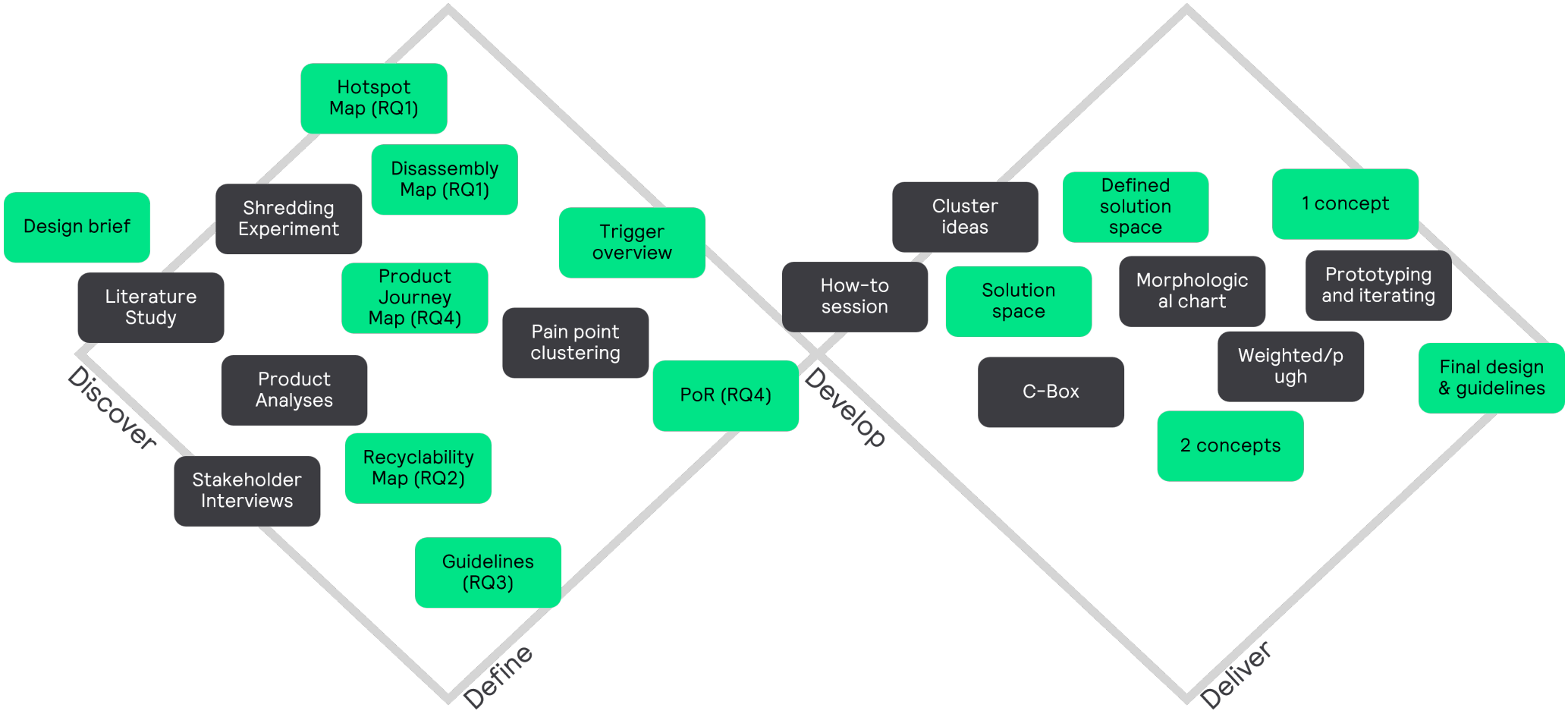


Figure 2: Design approach following the double diamond method. The grey squares are actions performed, the green ones are the deliverables.

Chapter 2.
Background

This chapter outlines background information that is important to understand for this report.

2.1 WEEE

Currently, the increase in electrical waste is a big problem. With the advancements in technology and the increasing dependance on connected devices, this waste stream will only increase. In 2021, the generation of Waste Electrical and Electronic Equipment was growing at a rate of 3-5% per year (Shittu et al., 2021).

To combat this increase in e-waste, the European Parliament introduced the WEEE directive (2012). This directive has the objective to improve the sustainability of WEEE by addressing the production, consumption, prevention, re-use and recycling (European Parliament, 2012).

WEEE can contain hazardous materials like mercury, cadmium, flame retardants and others. They can also contain valuable materials like copper and gold (Zhuang, 2019). This makes the recycling of WEEE both very difficult and important.

Luma as WEEE
The WEEE directive includes many types of equipment that require electrical power to work, amongst them lighting equipment as a specific WEEE category. Therefore, the recyclability testing and experimenting in this design research have been done at a recycling company specialized in the recycling of WEEE.

2.2 Repairability

One of the key factors in determining the circularity of a product, is to assess its repairability. The ease of repairability directly influences the Reuse, Upgrading, and Remanufacturing loops from the framework by Balkenende et al. (2017).

A lot of awareness is being generated recently regarding repairability. The European Counsil gave her final approval for the directive on common rules promoting the repair of goods (Council of the EU, 2024), further increasing the need for companies to focus on the repairability of their products.

To test the repairability of products, multiple scoring systems have been developed. Dangal et al. (2022) made a comparison of these scoring systems. How a product is designed and what the product architecture looks like, can greatly influence the repairability. This is generally determined by the ease of disassembly, information provision, accessibility of priority components, modularity, and standardization of components and interfaces (Dangal et al., 2023). For this design research we focus on the disassembly, accessibility, and modularity of the Luma as these are important aspects for the maintenance of outdoor luminaires. Since the Luma uses specific drivers and LED boards, changing the interface of these components is out of scope.

2.3 Recyclability

The recycling of WEEE requires a specialized process as it involves the processing of hazardous and valuable materials, which can pollute waste streams (Managing Director at a WEEE recycler, personal communication, 30 May 2024).

For this research, the recycling practices of a Dutch WEEE recycler have been taken as a reference. Currently, they are one of the biggest recyclers of WEEE in the Netherlands, processing over 80.000 tons of WEEE per year (Managing Director at a WEEE recycler, personal communication, 30 May 2024).

Their recycling process shown in Figure 3 is based on their recycling practices and specified for the different components of the Luma Gen2.

It starts with manual depollution of the incoming waste stream. Batteries and other hazardous components are removed by hand by workers standing next to the belt.

This is followed by the waste stream going through a shredder, where it is cut into small pieces using rotating cutting knifes. The aim of this stage is to liberate all components and connections into homogeneous fragments (fragments of the same material).

After that, the stream of fragments undergoes a series of separation methods. This should result in the homogeneous fragments ending up in the correct fraction. Furthermore, the heterogeneous fragments (consisting of multiple materials) should end up in either the most valuable fraction, or the fraction where they are least likely to pollute said fraction.

The separation starts with magnetic separation stage, in which the ferrous materials are separated from the stream of fragments. This is followed by an eddy current stage, in which the aluminum is separated. Afterwards, the remaining metals are separated with the use of induction. These remaining metals are then sorted by hand. The remaining fragment stream is then separated using an image recognition process, filtering out the plastics. All other materials are considered waste. The plastics are then separated in a sink/float bath, filtering out the plastics with a density higher than 1.1. These plastics are considered waste. There are recycling facilities that can separate these plastics further (Galloo Plastics, 2024), however, this is not common practice. Therefore, plastics with a density of 1.1 or lower will be considered more recyclable.

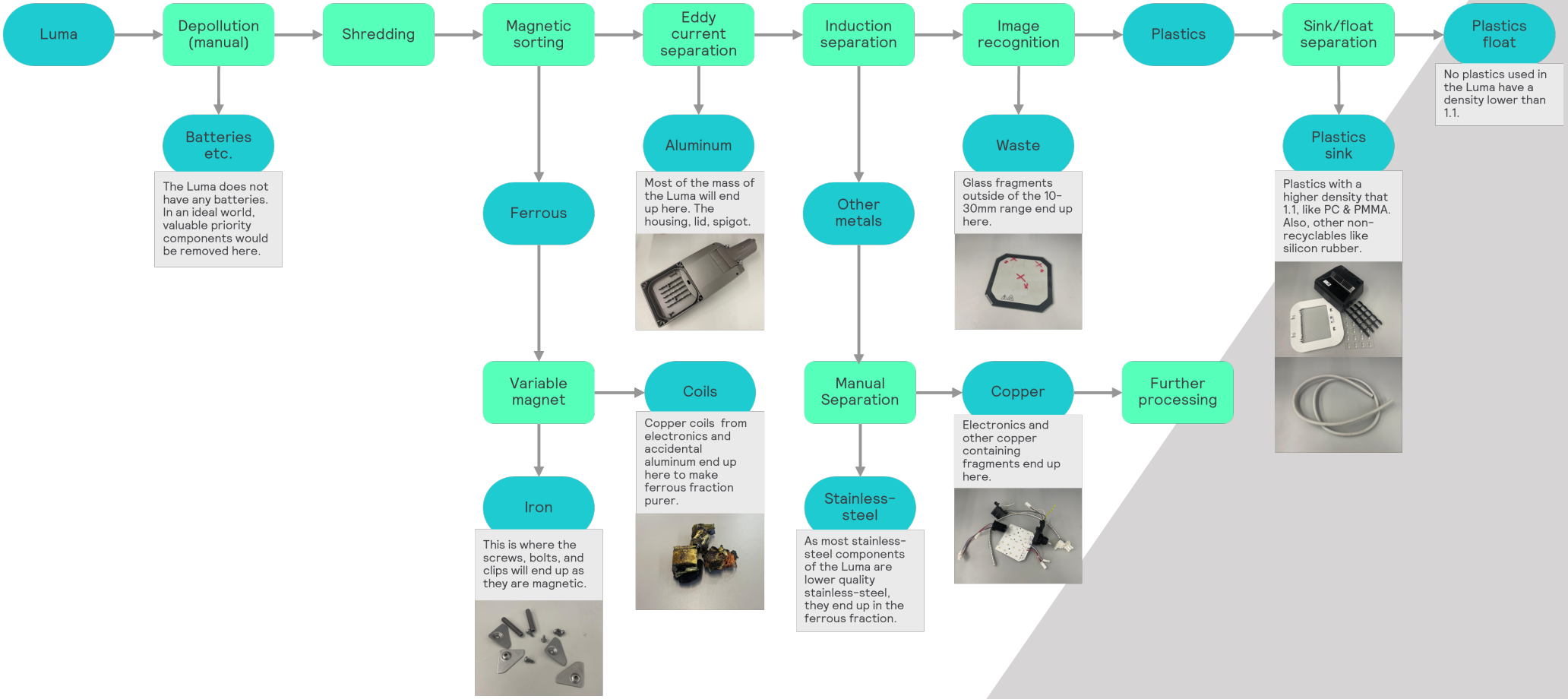


Figure 3: Recycling process based on findings by van Dolderen (2024), specified for the Luma luminaire.

Chapter 3.
Repairability Analysis

In this chapter, the repairability of the Luma luminaire will be analyzed to answer research question 1:

RQ1: How does the current product architecture determine the repairability of the Luma?

This has been done using information from dismantling a Luma Gen2, creating a hotspot map & disassembly map. Furthermore, we conducted literature research, field research and interviewed experts. Details on these methods will be provided in their respective sections.

A photo of the internal architecture of the Luma Gen2 Nano can be seen in Figure 4.



Figure 4: Luma Gen2 with opened lid.

3.1 Bill of Materials

To get a general understanding of the components that make up the Luma luminaire, a Luma Gen2 Nano was taken apart, resulting in the bill of materials (BoM) shown in Table 2. The colored segments in the table indicate the driver and L2 assemblies. Furthermore, an exploded view was created (Figure 5). The numbers in this exploded view correspond with numbers shown in the BoM.

Please note that the exploded view misses the screws holding in the driver and the Starlock washers fastening the latch and driver connector holders. Furthermore, it does not show wires due to model limitations. The BoM is complete.

PART #	NAME	AMOUNT	MATERIAL	WEIGHT (G)	TOTAL WEIGHT
1	Spigot holders	2	Stainless steel	13	26
2	Spigot	1	Aluminum	858	858
3	Glass clamps	4	Stainless steel	1,5	6
4	Glass panel	1	Glass	564	564
5	Glass seal	1	Silicon rubber	54	54
6	Reflector	1	PC	72	72
7	Light blocker	1	PC	14	14
8	Lens	1	PMMA	43	43
9	L2	1	Mixed/electronics	47	47
10	GearFlex box top	1	PC	113	113
11	Driver	1	Mixed/electronics	522	522
12	Driver connectors	2	Mixed/Wires	40	80
13	GearFlex box bottom	1	PC	105	105
14	Rubber bushings	2	Rubber	0,3	0,6
15	Spring plates	2	Stainless steel	0,6	1,2
16	Driver/power connector holder	1	PC	15	15
17	Driver/L2 connector holder	1	PC	15	15
18	Driver L2 connector 1	1	Mixed/Wires	45	45
19	Main power connector	1	Mixed/Wires	131	131
20	Driver/L2 connector 2	1	Mixed/Wires	12	12
21	Driver/power connector	1	Mixed/Wires	53	53
22	Lid support rod	1	Stainless steel	7	7
23	Support rod guide	1	Stainless steel	30	30
24	Lid seal	1	Silicon rubber	66	66
25	Lid	1	Aluminum	1094	1094
26	Locking bar	1	Stainless steel	17	17
27	Latch	1	Aluminum	67	67
28	Main body	1	Aluminum	2761	2761
29	T20 12mm	15	Stainless steel	1,5	22,5
30	T20 14mm	2	Stainless steel	1,6	3,2
31	Strarlock washers	5	Stainless steel	0	0
32	Spring steel pins	2	Stainless steel	1,7	3,4
33	A6 Hex bolt	2	Stainless steel	25	50
34	A4 Hex bolt	2	Stainless steel	13	26
				TOTAL	**6923,9**

Table 2: Bill of materials of a Luma Nano Gen2.

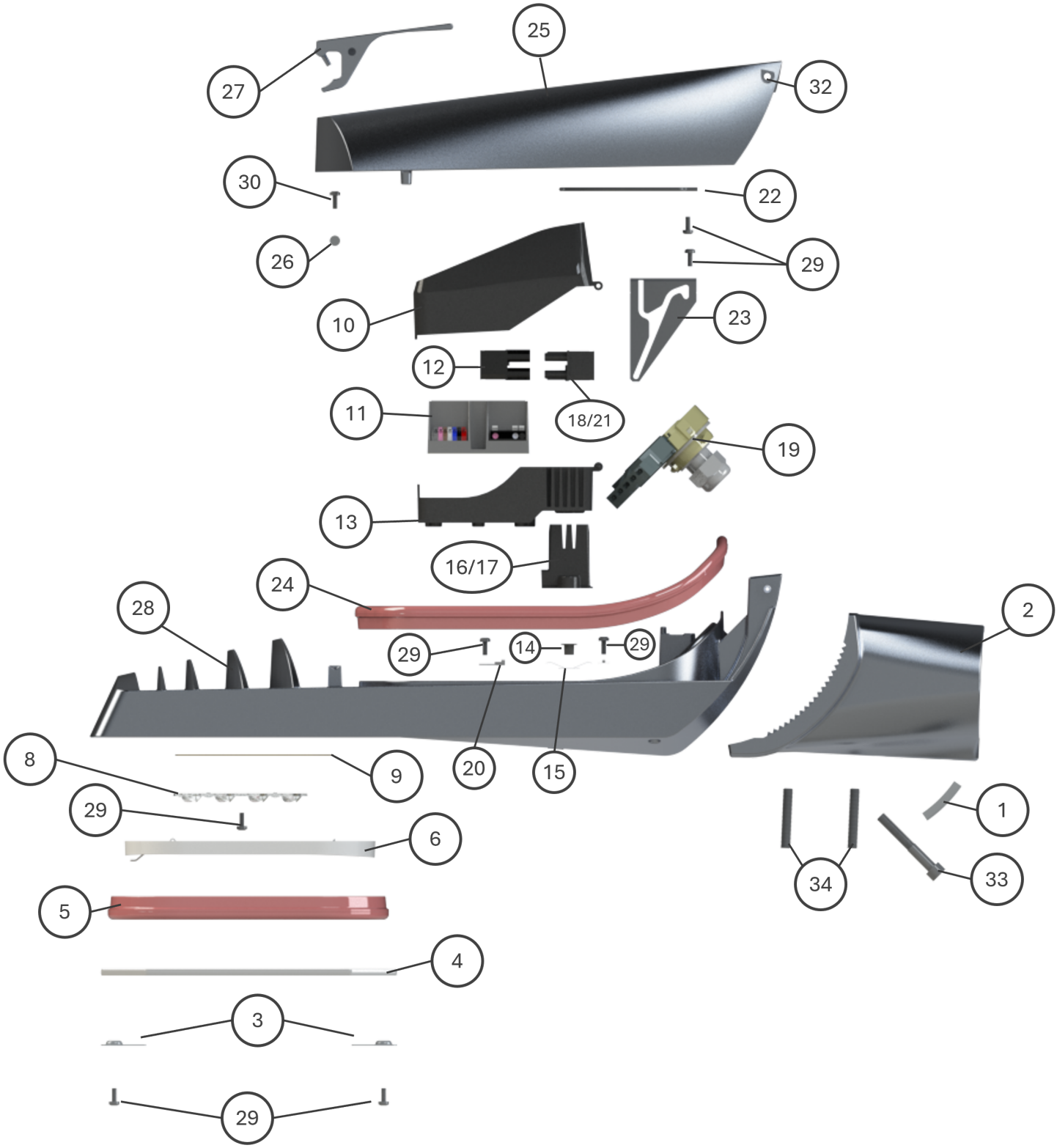


Figure 5: Exploded view of a Luma Nano Gen2. The number correspond to the numbers in the BoM.

The bulk of the Luma Gen2, around 70%, is made from aluminum. The other 30% consists mostly of the driver and glass panel. Aluminum is relatively valuable and well-separable during the recycling process. Therefore, good liberation of the aluminum should be considered for the new design.

3.2 Hotspot Map

To assess which parts inside the Luma gen2 are most critical for ease of disassembly, a hotspot map was generated following the method described by Flipsen et al. (2020). The full hotspot map can be found in Appendix B.

Critical parts are parts with a high failure rate or maintenance need and/or with a high economic or environmental value.

The hotspot map makes a distinction between parts with a high failure rate, parts with high environmental value and parts with high economic value. An overview of these priority parts can be seen in Table 3.

Failure	Environmental	Economic
Driver	Driver	Driver
L2 LED	L2 LED	L2 LED
Glass Seal	Lid	Lid
Lid Seal	Spigot	Spigot
	Main Body	Main Body
	Wires	Wires
	Latch	

Table 3: Luma Gen2 priority parts.

Most priority components are both environmentally and economically important. The driver, LED panel, and seals are considered highest priority for repairability, as they are more susceptible to failure while essential for the functionality of other components or the luminaire as a whole.

This is confirmed by internal research at Signify (personal communication, 6 May 2024). Reliability testing and the analysis of customer field returns show that the driver, L2 and seal failures are the reason for most returns; the cause of failure can be wearing out of components, lightning strikes, or vandalism. Enabling easy service on these priority components should be considered when redesigning the Luma.

Furthermore, a redesign requires that the luminaire is at least IP66 waterproof to minimize water ingression, as this can cause reliability issues for the electrical components. This can be done by making sure the seal functions properly and will keep doing so after opening and closing of the luminaire.

3.3 Electronics

The Luma gen2 contains multiple electrical parts: the driver, L2, wiring and connectors. Some of these components can be repaired, like the connectors and wires. The driver and L2 units cannot be repaired.

The driver is potted, meaning that the internal electrical components are covered with asphalt. This is done to waterproof the electrical components and make them more shock resistant (personal communication, 1 November 2024). However, this makes any repairs on the driver internals impossible. If, for example, a resistor on the driver PCB burns out, repairs are not possible, and the complete driver unit is disregarded.

The same is true for the L2, which is made from an aluminum plate with copper tracks printed on top. The LED's are soldered on the copper tracks and a thin layer of white paint is applied to the remaining surface. The aluminum plate is needed to disperse the heat generated by the LED's to the housing. However, it means that the soldered LED's are difficult to remove and repair, which is therefore economically not feasible. If one LED fails, the complete L2 is replaced.

A driver without potting would enable the repair of internal components, resulting in less waste. Individually replaceable LED's on the L2 would have a similar effect. Redesigning the driver and L2 are out of scope for this research project, as they are standardized modules used in multiple products. The redesign should therefore focus on optimal disassembly and liberation of the driver and L2.

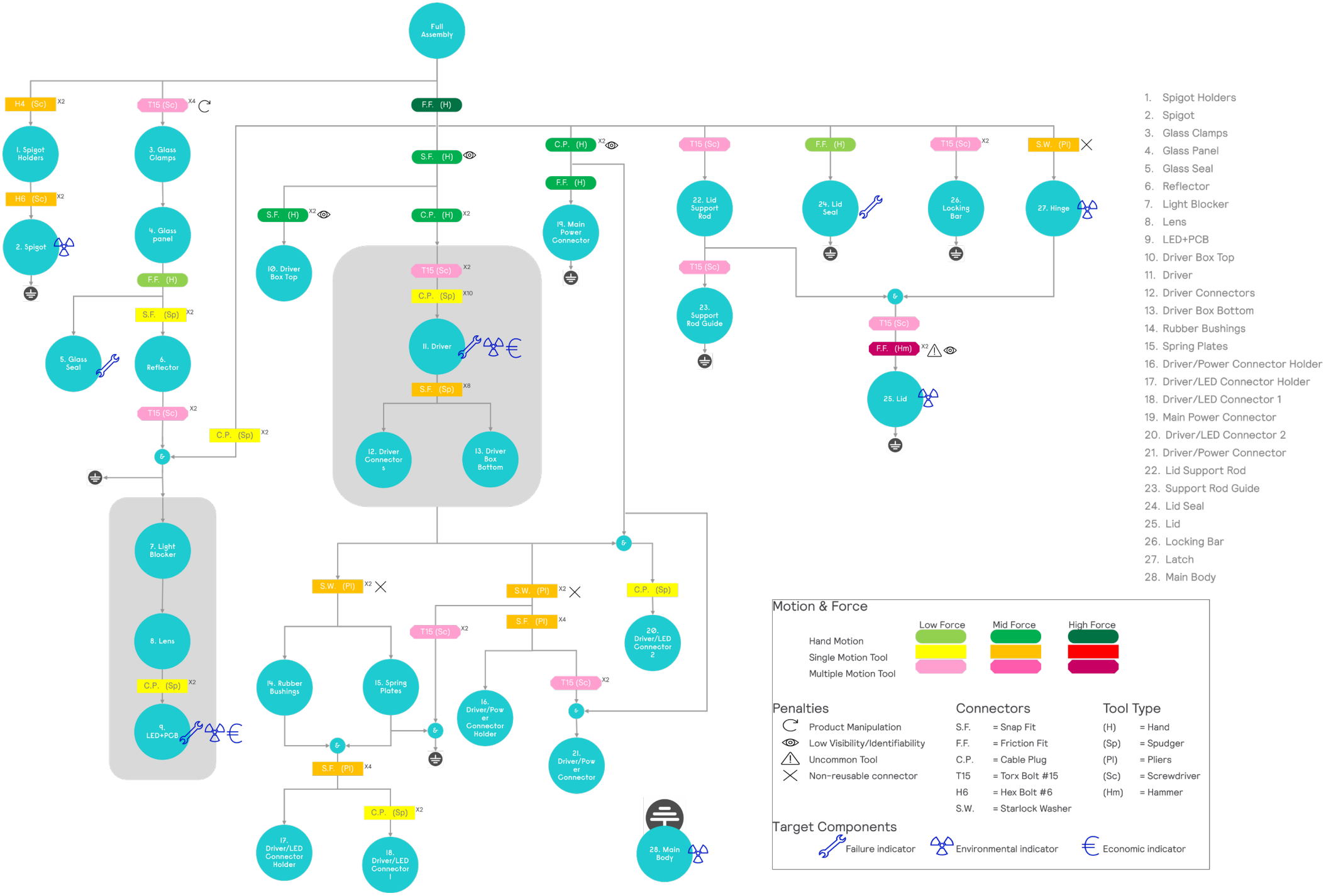


Figure 6: Luma Gen2 Nano Disassembly Map.

3.4 Disassembly Map

As mentioned in Section 2.2., the repairability of a product is to a large extend determined by the ease of disassembly, accessibility, and modularity. This is related to the internal architecture of components and connections. Following the method described by De Fazio et al. (2021), a disassembly map was made (Figure 6).

This map highlights all components of the Luma, how they are connected, and how they are nested within the structure of the Luma with regards to each other.

The driver is located in its own separate assembly (components 10-13, 16 & 17). This black box, hereafter referred to as the GearFlex box, contains multiple components such as the driver and other electrical units like an over voltage protection. This GearFlex box can be swapped without the use of any tools (Product Designer at Signify, personal communication, 11 June 2024). The driver itself is mounted to the GearFlex box by 2 screws and 10+ wires. This makes replacing the individual driver a long and precise process.

To reach the L2, the Luma needs to be opened from underneath. The disassembly map shows that, while only needing to undo 4 screws and 2 cable plugs, the L2 is part of a big sandwich of components, making it challenging to remove (especially upside down).

One of the most environmentally and economically valuable components, the aluminum housing, is also the base to which all other components are attached. This makes it difficult to separate.

Most components of the Luma are connected using stainless steel screws. These screws are tapped directly into the aluminum body, making them easy to remove. Some parts, however, are connected using Starlock washers (Figure 7). These Starlock washers are tricky to remove and are meant for single use only. Finding solutions to use reversible fasteners would be beneficial for repairability. A potential redesign should take this into consideration.



Figure 7: Starlock washer.

3.5 Repair Practices

To understand which service and maintenance practices exist, interviews have been conducted with a Product Manager Outdoor and Product Marketeer of Signify. The lists of notes can be found in Appendices C & D respectively.

Furthermore, a repair session of broken luminaires has been attended to assess the real-life repair practices. We were able to observe a repair crew that repairs Signify luminaires within a certain area of northern Belgium. A list of notes can be found in Appendix E. Figure 8 shows repairs being conducted on the GearFlex assembly. Here, the person is attaching the individual wires to the driver. Figure 9 shows the luminaire placed upright due to the orientation of the spigot.



Figure 8: The repair team working on a Gear-Flex box.



Figure 9: The repair team working on an upright mounted luminaire.

The idea of the GearFlex Box is to allow for quick & easy on the spot replacement of the electronic components. However, the large variety in driver/GearFlex box combinations can require customers to keep a lot of stock. Therefore, some of Signify's customers prefer to collect the failing luminaires and bring them to a central repair hub (Repair crew, personal communication, 12 June 2024).

At the repair hub a diagnostic is done to find out which component is causing the failure. When this is the driver, it is replaced in the GearFlex box by a new one (Figure 8). This process is more time consuming and precise than swapping out the GearFlex box and is therefore done at a central repair hub instead of on the spot, which can be environmentally challenging and expensive (Product Marketeer at Signify, personal communication, 26 June 2024). Changing the driver can involve detaching and re-attaching multiple wires (in some case as many as 10).

For the time being, a temporary luminaire is put on the pole. The downside is that a servicing crew must dismount and mount a luminaire twice.

Feedback gathered through discussions with product management at Signify (Product Manager at Signify, personal communication, 8 October 2024) shows that customers that do repairs on-the-pole would also like to see easier replacement of the control gear. In the redesign both ways of repair should be addressed.

When it comes to replacing the L2, customers mention that it takes too long to do so (Product Manager at Signify, personal communication, 10 June 2024). This is caused by the L2 being mounted upside down, behind multiple layers of other parts. This makes on the spot L2 replacements very impractical. Even though the L2 has a lower chance of failure (Section 3.2.), it is a priority part in all three categories (failure, environmental, and economic), and should therefore be easy to repair.

3.6 Conclusion

Previous research was conducted to answer SQ1: How does the current product architecture determine the repairability of the Luma?

The hotspot map shows that the priority parts for repair are the driver, L2, and seals.

While most components are easily repairable, the driver and L2 lie deep within the architecture, making them more difficult to remove. The driver is potted and the L2 is a metal core PCB, making repairs on individual electrical components impossible and resulting in the need to swap the complete driver and L2 modules when broken.

Furthermore, observing a repair crew has shown that repairs are not always performed in the way they have been intended. The driver is placed within the GearFlex box, enabling the repair crew to switch the complete boxes. However, individual drivers are replaced instead of the GearFlex box. A redesign should therefore offer a better solution for individual driver replacement.

Water ingress is one of the causes for the failure of priority parts. Therefore, a redesign should offer the possibility to keep seal the internals, keeping the water out.

The depth of the L2 in the product architecture and the upside-down removal of components make the L2 difficult to remove. As the L2 is a priority component, easier removal should be accommodated.

The ease and time of repair of the Luma should make repairs on the spot the favorable option, resulting in less movements.

To answer research question 1, the above insights have been summarized in Table 4.

Conclusion	Desgin Implication
Priority components are the driver, L2 and seals.	Driver and L2 should be easily removable. Seals should not fail.
The individual driver and L2 lie deep within the architecture.	Driver & L2 should have faster removal and better accessibility.
Repairs are not always done on the spot as intended due to difficult and long repairs.	Repairs should be easy and fast enough to make repairs on the spot the favorable option.

Table 4: Repairability analysis conclusion.

Chapter 4.
Recyclability Analysis

In this chapter the recyclability of the Luma Gen2 will be analysed to answer research question 2:

RQ2: How does the current product architecture determine the recyclability of the Luma?

This has been done by conducting a shredder experiement to determine the material liberation and fraction purity of the Luma Gen2 during the recycling process. Using these findings, a recyclability map has been made.

4.1 End-of-Life Scenarios

From the conducted research and interviews it became clear that there are currently multiple scenarios regarding the end-of-life treatment of the Luma. These scenarios depend on the luminaire collection logistics and recycling practices of different recyclers.

The ideal end-of-life scenario would involve (partial) disassembly of the Luma before being processed at a WEEE recycler. This way, valuable materials can be harvested and certain components can be reused. According to the Product Marketeer at Signify (personal communication, 26 June 2024), special logistical companies within the Netherlands facilitate this disassembly.

A less ideal scenario was presented to us by the WEEE recycler (personal communication, 25 September 2024). In their case, disassembly is too labor intensive and not economically feasible. Therefore, the luminaires are directly processed in the shredder, resulting in more polluted waste streams and potential loss of valuable materials.

To create a redesign of the luminaire that can be applied in all scenarios, the latter scenario has been as a guiding principle for the shredder experiment in Section 4.2. and following research in this chapter.

The full scenarios with visuals can be found in Appendix G.

4.2 Shredder Experiment

To determine the behavior of the Luma Gen2 during the recycling process, a shredder experiment was conducted. The full report of the experiment can be found in Appendix H.

4.2.1 Aim

During this experiment, 7 nearly identical Luma Gen2 Mini luminaires were processed in the shredder. The fragments then followed the first two steps of the industrial separation process (magnetic sorting & Eddy-current separation).

This experiment was conducted to obtain answers to two questions:

1. **What is the degree of liberation of the connections within the luminaire?**
2. **How big is the pollution of fractions after separation?**

Answering the first question gave us insights into which connection should be used when redesigning the luminaire, and which should be avoided. Connections that are easily liberated during shredding are preferred when recycling the luminaire.

The second question helped to understand which materials are easy to separate and how they are processed to improve material usage and form language of a redesign.

Please note that, even though the Luma Gen2 Mini is bigger than the Gen2 Nano analyzed in chapter 3, they have similar internal architecture and components and therefore we expect them to behave in similar fashion during shredding and sorting.



Figure 10: The 7 Luma Gen2 Mini's used in the shredder experiment.

Figure 10 shows the luminaires before the experiment. Figure 11 shows the results of the shredding and separation process. The luminaires were painted in different colors to make fragment sorting easier, as well as to have possibility for luminaire-specific fragment retrieval.



Figure 11: The fragments after shredding and sorting. Box #1 contains the ferrous fraction. The two cardboard boxes in box #1 contain electronic components from the "other" fraction. Boxes 2, 3, & 4 are the aluminum fraction. Box #5 is the "other" fraction.

4.2.2 Results

Recovered Mass

It is good to understand the amount of mass that we recovered. Figure 12 shows this per material. Note that this is the total amount of recovered mass, so independent of the fraction the mater ended up in.

It can be seen that we retreived over 80% of the material that entered the shredder. The material we did not manage to retrieve is most likely stuck somewhere within the recycling line. Since we used a limited amount of material, this was to be expected. More material will most likely push the "stuck" material through. However, 80% is still relatively high and it allows us to make meaningful conclusions.

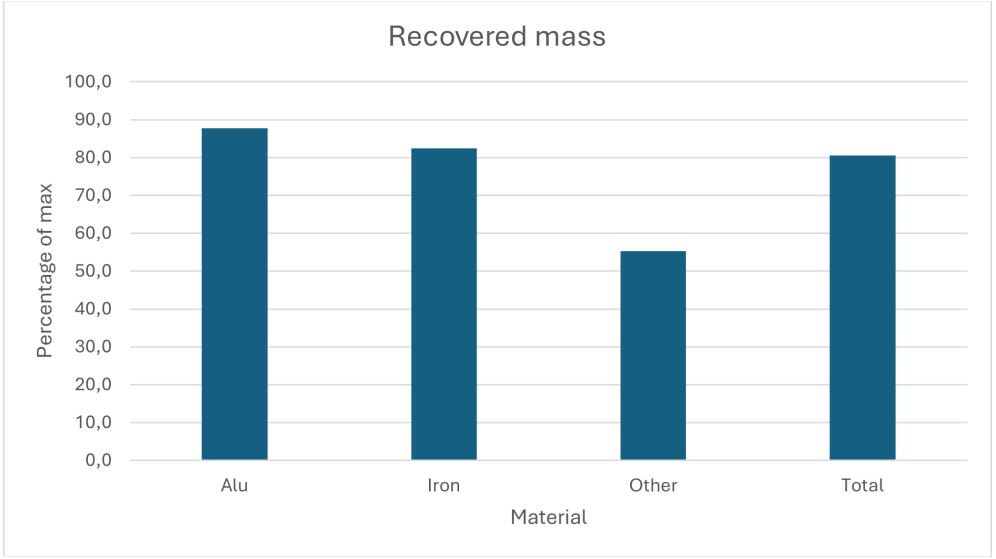


Figure 12: Total recovered mass per material.

Liberation

Figures 13, 14, & 15 show the most common heterogeneous connections. Figure 13 shows the A6 bolts that are still fully present in the spigot. Figure 14 show the A4 bolts holding together the clamps of the spigot. Figure 15 shows the T15 bolt holding in the clamp for the glass panel

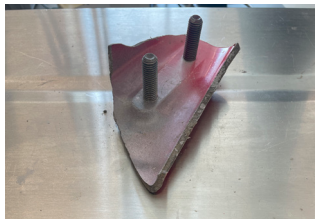


Figure 13: Fragment with A6 bolt.



Figure 14: Fragment with A4 bolt.

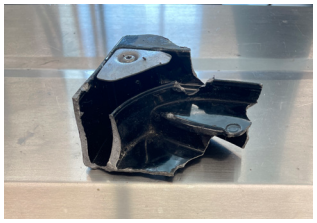


Figure 15: Fragment with glass clamp.

Table 5 shows the liberation per connection. The last three columns are the most interesting to look at. The first shows the minimum liberation, the second the maximum liberation, and the third the average. These values have been adjusted for the maximum amount of recovered material. For example, if a ferrous T15 screw connector was used a total of 100 times, but only 60% of the ferrous material has been recovered, we calculated

Connections	Non-liberated	Liberated	Theoretical max	Adjusted max*	Liberation min	Libration max	Liberation average
A4	10	1	14	**12**	8,7	13,3	11,0
T15	85	10	147	**121**	8,3	29,8	19,0
A6	10	3	14	**13**	23,1	23,1	23,1
Friction Fit	6	2	14	**12**	17,3	48,0	32,7
Snap Cable Plug	15	10	71	**39**	25,5	61,8	43,6
Starlock Small	4	1	35	**29**	3,5	86,1	44,8
Starlock Big	7	4	21	**17**	23,1	59,5	41,3
Snap Fit	34	52	141	**86**	60,5	60,5	60,5
Big polymer nut	1	4	7	**5**	80,0	80,0	80,0
Friction Cable Plug	0	18	24	**18**	100,0	100,0	100,0
Press fit	0	14	14	**14**	100,0	100,0	100,0

* Adjusted values are calculated according to **fraction** recovery. If recovered amount is higher than mass-adjusted amount, this value is used.

Table 5: Liberation results.

with an adjusted maximum of 60% of 100 connectors, meaning 60 T15 connectors as maximum. While not optimal, this does take the material losses into account.

The A4, T15, and A6 screws show the least amount of liberation. The press fitted components, friction cable plugs, and polymer nuts have the best liberation. The small Starlock washers show the largest range, as not a lot of them were recovered.

Fraction Purity

Table 6 shows the fraction purity after the first two steps of separation. These percentages represent the composition of each fraction. For example: the resulting iron fraction contained 57.2% aluminum, 35.3% iron and 7.5 % wires and other materials. Almost all the material found in the aluminum fraction is aluminum, while the iron (ferrous) fraction also consists mostly out of aluminum.

Fraction >	Alu	Iron	Other
% Alu	97,9	57,2	26,6
% Iron	0,9	35,3	3,3
% Other	0,5	0,2	35,4
% Electrical/Wiring	0,7	7,3	34,7

Table 6: Fraction purity results.

4.3 Electronics

As mentioned before, the driver unit is potted, meaning that the driver electronics are covered in asphalt. These electronics consist of almost 200 grams of valuable materials like copper, aluminum, and solder. The shredder experiment showed the potting to be a problem, as the driver electronics are difficult to liberate and often remain encapsulated in pieces of asphalt. These heterogeneous fragments will end up in the “other” fraction, which is sent in its entirety to a smelter. The metals can be recovered, but the asphalt and other materials will be used as fuel for the smelter, therefore decreasing the overall recyclability of the driver.

The L2, which is made from aluminum plates with copper trails on it cannot be recycled properly. The shredder experiment showed that the aluminum, copper and LED’s are not liberated and ended up in the aluminum fraction. The L2 holds around 5 grams of copper, resulting in pollution of the aluminum fraction and loss of copper.

Ideally, the driver would be designed in a way that mitigates the need of potting. This would improve liberation during shredding, allowing for better material recovery. The same can be said for the L2, which could be made from a material that does not end up in the aluminum fraction and is less polluting for other fractions.

4.4 Recyclability Map

Using the method described by Versloot (2024), a recyclability map has been made to better understand the behavior of the Luma during the recycling process.

The recyclability map shows 1) the degree of liberation of connections, 2) whether the parts are recyclable or not, and 3) if there are any valuable or hazardous materials. The colors and percentages indicating the degree of liberation are based on the liberation results from the recyclability experiment in 4.1.

In the method described by Versloot, recyclable and non-recyclable materials are distinguished by a green or red outline. In the recyclability maps shown below, orange outlines have been added. This is done for materials that are theoretically recyclable but are not always recycled in practice, like the PC.

The electronics and wires are also colored orange. This is done as their material is partially recoverable. For example, the copper in the wires and connectors will be recovered in the smelter, while the plastic of the connector itself is used as fuel and therefore lost.

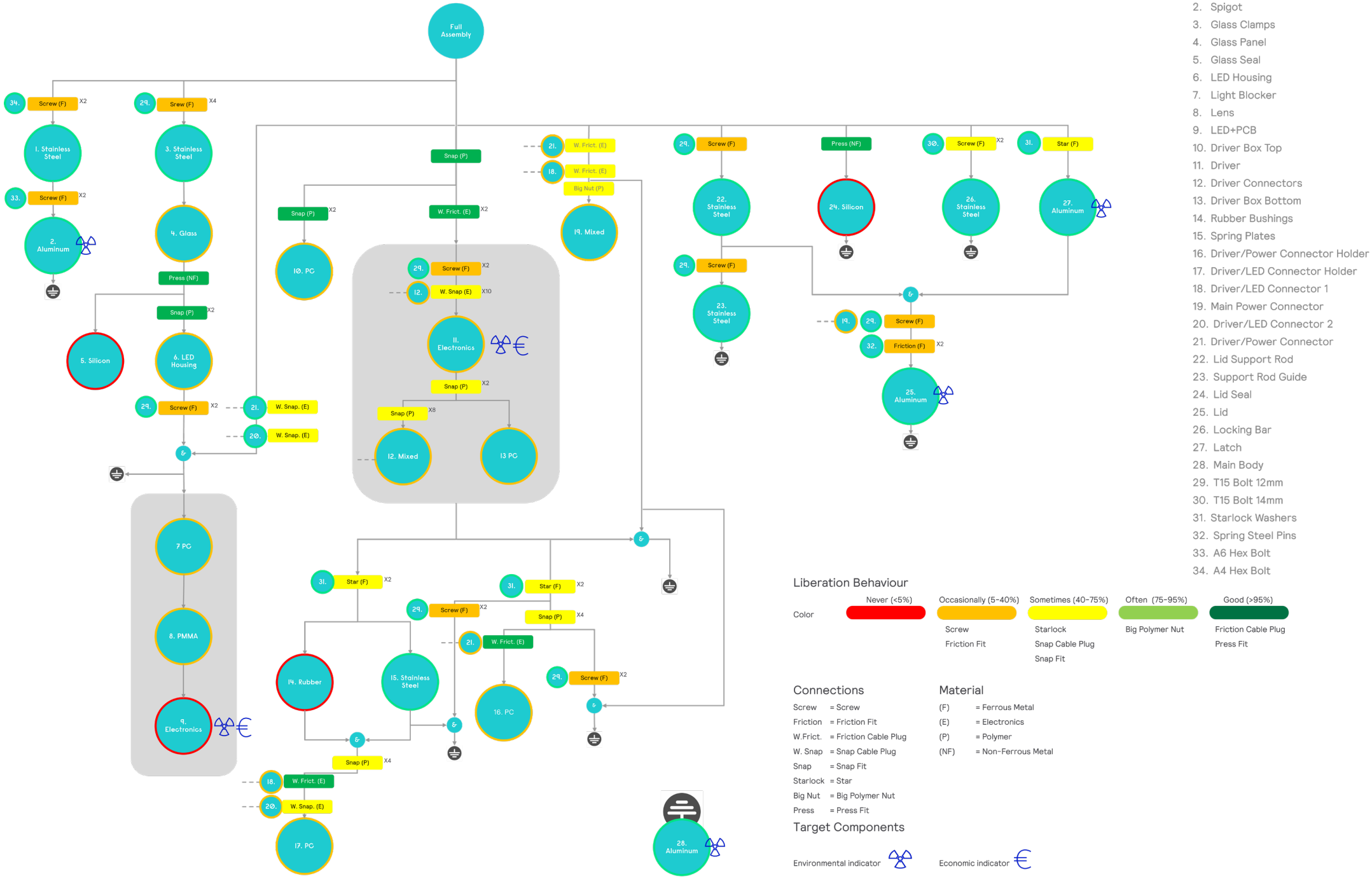
The full recyclability map can be seen in Figure 16.

It shows that there are many screw connections. Results from the shredder experiment indicated that these screw connections are likely to not liberate from the aluminum (between 10 & 25% liberation on average). The A4 and A6 screws have the more mass, resulting in a polluted aluminum fraction when not liberated. The T15 screws hold down the hazardous and valuable parts like the driver and L2.

The L2s contain valuable metals like copper and gold and should therefore end up in the “other” fraction, where they can be processed further to retrieve these valuable metals. However, to facilitate better heat dissipation, the L2 is a Metal Core PCB (MCPCB). This is a PCB printed on an aluminum plate. This means that, even when fully liberated, the L2’s still end up in the aluminum fraction. Facilitating full liberation of the L2 is a priority, but changing the design of the L2 itself is out of scope for this project. Investigating alternative L2 options is however highly recommended.

As mentioned before, the main body is one of the most valuable components, as it consists of a big piece of aluminum. As seen in the recyclability map, most components are attached directly to the main body, either via screws or Starlock washers. This makes it highly unlikely for all parts to separate from the main body.

Due to safety reasons, the whole luminaire is grounded to earth. This is done by attaching wires to both the lid and main body using the T15 screws (with a liberation between 8 & 30%). These copper wires can pollute the aluminum fraction as a low percentage of copper can be very hard to separate in the later stages of the aluminum recovery process. Therefore, a maximum of 0.5% copper is allowed in the aluminum fraction (Process Controller of WEEE recycler, personal communication, 17 June 2024).



1. Spigot Holders
2. Spigot
3. Glass Clamps
4. Glass Panel
5. Glass Seal
6. LED Housing
7. Light Blocker
8. Lens
9. LED+PCB
10. Driver Box Top
11. Driver
12. Driver Connectors
13. Driver Box Bottom
14. Rubber Bushings
15. Spring Plates
16. Driver/Power Connector Holder
17. Driver/LED Connector Holder
18. Driver/LED Connector 1
19. Main Power Connector
20. Driver/LED Connector 2
21. Driver/Power Connector
22. Lid Support Rod
23. Support Rod Guide
24. Lid Seal
25. Lid
26. Locking Bar
27. Latch
28. Main Body
29. T15 Bolt 12mm
30. T15 Bolt 14mm
31. Starlock Washers
32. Spring Steel Pins
33. A6 Hex Bolt
34. A4 Hex Bolt

Figure 16: Recyclability map of the Luma Gen2 Nano.

4.5 Recycling Practices

To get a better understanding of the real-life recycling process of the Luma Gen2, multiple visits to a WEEE recycler have been made.

The aim of the first visit was to get a better understanding of the general recycling process of WEEE. We interviewed the Managing Director (Managing Director at WEEE recycler, personal communication, 30 May 2024). During the second visit, a Luma luminaire was shown and analyzed by the Process Controller (Process Controller at WEEE recycler, personal communication, 17 June 2024). The full notes can be found in Appendix F.

The recycler has a special stream for aluminum with a purity of 95% or higher. This stream will be processed separately and is more valuable as they can promise a purer fraction to their clients. Currently, 70% of the total weight of the Luma Gen2 Nano is aluminum. Calculations were made by the Process Controller to see whether manual disassembly to reach 95% aluminum is worthwhile. They concluded that there was no financial benefit. Therefore, it can be interesting to take the 95% aluminum stream into account when redesigning.

The “other” waste stream (non-ferrous, non-aluminum) is a mix of multiple types of materials. This stream contains most electronics, wires, glass, and plastics. Some of these materials are considered non-recyclable by the WEEE recycler that we visited. In the case of the Luma, the PC, PMMA, silicon rubber, and glass fall within this category. The glass is considered non-recyclable as it breaks into pieces smaller than 10mm, which is a fragment size that the WEEE recycler cannot recover. The plastics and silicon rubber have a density higher than 1.1. While some recyclers will recycle these plastics (Galloo, 2024), the WEEE recycler we have taken as reference does not. This means that these components end up as waste and will be burned. Figure 17 shows a silicon rubber density test performed at the recycler (at a density of 1.1). While the silicon is easy to liberate, but the PC and PMMA exist deep within the product architecture, increasing the chance of pollution and reducing the recyclability.

The wires and electronics are processed further to recover valuable metals. This is a complicated process and at the time of visiting, the WEEE recycler was upgrading this line to improve recovery numbers. Important is that during this process, fragments containing metals and plastics, like most electrical connectors, are difficult to separate, resulting in material losses and pollution of fractions.

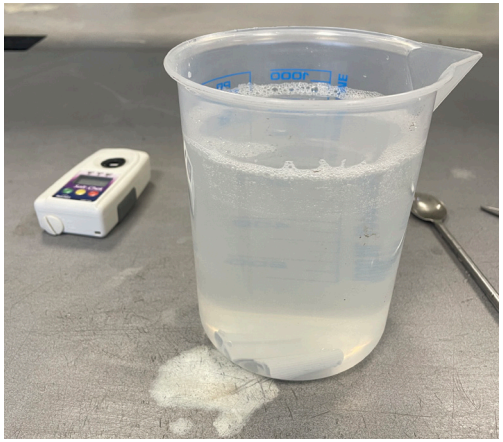


Figure 17: Sink/float test at a water density of 1.1. Notice the silicon rubber at the bottom of the cup.

4.6 Conclusion

This research was conducted to answer SQ 2: How does the current product architecture determine the recyclability of the Luma?

The Luma Gen2 contains many screw connections, which are rarely fully liberated during shredding. The A4 & A6 screws contribute most to fraction pollution, while the T15 screws are used to fasten the (economically and environmentally valuable) priority components. Creating a design in which the product architecture allows for good liberation of these components is desired. This is especially important for the driver and L2, as they contain valuable metals that can pollute other waste streams and would otherwise be lost.

The wires and electrical connections of the Luma are hardly liberated during shredding and are difficult to separate in the sorting process, resulting in loss of copper and pollution of other streams. An optimized redesign would limit the use of wires and electrical connectors.

The main body of the Luma Gen2 is made from aluminum, heavy, and therefore valuable for recycling. A redesign of the luma should facilitate

the liberation of components connected to the main body to create homogeneous aluminum fragments, resulting in a purer aluminum fraction.

The Luma Gen2 contains materials like PC, PMMA, and glass, which are technically recyclable, but in some cases treated as non-recyclable. The silicon rubber is also seen as a non-recyclable. Limiting the use of these materials, or changing to recyclable alternatives, could prove beneficial for the recyclability of a redesign.

Lastly, creating a design that takes significantly less time to disassemble, can also be beneficial for the recycling process. If it becomes economically feasible to (partially) disassemble before shredding, valuable materials will be recovered and fractions will be less polluted.

To answer research question 2, the above insights have been summarized in Table 7.

Conclusion	Design Implication
Many screw connections are used that are not liberated during shredding.	Improve liberation of screws, limit screw usage, or use no screws at all.
Wires and electrical connections are unlikely to separate during the shredding and sorting process.	Limit use of wires and electrical connections.
Most components are connected to the aluminum housing, which can pollute the aluminum fraction.	Design for full liberation of the aluminum housing/body.
The Luma contains non-recyclables like the silicon rubber, PC, PMMA, and glass.	Limit the use of these materials or find alternatives.
Disassembly before shredding can improve material recovery and decrease fraction pollution.	Make disassembly faster to encourage disassembly before shredding.

Table 7: Recyclability analysis conclusion.

Chapter 5.
Design Guidelines

This chapter is dedicated to addressing research sub-question 3:

RQ 3: Which existing design guidelines are important for the design of an outdoor luminaire with regards to repairability and recyclability?

To answer this question, first existing guidelines were analyzed and the compliance of the Luma Gen2 was tested.

Furthermore, the repairability and recyclability guidelines were compared with each other to understand how they are interdependent.

To assess the significance and usefulness of the guidelines during the design of an outdoor luminaire, the guidelines have been used during the redesign of the Luma. Therefore, the final set of specific design guidelines for outdoor luminaires will be presented in Chapter 9.

5.1 Repairability Guidelines

To establish the initial repairability guidelines, we adopted the guidelines formulated by Dangal et al. (2023). During the development of these guidelines, Dangar et al. considered the four biggest reparability scoring systems, mainly: the French Repairability Index, the Joint Research Centre scoring system, the iFixit scoring system, and ONR 192102. This results in a very complete and up to date overview of guidelines.

The guidelines can be found in Table 8, as well as the conformity of the current design of the Luma Gen2.

Group REP Repairability	Current Compliance
1. Disassembly and Reassembly	
1.1. Clumping	
1.1.1. Designing products such that non-priority parts are clustered in a sub-assembly that can be removed as an entity during disassembly process.	Bad - Most non-priority parts are disassembled individually.
1.2. Surfacing	
1.2.1. Surfacing refers to repositioning a priority component such that less components need to be removed before the priority part is reached.	Partially - Driver depth is low, while LED panel is deep.
1.3. Trimming - Optimizing Fasteners	
1.3.1. Minimize the diversity of fasteners along a disassembly pathway of a priority part.	Partially - Diversity is low, but many fasteners are used.
1.3.2. Simplify the design so that less fasteners are used.	Bad - Many fasteners are used.
1.3.3. Use fasteners that require no tools or basic tools to disassemble.	Good - All disassembly can be done with basic tools.
1.3.4. Avoid gluing components together.	Good - No parts are glued together.
1.3.5. Provide access to fasteners from same direction.	Partially - Fasterners are mounted from the top and bottom.
1.3.6. Use connections that are visually accessible.	Partially - Few connections are badly visible.
1.3.7. Use fasteners allowing repeated use.	Partially - Except for the starlock waskers, all fasteners are reusable.
1.3.8. Avoid the use of high strength (>20N) press fits and snap fits.	Partially - Lid assembly requires high strength.
1.4. Trimming - Provide disassembly and reassembly cues	
1.4.1. Visible fasteners.	Partially - Few connections are badly visible.

1.4.2. Fastener indication.	Partially - Some cues are given.
1.4.3. Seams.	Good - Gearflex box clearly consists of 2 parts.
1.4.4. Keying.	Bad - Connectors can fit in multiple places.
1.4.5. Marking connections.	Partially - Some cues are given.
1.4.6. Coloured wires.	Good - Most wires are color coded.
1.4.7. Auditory verification.	Does the app or driver give a sound?
1.4.8. Cable guides.	Bad - Also a bit redundant for these short wires.
2. Information Provision	
2.1. Passive information important for maintenance, diagnosis, and repair in the form of i.e. a manual.	Good - Extensive installation manual is available.
2.2. Active information provision to the user, like sound or text signals.	Good - Diagnosis and repair can be seen in the app.
3. Accessibility of priority components	
3.1. Lid/valve/door.	Partially - Driver is hidden underneath 2 lids. LED panel is badly accessible.
3.2. Wide geometry opening.	Partially - Lid cannot be opened fully.
3.3. Testing points.	Partially - Driver connectors can easily be reached.
3.4. Clustering maintenance points.	Partially - Gearflex box contains most priority parts.
3.5. Full view of the components.	Partially - For the driver, yes. For the LED panel, no.
3.6. Material transparency.	Partially - LED panel can be diagnosed through the glass.
3.7. Symmetric positioning of components.	Partially - Connectors and Gearflex box are not symmetrical.
4. Modularity	
4.1. Make modules easily removable.	Partially - Gearflex box is relatively easily removable.
4.2. Avoid bundling priority parts to other parts using non removable fasteners.	Good - No priority parts are attached with non removable fasteners.
4.3. Priority parts should be individually removable.	Partially - All priority parts can be individually removed, but all need many steps to reach.
5. Standardised components and interfaces	
5.1. Make components interchangable and compatible across different products or brands.	Partially - Some gearflex boxes and drivers are interchangable within the product line. However, it is no industry standard.

Table 8: Current repairability guidelines.

5.2 Recyclability Guidelines

There are numerous sets of design guidelines on recyclability available in literature. Dorien van Dolderen (PhD candidate, TU Delft) compiled an overview of published guidelines that includes 16 sources ranging from 1993 to 2021. Among them, Peters et al. (2012), Fakhredin (2018), and Berwald et al. (2021) developed guidelines in collaboration with recyclers. Given that recyclers possess significant knowledge on recycling practices, guidelines developed with their input are considered more valuable than those without. The guidelines proposed by Berwald et al. (2021) are more recent and likely to be more representative of current recycling practices than those by Peters et al. (2012). Therefore, the guidelines developed by Berwald et al. (2021) are used as a starting point for this project.

These guidelines can be found in Table 9, as well as the conformity of the current design of the Luma Gen2.

Group REC Recyclability	Current Compliance
Product Level	
1. Enabling easy access and removal of hazardous or polluting parts	
1.1. Use click/snap solutions to fix batteries in a product. Avoid permanent fixing such as glued, welded, and enclosed solutions.	N.A.
1.2. Fix valuable parts (e.g., printed circuit boards (PCBs), cables, wires, and motors) in a product with metal screws, click fingers, press-fit, shrink foil, self-screwed/tapering, or connectors. Avoid permanent fixings such as pressure sensitive adhesive (PSA) tapes, glue, and welded solutions.	Good - Both the driver and the LED panel are attached with metal screws.
1.3. Use drains for operating liquids and gasses and enable easy removal of parts such as oil tanks, compressors, and hoses.	N.A.
1.4. Use detachment possibilities for hazardous and polluting parts/materials (e.g., dust bags, lamps, cord sets, cord winders, paper, cardboard, textiles, wood, foams, glass, and ceramics).	Partially - Polluting materials, like glass, is detachable after undoing 4 screws.
1.5. Use one module for hazardous parts in the product structure to enable taking out one non-recyclable module instead of searching for several different hazardous parts.	Partially - Gearflex box contains some, but not all, hazardous parts.
2. Use of recyclable materials that will be recycled by WEEE recyclers	

2.1. Avoid thermosets and composites.	Bad - Silicon rubber is used.
2.2. Do not use plating, galvanizing, and vacuum-metallization as a coating on plastics.	Good - These methods are not used.
2.3. Avoid the use of coatings on plastics.	Good - The plastics used are not coated.
2.4. Minimise the use of thermoplastic elastomers.	Good - No TPE's are used.
2.5. Avoid the use of foam.	Good - No foam is used.
2.6. Minimise the use of magnets.	Good - No magnets are used.
3. Use of material combinations and connections that allow easy liberation	
3.1. Avoid moulding different material types together by multiple-K processes (different plastic materials injected into the same mould, over-moulding, or in-mould decoration).	Good - These methods are not used.
3.2. Avoid connections that enclose a material permanently. Avoid methods such as moulding-in inserts into plastics, rivets, staples, press-fits, bolts, bolt and nuts, brazing, welding, and clinching.	Partially - The pins of the lid can be considered press fits. Just like the Starlock washers.
4. Use of recycled materials	
4.1. Consider more textured surfaces for injection moulding plastic parts. Avoid uniform high-gloss surfaces.	Bad - All plastic parts have gloss surfaces.
Part Level	
5. Avoidance of hazardous substances	
5.1 Avoid the use of brominated flame retardants (BFRs) such as polybrominated diphenyl ethers (PBDEs), tetrabromobisphenol A (TBBPA), polybrominated biphenyls (PBBs), Hexabromocyclododecane (HBCD), etc., in the product.	Partially - Signify is phasing out the use of BFRs in their products (Signify, n.d.-c)
5.2 Avoid the use of substances of very high concern (SVHC) according to the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation [40] and substances classified as carcinogenic (Carc. 1A or 1B), mutagenic (Muta 1A or 1), or reprotoxic (Repr. 1A or 1B) by the Classification, Labelling and Packaging (CLP) Regulation in housing/housing parts [41].	Good - Signify adheres to REACH regulations (Signify, n.d.-c)
5.3. Avoid the use of substances that are listed on the 'SIN list' [42].	N.A.
5.4. Do not use halogenated polymers (e.g., Polyvinyl chloride (PVC), Polytetrafluoroethylene (PTFE)).	Good - These materials are not used.
6. Enable easy access and removal of hazardous or polluting parts	
6.1. Avoid magnetic parts on printed circuit boards (PCBs).	Good - No magnets are used.

7. Use of recyclable materials that will be recycled by WEEE recyclers	
7.1. Use common plastics in the product such as ABS, PP, PA, PC, PC/ABS, HIPS, PE (polyethylene), where possible.	Partially - These plastics are mostly used.
7.2. Avoid polymer blends.	Good - These materials are not used.
7.3. Avoid glass fibre-filled plastics.	Good - These materials are not used.
7.4. Minimise the use of thermoplastic elastomers.	Good - These materials are not used.
7.5. Avoid the use of thermoset rubbers.	Bad - Silicon rubber is used.
7.6. Minimise additives in plastic materials.	Unknown >>>
8. Use material combinations and connections that allow easy liberation	
8.1. Avoid fixing ferrous metals to non-ferrous metals in either parts or fasteners. For example, do not use a screw (ferrous metal) to attach a part to aluminium (non-ferrous).	Bad - This is done 24 times.
8.2. Do not permanently fix aluminium (Al), copper (including brass), stainless steel, or steel together in the following combinations: - If the main material in a part is Al (cast), do not attach a part of stainless steel, or steel on it. - If the main material in a part is Al (wrought), do not attach a part of Al (cast), copper, stainless steel, or steel on it. - If the main material in a part is stainless steel, do not attach a part of copper on it. - If the main material in a part is steel, do not attach a part of copper or stainless steel on it. - If the main material is copper, do not permanently fix a part of iron, lead, antimony, or bismuth to it.	Good - The luminaire does not contain any permanently fixed connections.
9. Use of recycled materials	
9.1. Choose geometries for injection-moulded parts that allow easy flow paths. Avoid tight and narrow geometries.	Good - Are parts are designed relatively simple.
9.2. For injection mould plastic parts, do not use long injection paths.	Unknown - Depends on the die design.
9.3. For injection mould plastic parts, consider more or wider venting ports.	Unknown - Depends on the die design.
9.4. Use virgin plastics for very demanding parts (e.g., transparent light guides).	Good - 90% of material used is already recycled.

Table 9: Current recyclability guidelines.

5.3 Guideline Comparison

In order to evaluate the balance between repairability and recyclability, the guidelines were cross-checked to ensure their compatibility. Table 10 displays the guidelines that complement each other. It also shows one pair of guidelines that could cause tension.

As indicated, the majority of guidelines do not have a direct impact on each other, while only a few are complementary. These complementary guidelines focus on the product's architecture and the disassembly/removal of its main components.

However, one guideline appears contradictory. Many of the "repeated use" connections (REP 1.3.7.) involve screws, which are made of ferrous materials. This contradicts guideline REC 8.1, which recommends the use of non-ferrous fasteners in the aluminum body of the Luma.

These tensions should be considered during the design process of the Luma.

5.4 Conclusion

Both for repairability and recyclability, the Luma does not comply with all guidelines.

In terms of repairability, not all priority parts are clustered, as the GearFlex box and L2 require different access points to remove, and many fasteners are used. The design also uses some non-reusable connectors like the Starlock washers. Furthermore, while the driver (GearFlex box) is easy to remove, the L2 requires upside down disassembly, going against the guidelines.

In terms of recyclability, the Luma contains some non-recyclable materials (as mentioned in section 4.3.4.). Silicon rubber is used for the seals, which are explicitly mentioned by the guidelines not to use. Lastly, the guidelines mention that you shouldn't use ferrous screw connections in a non-ferrous metal. This has been done 24 times in the Luma Gen2.

The complimentary design guidelines show that a simple, modular, and clustered design is preferred. The contradictory guidelines incentivize the use of reusable fasteners that don't include screw connections.

Complimentary			
REP	Guideline	REC	Guideline
4.1.	Make modules easily removable.	1.2. 1.4.	Fix valuable parts (e.g., printed circuit boards (PCBs), cables, wires, and motors) in a product with metal screws, click fingers, press-fit, shrink foil, self-screwed/tapering, or connectors. Avoid permanent fixings such as pressure sensitive adhesive (PSA) tapes, glue, and welded solutions. Use detachment possibilities for hazardous and polluting parts/materials (e.g., dust bags, lamps, cord sets, cord winders, paper, cardboard, textiles, wood, foams, glass, and ceramics).
1.3.2.	Simplify the design so that less fasteners are used.	8.1.	Avoid fixing ferrous metals to non-ferrous metals in either parts or fasteners. For example, do not use a screw (ferrous metal) to attach a part to aluminium (non-ferrous).
4.3.	Priority parts should be individually removable.	1.2.	Fix valuable parts (e.g., printed circuit boards (PCBs), cables, wires, and motors) in a product with metal screws, click fingers, press-fit, shrink foil, self-screwed/tapering, or connectors. Avoid permanent fixings such as pressure sensitive adhesive (PSA) tapes, glue, and welded solutions.
3.4.	Clustering maintenance points.	1.5.	Use one module for hazardous parts in the product structure to enable taking out one non-recyclable module instead of searching for several different hazardous parts.
Potential Tension			
1.3.7.	Use fasteners allowing repeated use.	8.1.	Avoid fixing ferrous metals to non-ferrous metals in either parts or fasteners. For example, do not use a screw (ferrous metal) to attach a part to aluminium (non-ferrous).

Table 10: Guideline comparison.

Chapter 6.
Requirements

For the redesign of the Luma Gen2, it is necessary to have clear design requirements. This chapter focuses on answering the main research question:

Which design requirements are important for the redesign of an outdoor luminaire with regards to repairability and recyclability?

To answer this question, a Product Journey Map (PJM) was created using insights from the previously conducted interviews and research questions. This PJM shows the journey of the Luma and its impact on product, organizational, and worldwide-level. Furthermore, the PJM shows which drivers influence the design and how they are interconnected. The Product Journey Maps can be seen in Appendix I.

The design requirements and wishes shown in Table 12 are set up in conjunction with a Product Architect at Signify and are derived from both customer and Signify needs. The requirements can also be traced back to drivers from the PJM.

The full program of requirements and wishes has been verified by the current Product Manager of the Luma (personal communication, 8 October 2024).

#	Requirement	Rationale	PJM Driver
1	All priority components of the luminaire must be able to be repaired on the spot within 5 minutes.	Less time needed results in cheaper labor and shorter road closures, leading to more repairs and less waste.	3, 5, 12
2	The priority components must be fully liberated during shredding/at least 70% (twice as much as now)	Better liberation means better material recovery and less pollution of fractions and waste. Signify needs.	17
3	The priority components must be secured within the luminaire.	The components cannot come loose due to long term vibrations. They need to work for at least 20 years.	6, 14
4	The luminaire must remain IP67 waterproof.	The luminaire needs to survive the outdoor environment. Making sure the components stay dry is necessary.	6, 14
5	The temperature difference between the housing and L2 must not be more than 25 degrees Celsius.	The L2 needs to be sufficiently cooled in order to maintain the desired lighting performance.	6, 7, 8

Table 11: Program of Requirements.

#	Wish	Rationale	PJM Driver
1	Cost should be as low as possible.	Low cost can increase demand and improve profitability for Signify.	6
2	Part liberation during shredding should be as high as possible.	Better liberation means better material recovery and less pollution of fractions.	17
3	Overall repairability should be as high as possible.	Less time needed results in cheaper labor and shorter road closures.	3, 5, 12
4	The design should be feasible (simplicity).	The design should be produceable to serve as a realistic concept direction.	10
5	The concepts should show inspiring solutions.	Per request of Signify, the concept should provide inspiring solutions for their design team.	9
6	Should be as reliable as possible.	The longer the luminaires are operational, the less maintenance they need and the lower their environmental impact.	6, 14
7	The look and feel should add to the perceived customer value.	A higher perceived customer value will result in an increase in demand.	6
8	The design should be scalable.	Since the Luma is part of a family of luminaires to cover a multitude of applications. The solutions in the concept need to be applicable to multiple sizes.	2, 12
9	The concept should provide good upgradability.	The internals have to be tailored to the client and be ready for technical updates.	15

Table 12: Program of Wishes.

Chapter 7.
Concept Development

In this chapter, the development of a concept focused on improving the repairability & recyclability is presented. To reach this concept, multiple design and selection methods have been used. These will be discussed in their respective sections.

7.1 Solution Space Exploration

To find interesting and impactful design directions for the redesign of the Luma, the solution space had to be defined. This section will explain the methods used and results of this exploration.

The most important insights and pain points found during the research and analysis phase have been summarized in Figure 18. This overview was used as the starting point of the solution space.

Disassembly Map	Recyclability Map	Field Research Repair	Field Research Recycle	General Research	Guidelines
Lots of different wires and connections.	Too many screw connections.	There are too many different luminaires to keep stock.	Copper can severely pollute other fractions when not separated properly.	Heterogenous fragments should end up in the most valuable fraction.	Priority parts are not clustered in a removable subassembly.
Certain priority components lie deep within the product architecture.	The snap fits, which are designed to come loose, remain stuck during shredding. Bad design.		95% pure aluminium stream is not reached (currently, the luminaire is 70% alu).		Many fasteners are used.
	Most non-recyclable parts are deep within the architecture.		Stainless steel is manually separated?		Not all wires have a dedicated connector.
	Lots of different wires and connections.		Most screws are stuck in the aluminium due to part geometry.		
			Glass can only be recycled if it breaks apart into pieces of 10-30mm.		

Figure 18: Main insights per source.

To find underlying themes and problems within this solution space, the problems were clustered, resulting in 4 different domains (Figure 19).

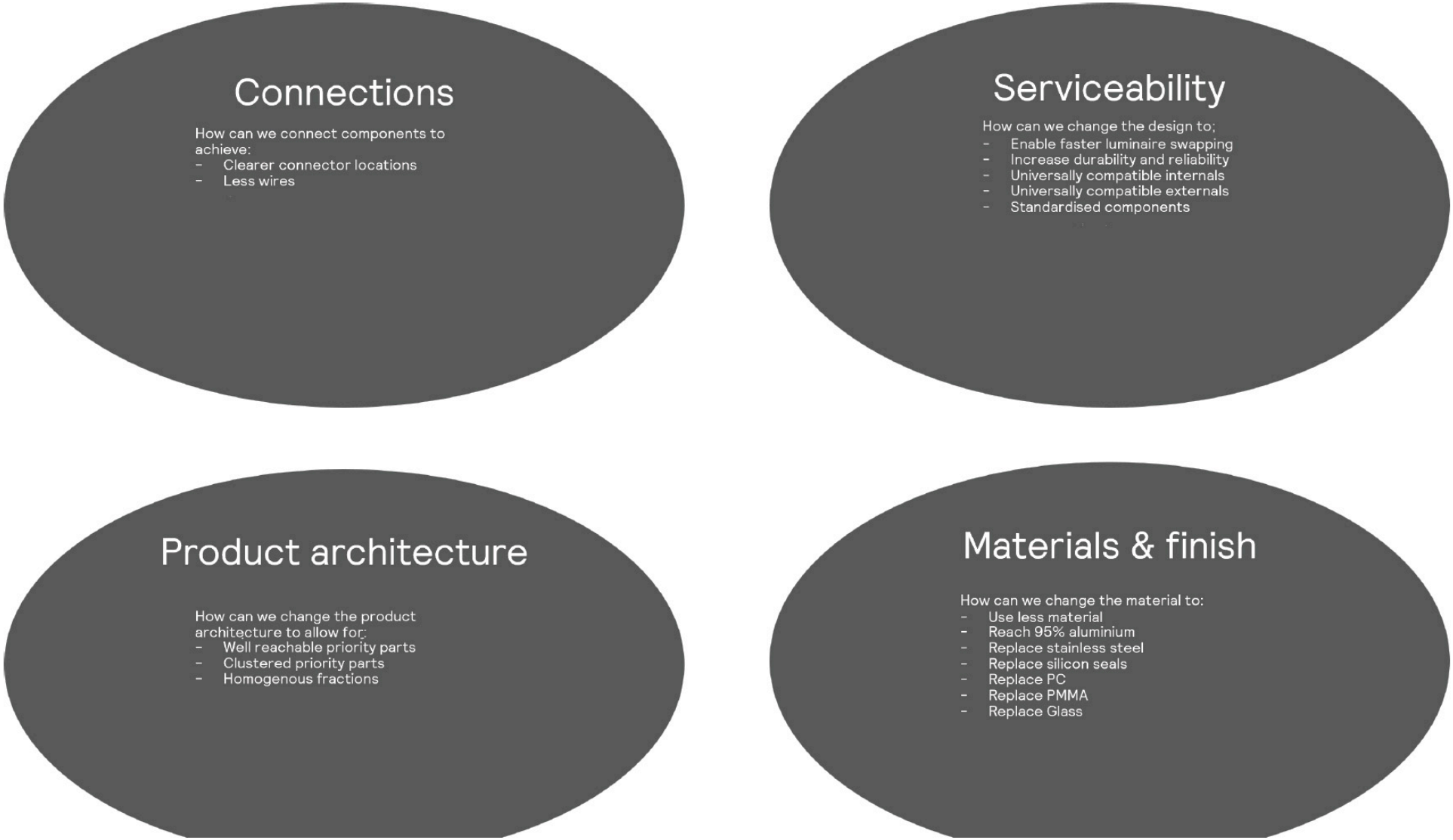


Figure 19: Solution space domains.

7.1.1 Diverging

To explore possible solutions within the domains defined in Figure 19, a brainstorm session was facilitated (Figure 20 & Figure 21) with an interdisciplinary team of experts on different subject within the context of the design project. The aim of this session was to diverge on the four domains, resulting in a wide variety of ideas and design directions.

During this brainstorm session, the "How-To" method was used, described by Van Boeijen et al. (2014). The questions from the four domains were used as "How-To" questions.



Figure 20: Brainstorm session using the "How-To" method.

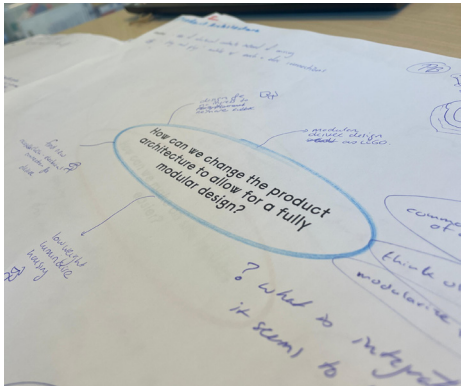


Figure 21: Brainstorm session results.

This brainstorm session generated 189 ideas. These ideas were analyzed, and any duplicate or similarities were removed, resulting in 67 distinct ones. The brainstorm session had an open-minded approach, which led to a diverse array of ideas, some of which were not suitable for the project's scope. These were discarded, along with any ideas that had no immediate effect on product design but were more focused on the context. These contextual ideas have been documented as suggestions in Chapter 10.

Refining these ideas resulted in 38 different directions, which can be found in Appendix J.

7.1.2 Converging

Because of the project's time limitations, it is not feasible to incorporate all ideas into a redesign. To determine which ideas could be the most interesting and impactful, several C-boxes were created. The C-box session adhered to the methodology outlined by Van Boeijen et al. (2014).

The ideas from section 7.1.1. were transferred onto post-it notes and then placed within multiple different C-boxes. This was done in collaboration with an expert on the project to generate intersubjective results. Table 13 shows which axes and combinations were used. The full C-boxes can be found in Appendix K.

y >	Feasibility	Repairability	Value for customers	Innovativeness	Simplicity	Recyclability	Reliability/quality /performance	Easy to implement
Feasibility								
Repairability								1
Value for customers	3							
Innovativeness								
Simplicity								
Recyclability		5			2			
Reliability/quality /performance				4				
Easy to implement								

Table 13: C-Box combinations. The number indicates the combination used in that round.

Results

The ideas in the C-box were given a rating from -5 to +5, depending on where we placed them with respect to the origin. The scores from all C-boxes were added, resulting in the list shown in Table 14.

Idea	
Use crush ribs	26
Use breaklines on the product	22
Improve top view accessibility	20
Geartray instead of box	20
Mount L2 from the top	18,5
Use clips/snap connections	18
Increase the size of the lid	18
[illegible]	17
[illegible]	14
[illegible]	12
[illegible]	11
[illegible]	11
[illegible]	10,5
[illegible]	10
[illegible]	8
[illegible]	8
[illegible]	7
[illegible]	7
[illegible]	6
[illegible]	6
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[illegible]	0
[illegible]	0
[illegible]	0
[illegible]	0
[illegible]	-2,5
[illegible]	-4
[illegible]	-4,5
[illegible]	-5
[illegible]	-6
[illegible]	-7
[illegible]	-7
[illegible]	-16

Table 14: C-Box Results.

The 7 highest rated ideas showed overlap and could be traced back to 3 main issues from the research and analysis phase:

1. Screws remain stuck in the aluminum when shredding, resulting in pollution.
2. It can be difficult to disassemble the luminaire from the top due to lack of space and upside-down mounted priority components.
3. The GearFlex box is difficult to open and remove, resulting in longer repair times.

Rewriting these issues resulted in four functional design goals, which are used as a basis for further concept development:

1. Attach internal components without screws.
2. Improve top-view repairability.
3. Improve no-tool driver swap.
4. Improve homogeneous aluminum liberation.

The first problem has been rewritten into two separate functions, as the luminaire contains screws with varying purposes. Some are used to fasten the priority components to the luminaire, and some are used to fasten the luminaire itself.

7.2 Concept Design

This section explains the development process from the four functional design goals to the 2 concepts of a redesign of the Luma.

7.2.1 Ideation

To find concrete ideas and solutions for the four functional design goals mentioned in Section 7.1.2., another brainstorm session with an interdisciplinary team was facilitated. This session followed a method as prescribed by Signify (Product Architect at Signify, personal communication, 16 September 2024).



Figure 22: Brainstorm results in the form of drawings.

First, the functional design goals were rewritten into 6 sub-functions:

1. Attaching the L2 to the housing.
2. No-tool driver swap platform.
3. Driver swap platform connection to the housing.
4. Attaching the driver to the driver swap platform.
5. Enabling top-view access to priority components.
6. Enabling homogeneous liberation.

Participants were asked to think of solutions, make drawings (Figure 22), and present them to each other. This would spark conversation and result in more refined ideas.

The resulting ideas per sub-function can be found in Appendix L. Note that some ideas can fulfill multiple functions and therefore show up multiple times.

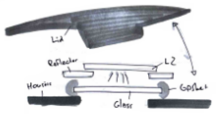
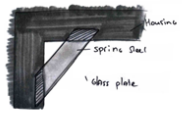
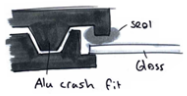
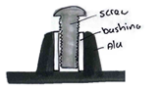
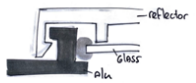
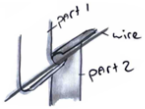
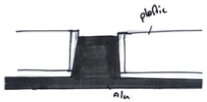
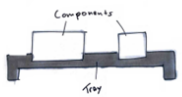
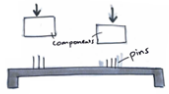
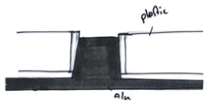
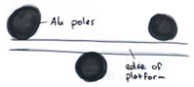
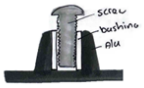
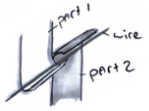
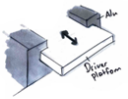
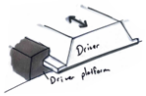
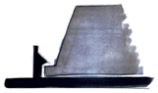
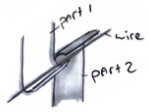
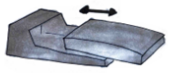
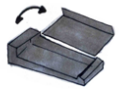
Sub	Idea #	1	2	3	4	5	6	7	8
	1	Clamp between lid & gasket	Corner fixation (picture frame)	Alu-alu crush fit	Plastic bushing with screw	Plastic nuts	Snap fit	Wire	Plastic crush ribs
1	Attaching the L2 to the housing								
	2	Geartray	Pennenbed						
2	No-tool driver swap platform								
	3	Plastic crush ribs	Clamps in between poles	Plastic bushing with screw	Plastic nuts	Shape features in alu	Wire	Slide in	
3	Driver platform connection to housing								
	4	Slide in	Plastic plugs	Plastic screws	Snap fit	Wire			
4	Attaching the driver to the driver swap platform								
	5	Slide of cover (drawer)	Sideways (book)	Reversed opening	Open from the bottom	Split design (current)			
5	Enabling top-view access to priority components								
	6	Weakening the aluminum	Composite/delamination						
6	Enabling homogeneous housing liberation								

Table 15: Morphological Chart.

7.2.2 Idea Combining

The generated ideas were placed in a morphological chart (Table 15).

A morphological chart can be a helpful tool in assessing viable combinations of solutions and can therefore lead to new concepts. Normally, some of the generated ideas are incompatible with each other, resulting in concepts using the ideas that are compatible. In our case however, only few of the generated ideas are not compatible with each other, leading to many possibilities in which the best concept can be overlooked.

Therefore, a selection of ideas was made using the guidelines as presented in Chapter 5. This resulted in 2 concepts that both showed improved repairability and recyclability, while one was focused on the first and one on the latter. These concepts would later be validified and ranked with experts. This method is visualized in Figure 23.

The two concepts and their combinations of ideas can be seen in Table 16.

Function	Repairability Concept	Recyclability Concept
Attaching L2 to housing	Clamp between gasket & lid	Clamp between gasket & lid
No-tool driver swap platform	“Pennenbed”	GearTray
Driver platform to housing	Slide in	Clamp in between poles
Driver to platform	Snap fit	Shape Features
Top-view access	Sideways	Reversed
Homogeneous liberation	Alu weakening	Alu weakening

Table 16: The 2 concepts and the combination of ideas per function.

The concepts presented in Section 7.3 are simplified versions to demonstrate and test their performance on the functions as described in Table 16. The last function, which would result in the use of breaklines in the aluminum housing, is not implemented into these concepts as it is not possible to test within the timeframe of this design research and not important for the decision-making process of Section 7.4.

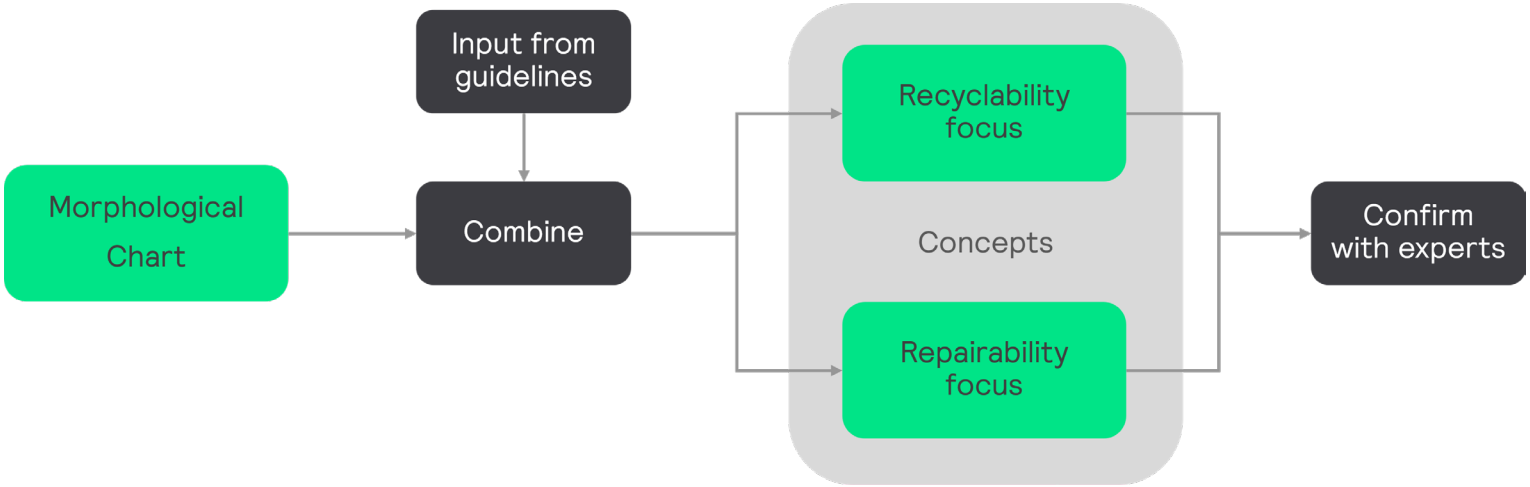


Figure 23: Concept selection method.

7.3 Concepts

This section will present the repairability and recyclability focused concepts, including a comparison of the new disassembly and recyclability maps.

7.3.1 Repairability Concept

This concept is focused on increasing the repairability of the Luma. Figures 24 & 25 provide an overview of the concept. More details about its functionality and improved repairability are presented below.

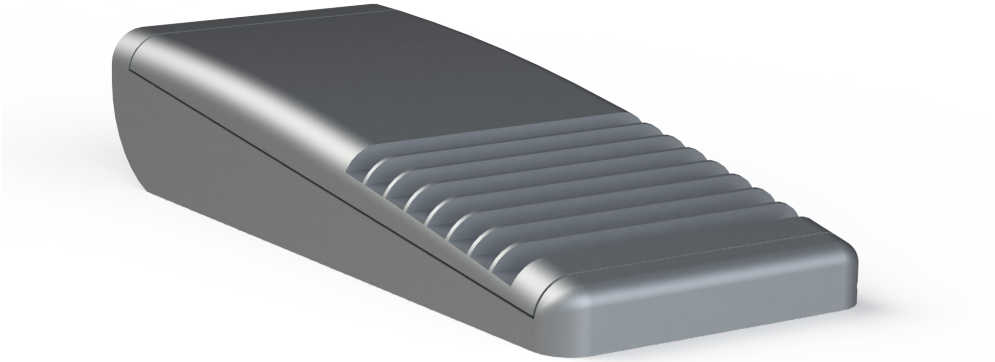


Figure 24: 3D view of the repairability concept.

L2

The lid is used to push down on the reflector, which pushes down on the seal between the glass and the aluminum housing (Figure 26). This results in an assembly that constrains the L2, reflector, seal, and glass panel, without the use of screws. Since the L2 lies on top of this “sandwich” of components, it becomes accessible from above and can be removed without the use of tools.



Figure 25: Repairability concept with opened lid.

Driver

The driver is connected to a new platform that replaces the GearFlex box. This platform (Figure 27), which will be called the GearTray, has an open top for easier access to the driver and other electrical components. On one side, the driver is connected using a reversible snap fit. On the other side, a special adapter is pressed onto the existing wire holes of the driver. This adapter changes the interface of the driver from female, upwards pointing connectors, to downwards facing male connectors (Figure 28). The GearTray is has rows of female connector holes that correspond with the pins on the adapter. This connector facilitates both the electrical and mechanical connection. Multiple rows of holes exist to facilitate different driver sizes. The driver/adapter combination can be removed in two movements (first the lid, then the driver), without the use of tools, enabling the repair crew to change individual drivers on the spot. This will solve the problem of having to remove the entire luminaire to change the driver.

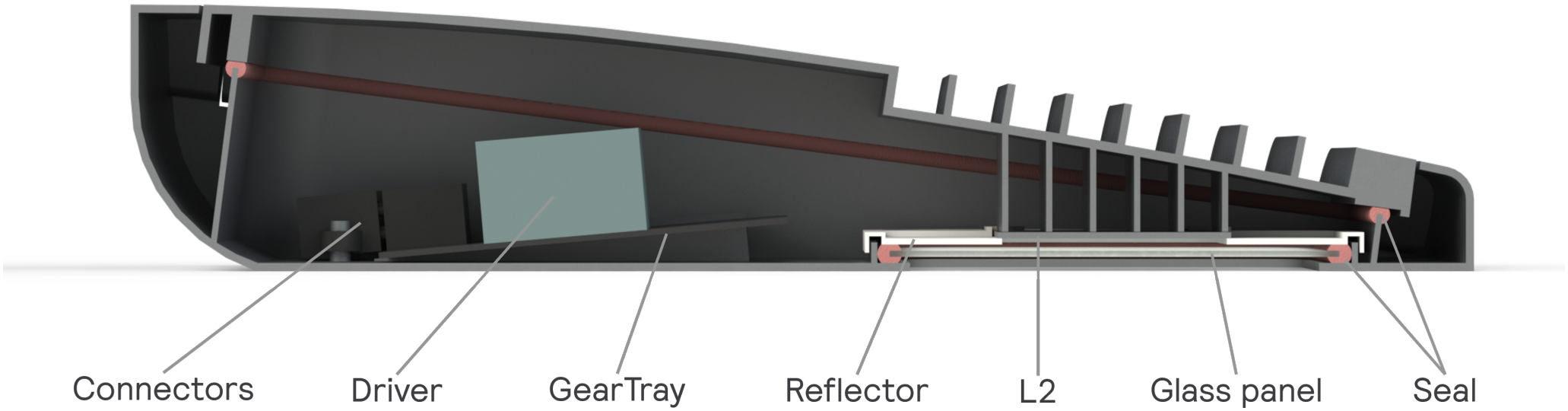


Figure 26: Side cross-section of the repairability concept.

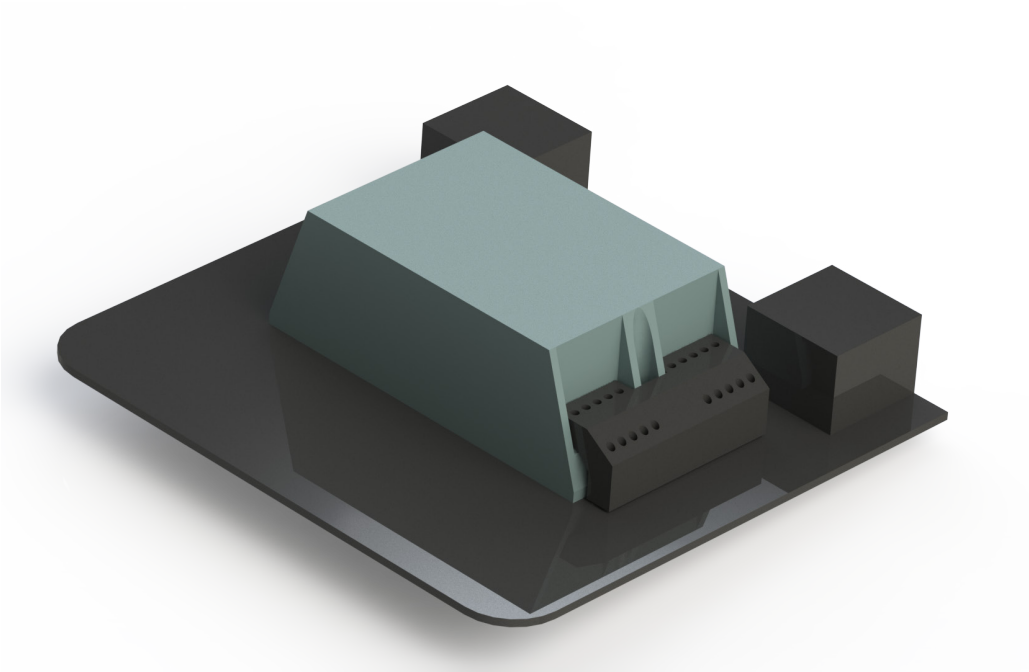


Figure 27: GearTray with driver and adapter

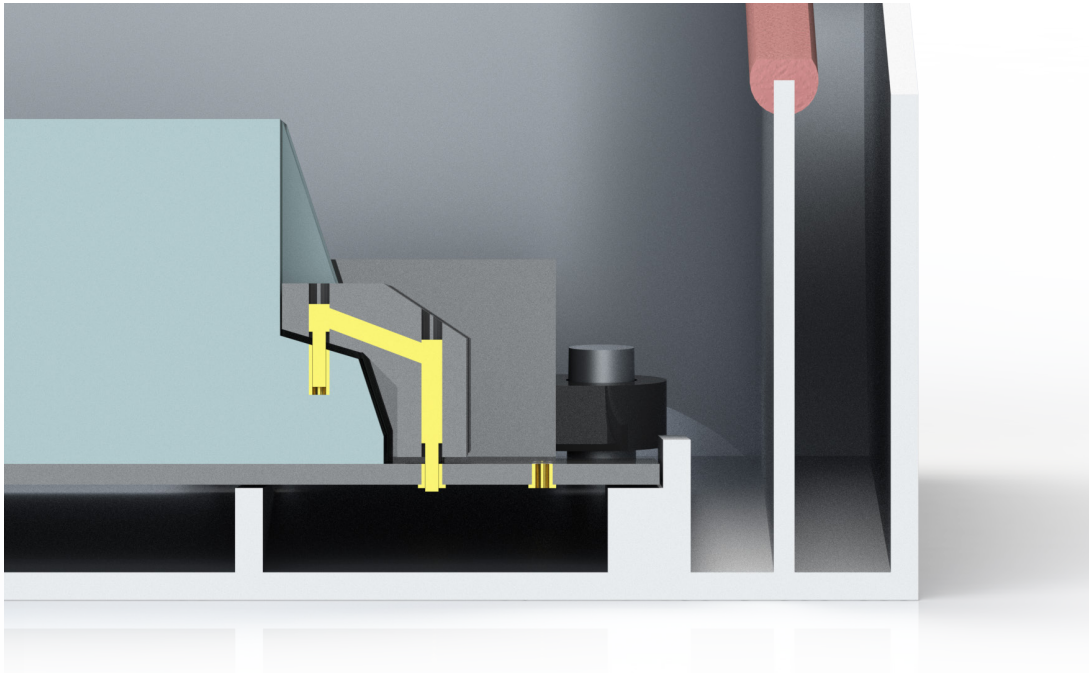


Figure 28: Cross-section of the adapter block, showing the change of electrical interface of the driver.

If needed, the GearTray can still be removed without tools by sliding it forwards (Figure 29). The GearTray is slightly angled to create clearance between the GearTray and reflector when sliding. It is connected using the same connectors that are currently present in the Luma Gen2 to hold down the GearFlex Box, therefore providing a secure mechanical and electrical connection to the rest of the luminaire.

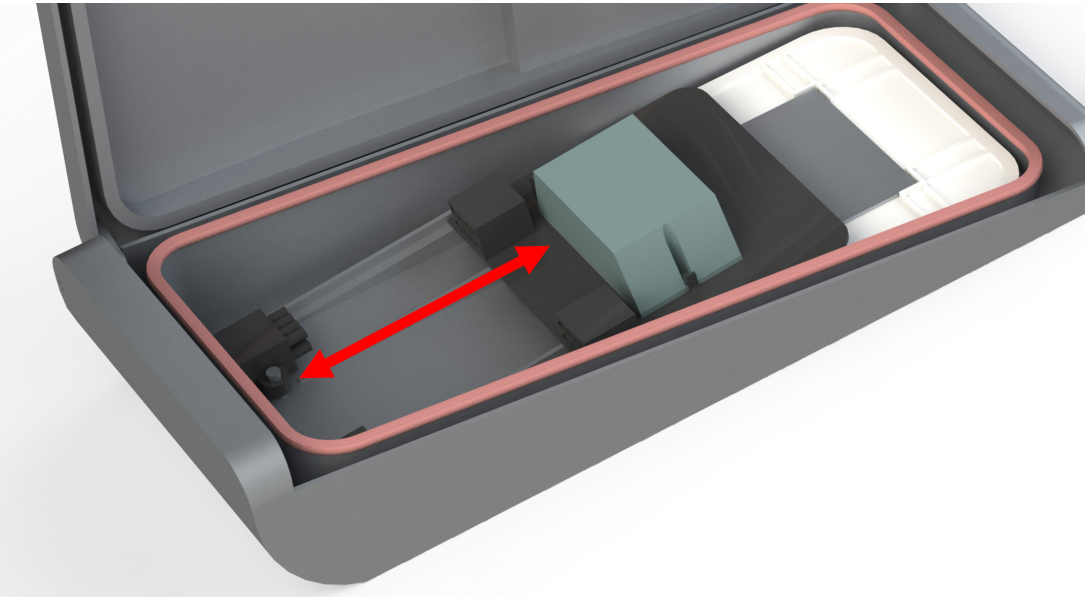


Figure 29: Sliding motion of the GearTray.

Lid

The lid spans across the whole luminaire and is opened from the side. This results in increased accessibility (Figure 30). Furthermore, it improves on the spot repair as the cherry pickers have an easier time positioning their vehicle when approaching from the side (Repair crew, personal communication, 1 October 2024).

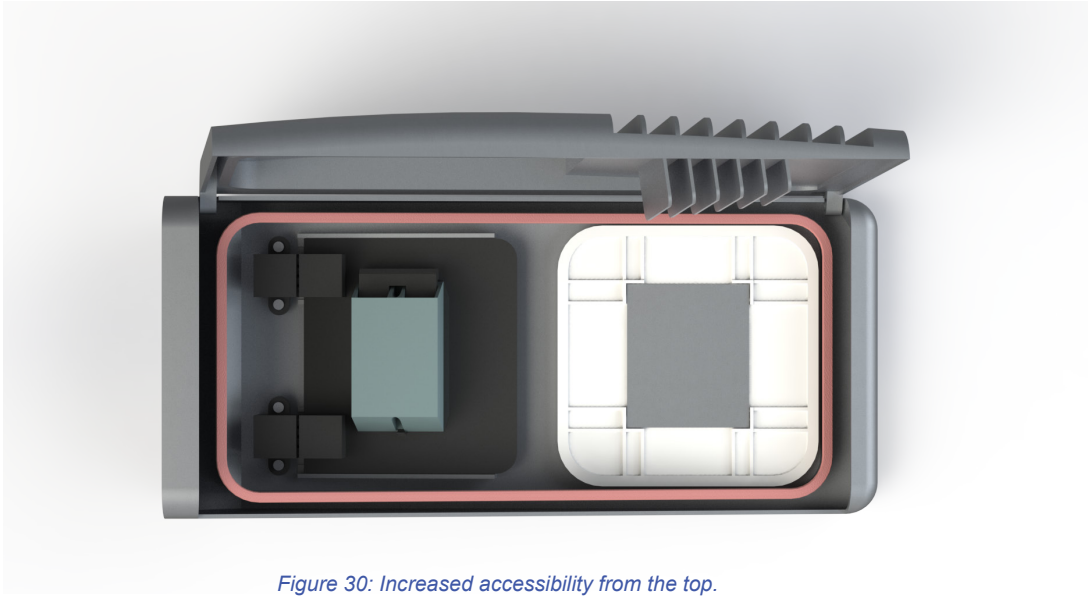


Figure 30: Increased accessibility from the top.

To show the functionality of the concept, a scale model has been 3D-printed at 40% scale (Figure 31).



Figure 31: Repairability concept scale model.

Figure 32 shows an exploded view of all components.

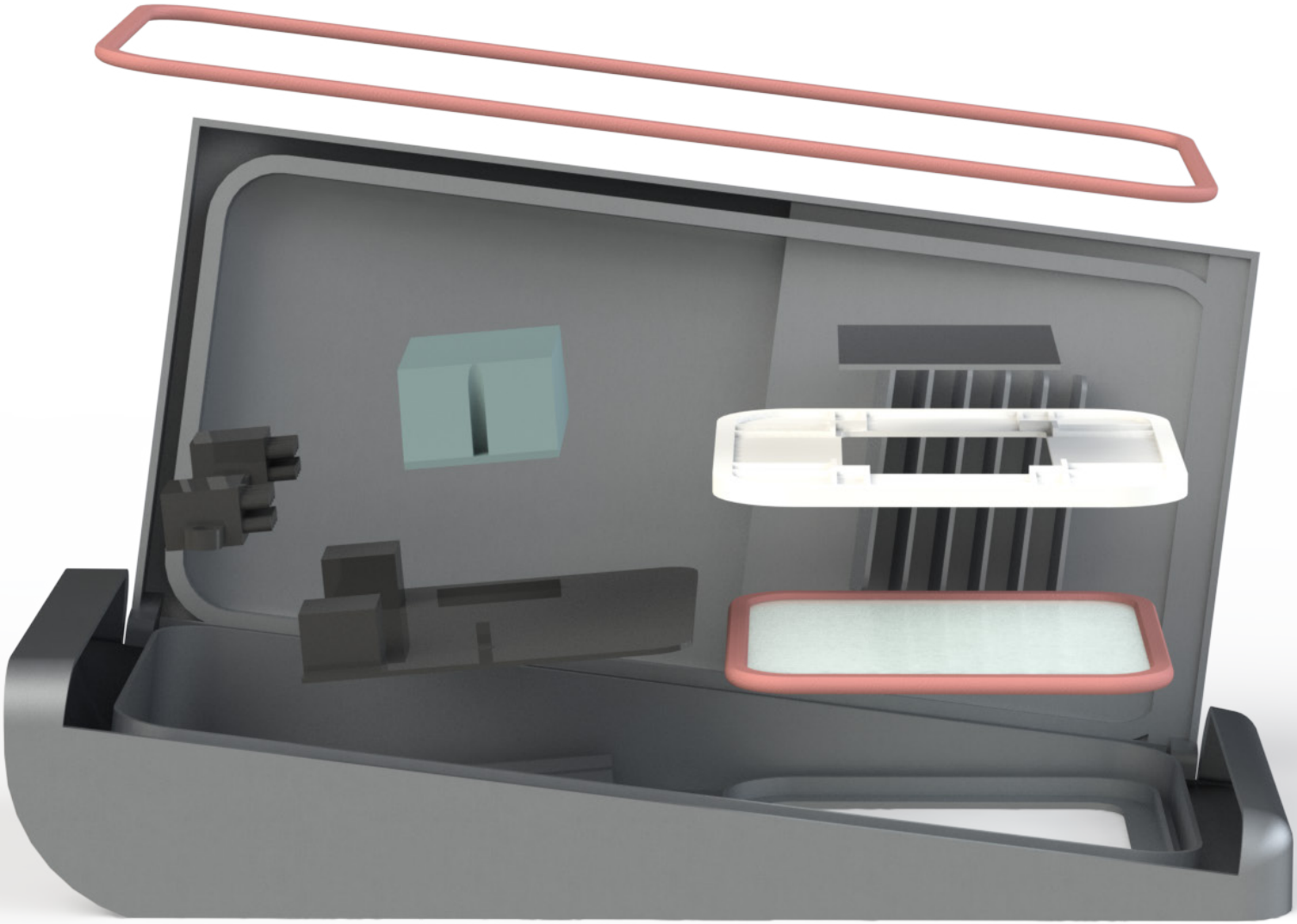


Figure 32: Exploded view of the repairability concept.

7.3.2 Recyclability Concept

This concept is focused on increasing the recyclability of the Luma. Figures 33 & 34 provide an overview of the concept. More details about its functionality and improved recyclability are presented below.



Figure 33: 3D view of the recyclability concept.

L2

The lid is used to push down on the reflector in the same way as presented in the repairability concept (Figure 35). In addition to the repairability benefits mentioned in Section 7.3.1., the assembly is designed to be fully liberated when processed in a shredder. As soon as the lid is detached, all components below will “fall apart”, resulting in homogeneous fragments.

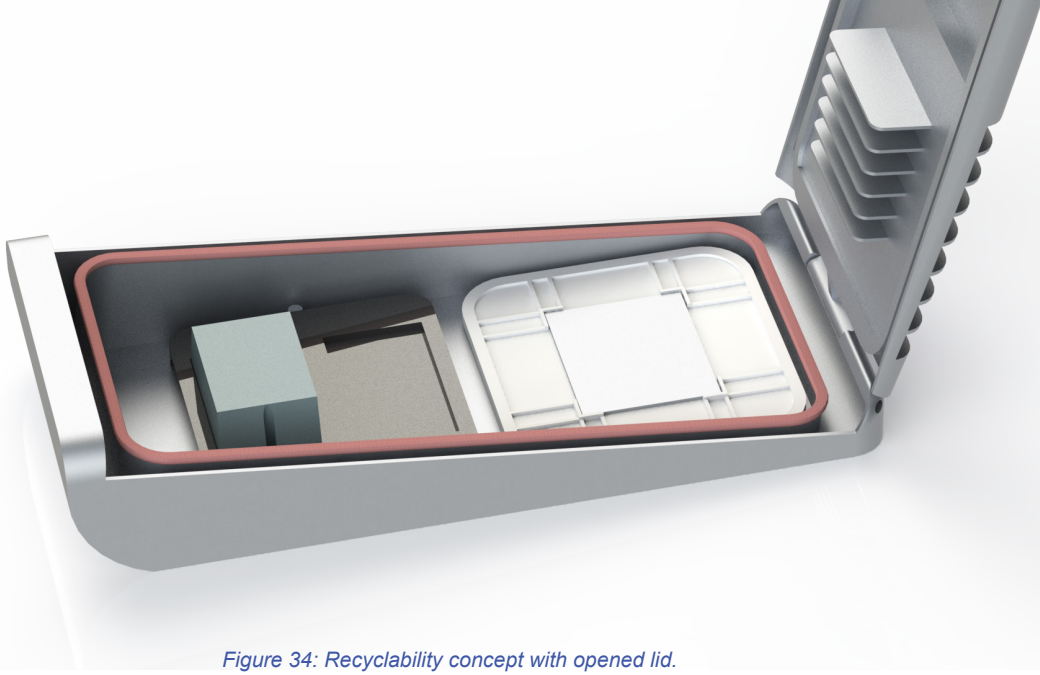


Figure 34: Recyclability concept with opened lid.

Driver

Similar to the repairability concept, the GearFlex box is replaced by a GearTray that houses the driver and other electrical components (Figure 36). In this concept, the GearTray has a purely mechanical function of (partially) securing the driver in place. The electrical connection is made by attaching the wires directly between driver and other electrical components. This eliminates the use of the GearFlex box connectors, which showed to be difficult to liberate (Section 4.2.), and therefore improves the recyclability.

The driver is constrained between shape features on the GearTray from below and the lid from above, resulting in the ability to fully liberate once the lid is detached.

The GearTray itself is attached by clamping the bottom edge on each side of the plastic between 3 extruded pillars in the aluminum body (Figure 37). When one of the pillars is broken off by the shredder, the GearTray can fully separate.

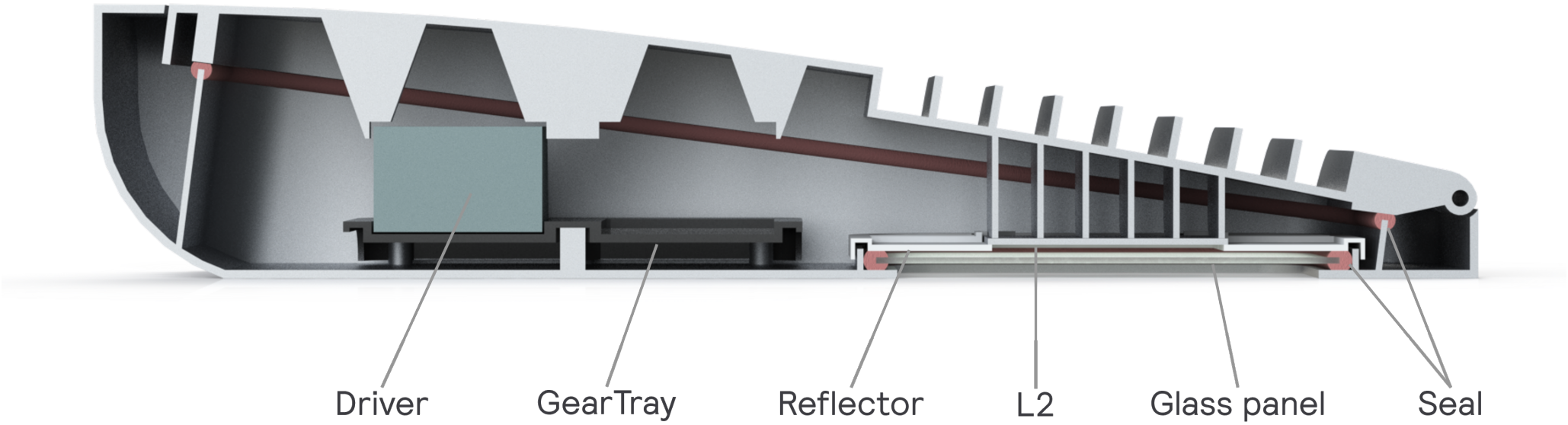


Figure 35: Side cross-section of the recyclability concept.

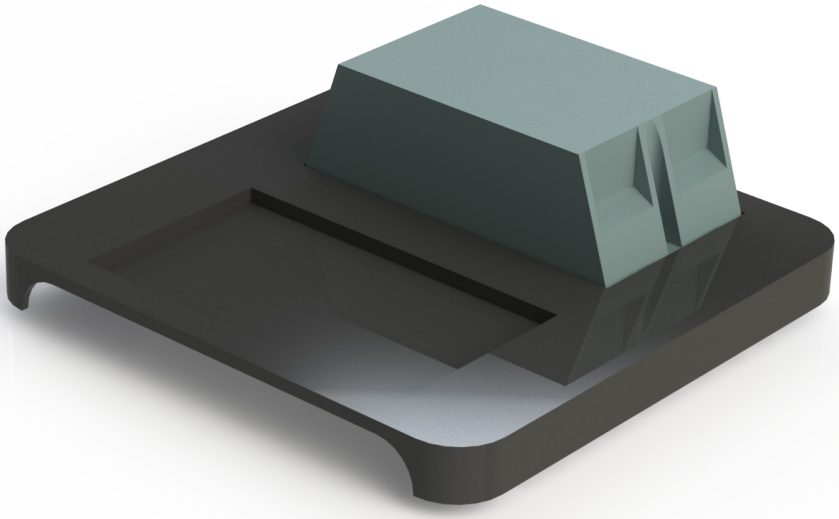


Figure 36: GearTray with driver.

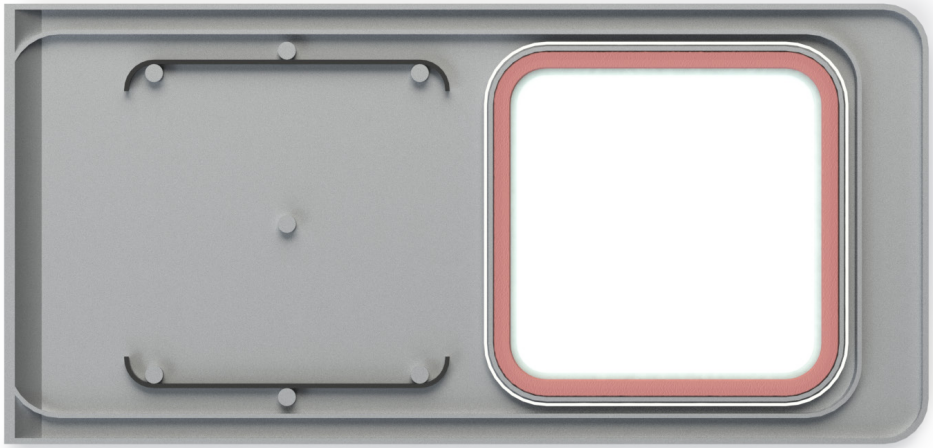


Figure 37: Top view cross-section showing the pillars and edges of the GearTray.

Lid

The lid spans across the whole luminaire and is able to open towards the front (Figure 38). None of the different opening mechanisms presented in Section 7.2.2. were specifically better for the recyclability of the luminaire. However, the forward movement allowed for better integration of the shape features that hold down the driver (due to angle of attack when closing the lid). Furthermore, it was interesting to see whether it could be integrated into a concept and if it would provide surprising insights. Compared to the Luma Gen2, this concept provides full access to all priority components.

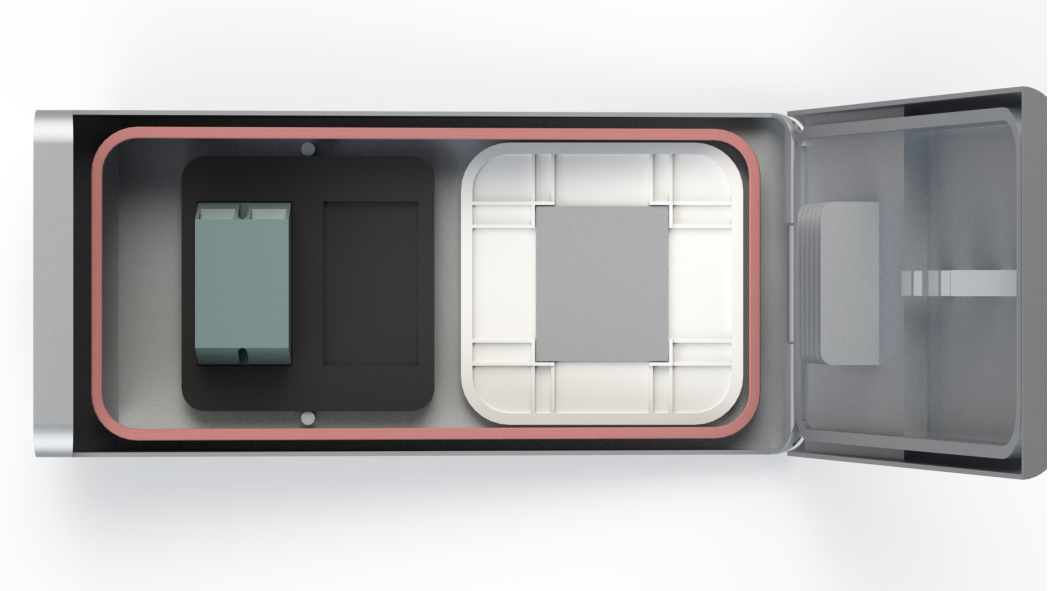


Figure 38: Increased accessibility from the top.

To show the functionality of the concept, a scale model has been 3D-printed at 40% scale (Figure 39).

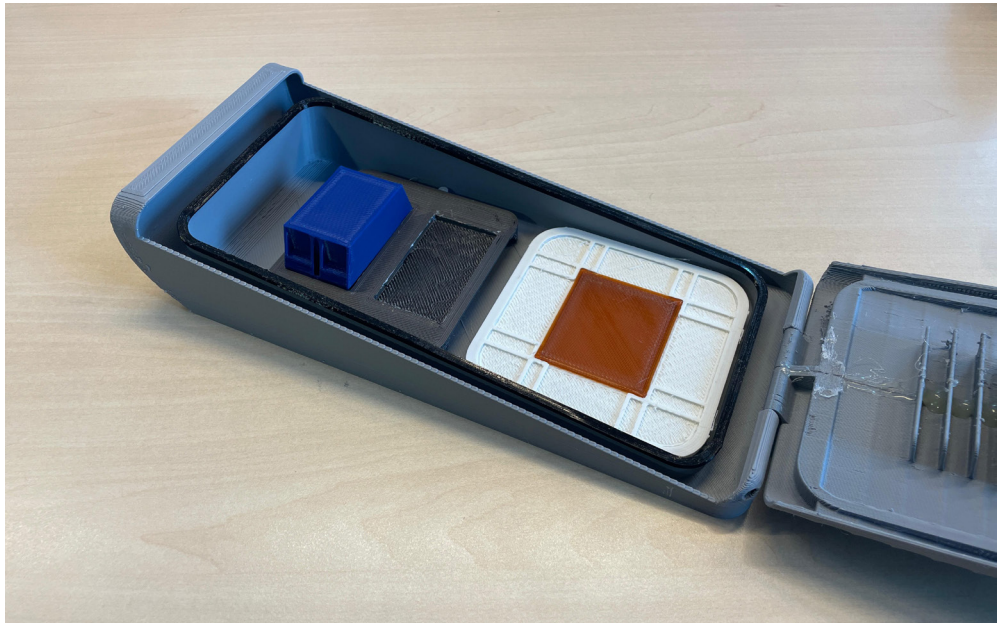


Figure 39: Recyclability concept scale model.

Figure 40 shows an exploded view of all components.

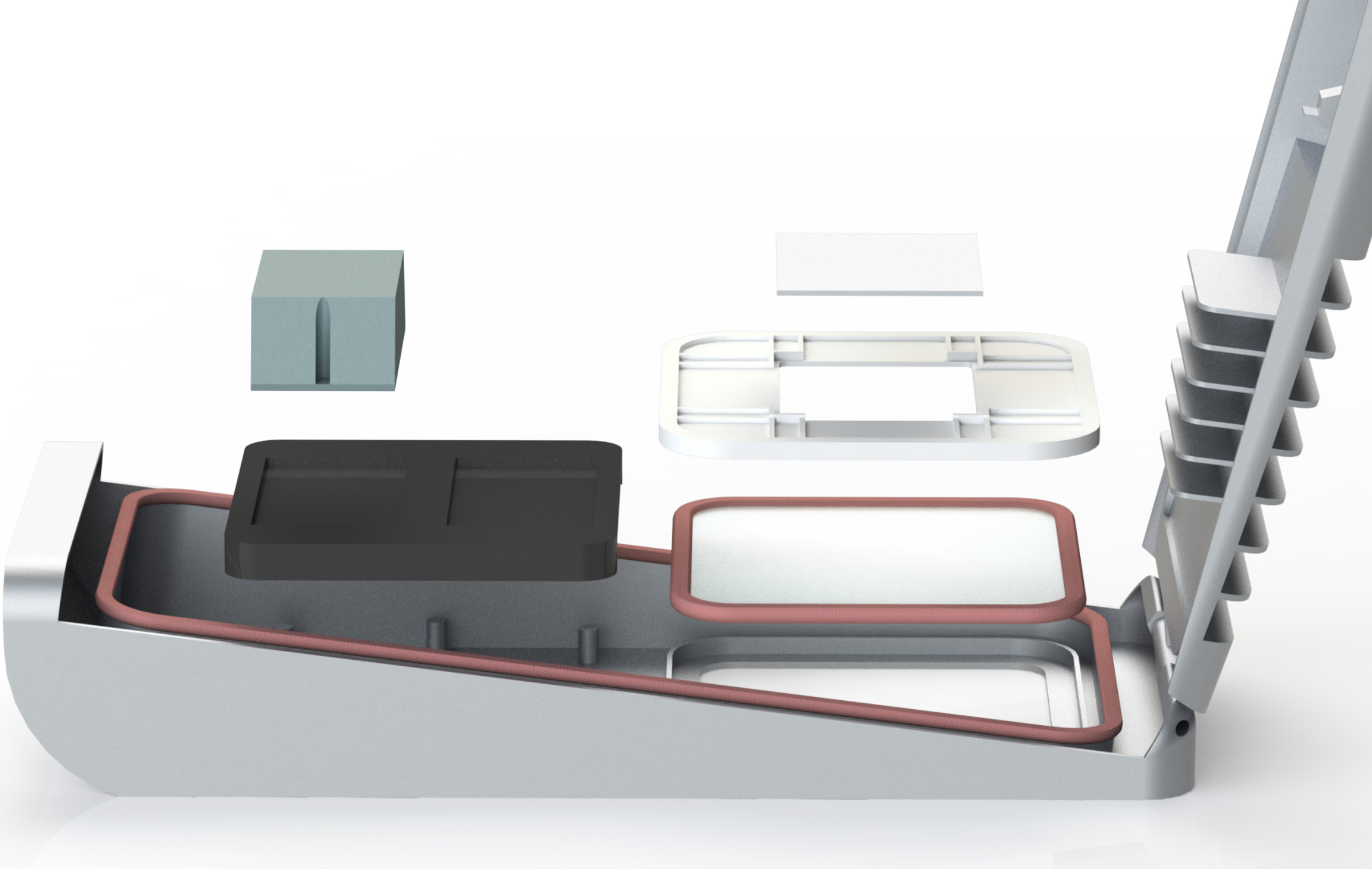


Figure 40: Exploded view of the recyclability concept.

7.3.3 Disassembly Maps

To compare the repairability of the concepts, new disassembly maps were made. Since the concepts are simplified compared to the original design of the Luma Gen2, the disassembly maps have only been updated in areas where the concept intentionally improves. Therefore, a fair comparison can be made. The full disassembly maps can be found in Appendix M. The assembly changes surrounding the L2 LED and driver are the most interesting and are therefore compared here.

L2

Figure 41 & 42 show a direct comparison of the L2 assembly. This assembly is similar for both concepts, but different from the Luma Gen2. The assemblies of the concepts require less connections to be undone to fully disassemble (Guideline REP 1.3.2.). Furthermore, the L2 is placed at the top of the architecture, also known as “surfacing” (REP 1.2.). Both changes will greatly improve the speed and difficulty of disassembly.

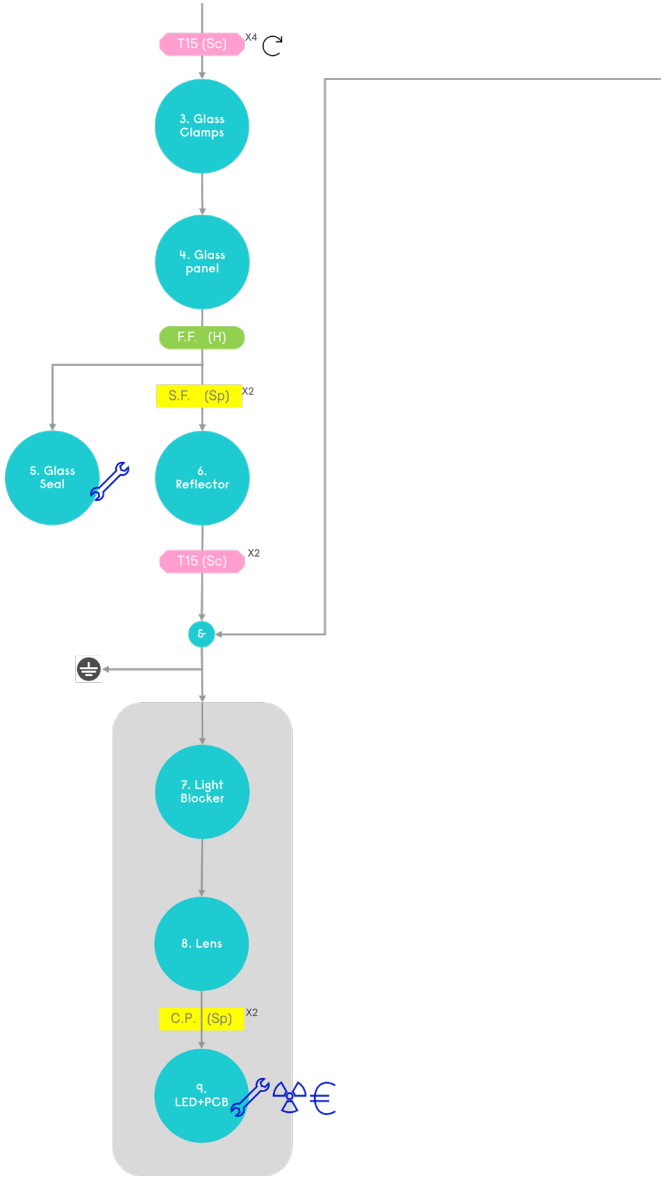


Figure 41: L2 Section of the Luma Disassembly Map.

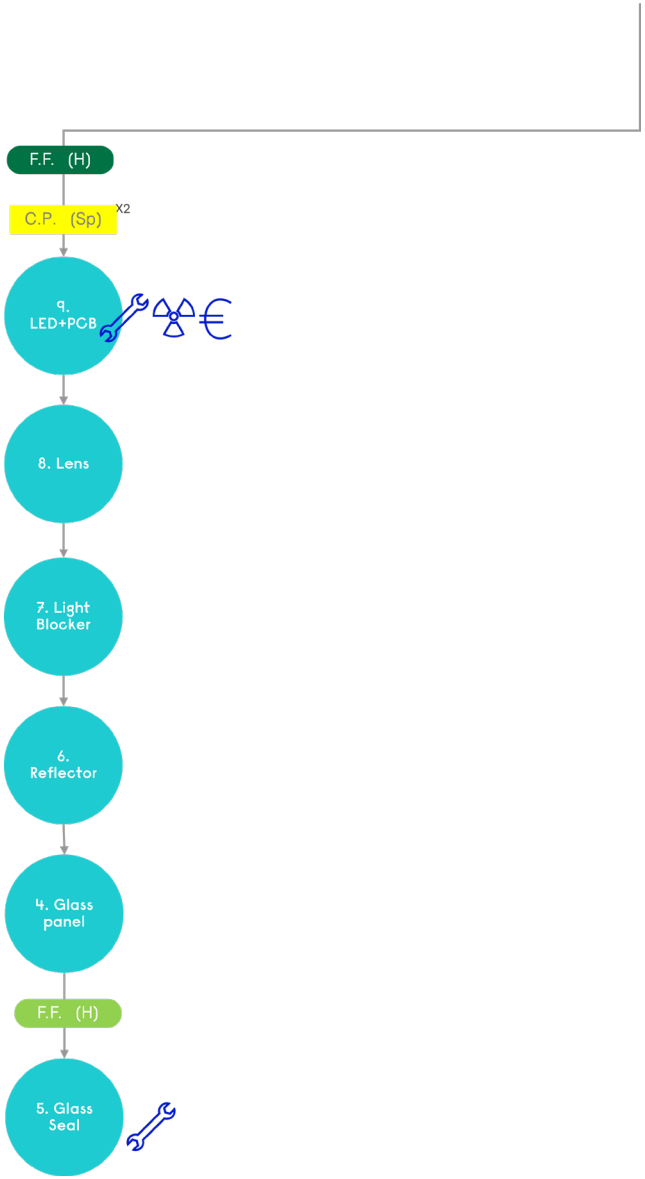


Figure 42: L2 Section of the Repairability & Recyclability concept Disassembly Map.

Driver

Figure 44, 45, & 46 present a direct comparison of the driver assembly. The repairability concept shows the driver and adapter as an assembly within the GearFlex assembly. This individual driver/adapter combination can be removed in 3 steps that of which none require any tools (REP 1.3.1., 1.3.2., 1.3.3., 4.3.). The GearTray can be removed in 2 steps, similar to the Luma Gen2. The recyclability concept appears to be much simpler, however, the only option for remove the driver is to undo all individual wires.

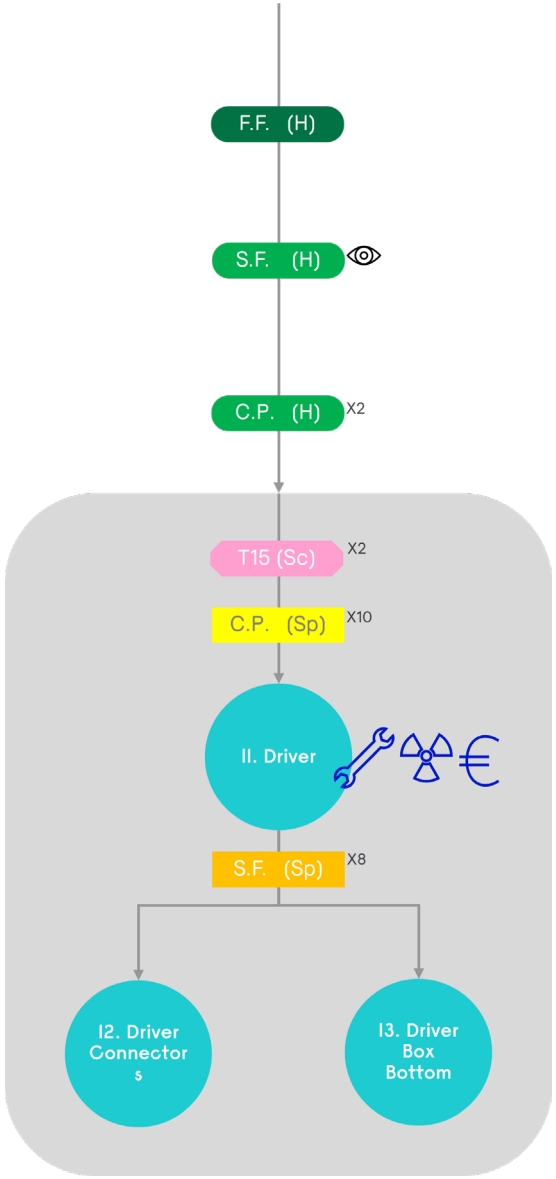


Figure 43: Driver section of the Luma Disassembly Map.

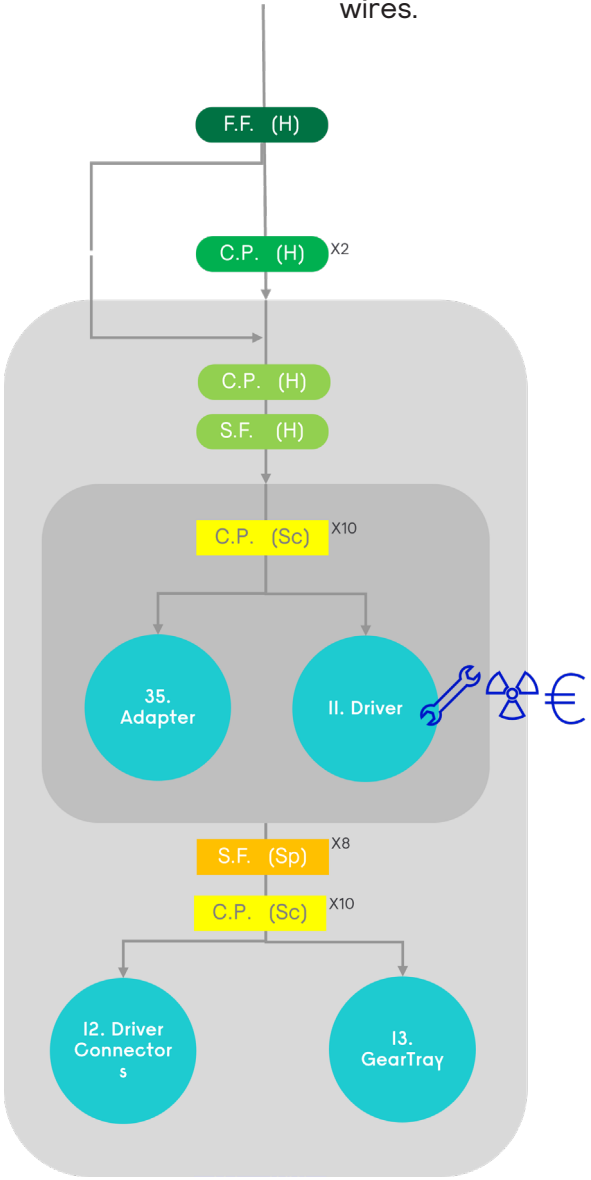


Figure 44: Driver Section of the Repairability concept Disassembly Map.

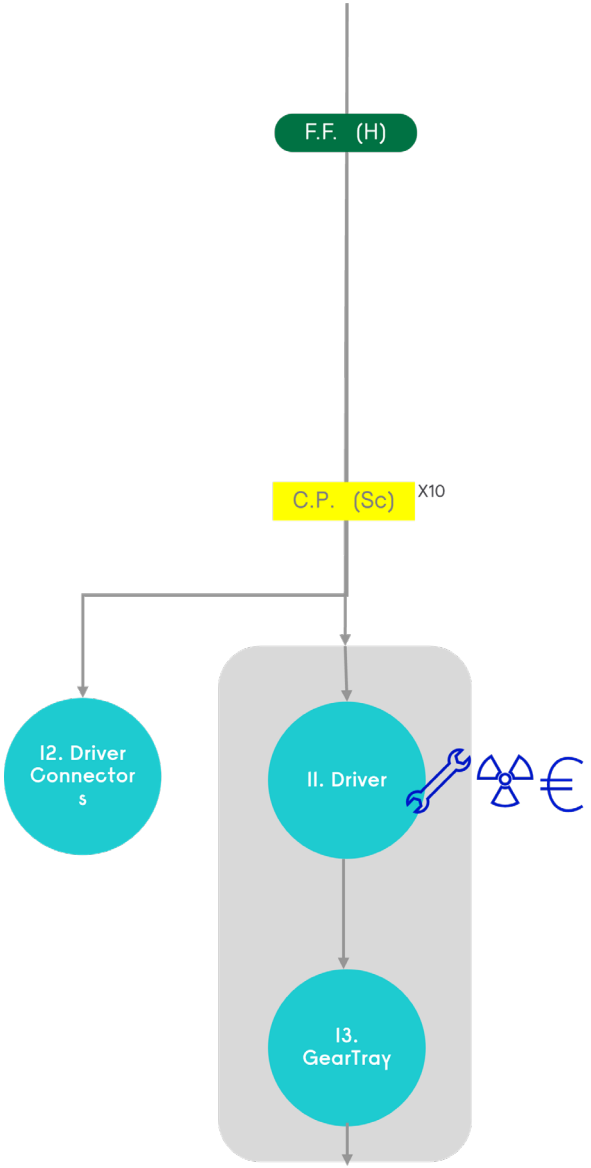


Figure 45: Driver Section of the Recyclability concept Disassembly Map.

7.3.4 Recyclability Maps

To compare the improved recyclability of the concepts, new Recyclability Maps have been made. The full maps can be found in Appendix M. In this section, a comparison between the architecture surrounding the L2 and driver has been made. The liberation behavior of the breaklines is unknown and has therefore not affected the liberation of the A4 and A6 screws in the full maps.

L2

Figure 46 & 47 show the L2 sections of the recyclability maps. In the new concepts, all components are able to break free as soon as the lid is opened. Only the L2 is still attached with the 2 cable plugs to make the electrical connection. The 6 bolts that holt the L2 in the Luma Gen2 are not necessary and therefore improving the liberation (Guideline REC 8.1).

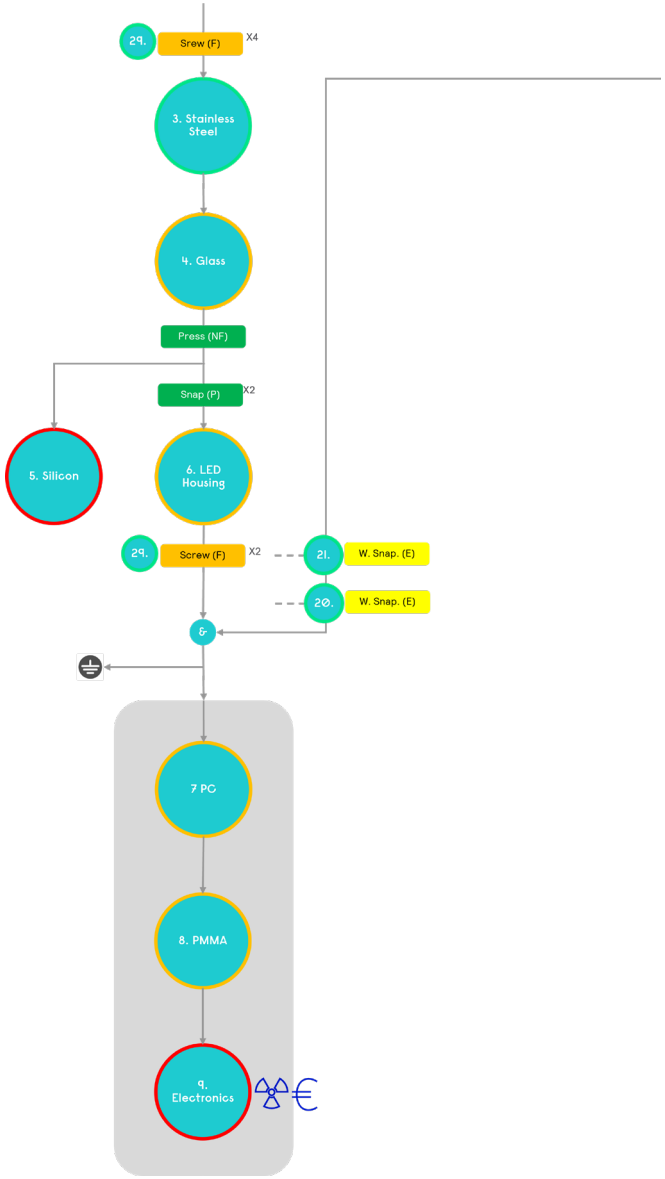


Figure 46: L2 Section of the Luma Recyclability Map.



Figure 47: L2 Section of the Repairability & Recyclability concept Recyclability Map.

Driver

Figure 48, 49, & 50 show the driver sections of the recyclability maps. The recyclability map of the repairability concept has become slightly more complicated as it has an added component (the adapter). However, the connections that hold the connecter and driver are more likely to liberate compared to the Luma Gen2. The recyclability concept shows a decrease in electrical and mechanical connections, as well as in components used.

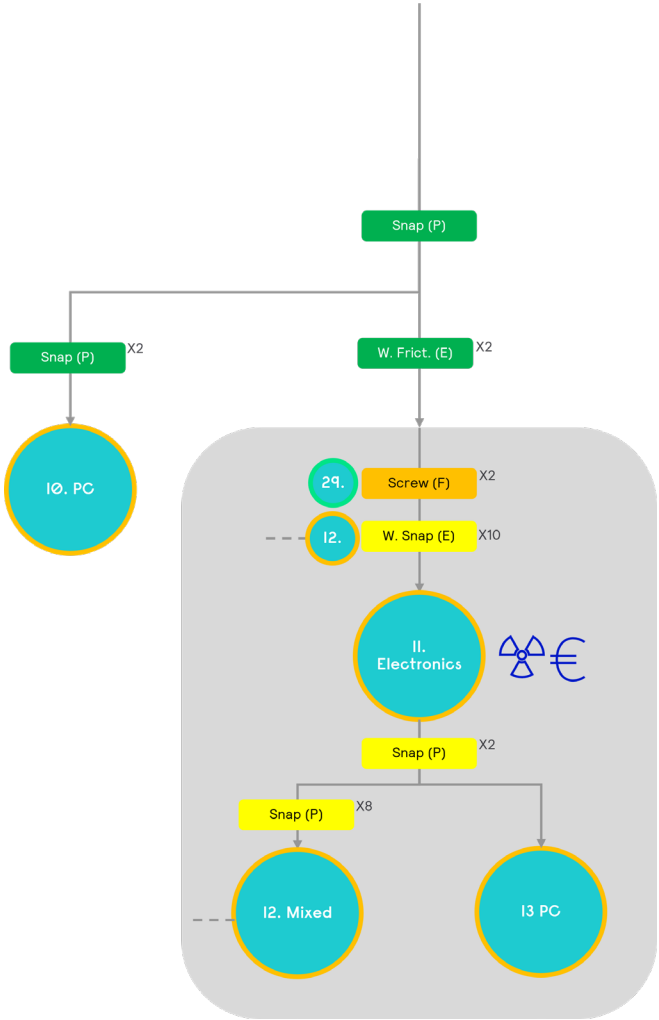


Figure 48: Driver Section of the Luma Recyclability Map.

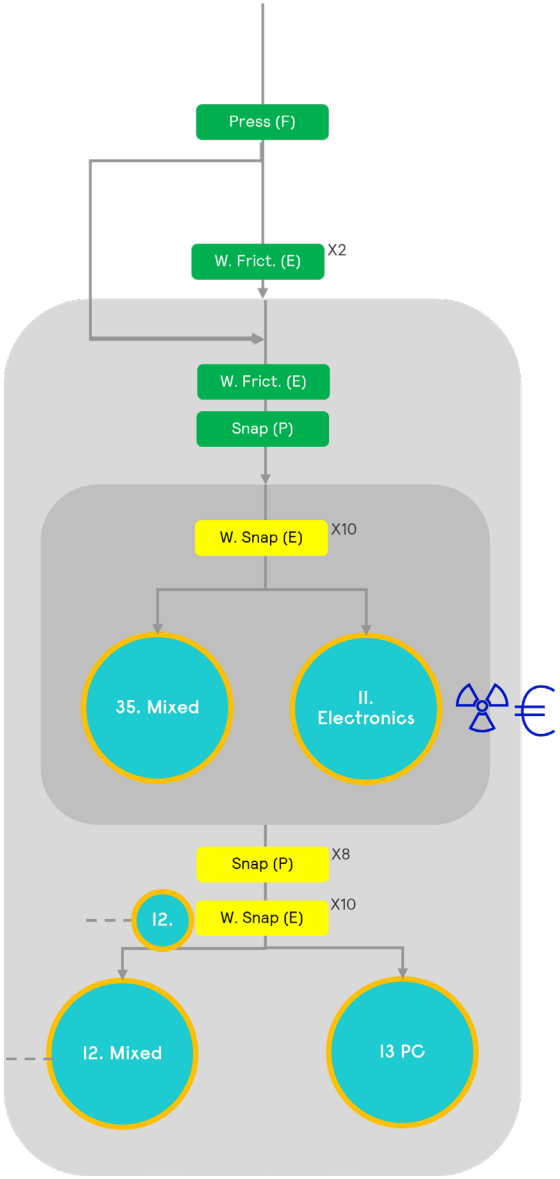


Figure 49: Driver Section of the Repairability concept Recyclability Map.

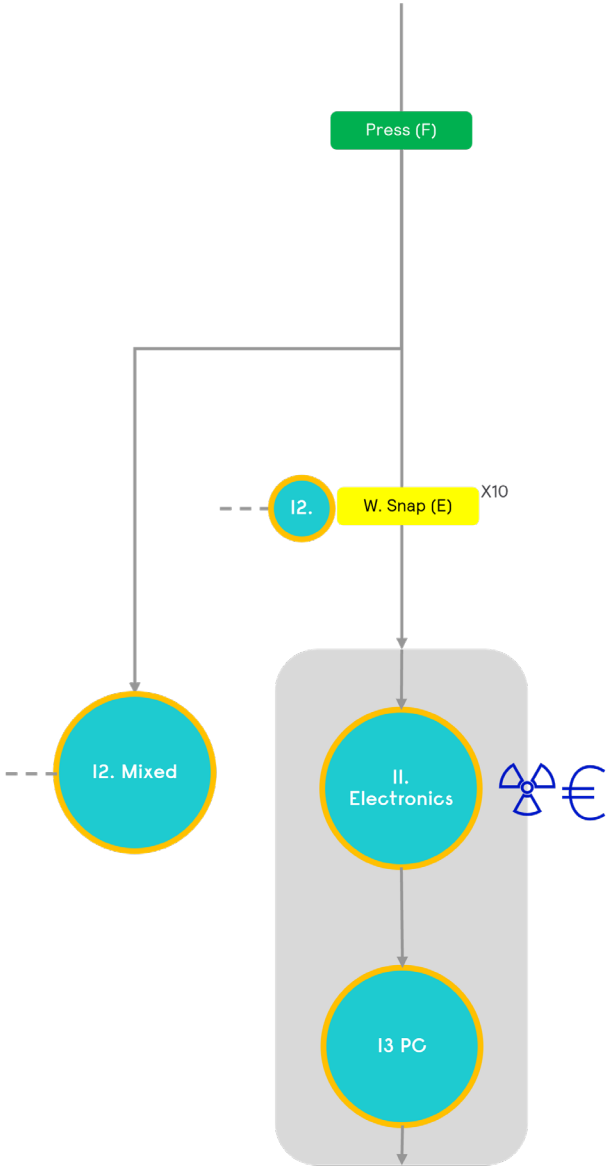


Figure 50: Driver Section of the Recyclability concept Recyclability Map.

7.4 Concept Selection

In order to identify the concept that would be most valuable for both Signify and its customers, a Pugh Matrix was created to rank the various concepts based on multiple criteria. For these criteria, the Program of Wishes from Chapter 6 was used.

The criteria were weighed, as some are more important for a redesign than others. This was done in collaboration with a Product Architect at Signify (personal communication, 2 October 2024).

5 different experts in the field of the wishes were approached and the 2 concepts were presented to them using renders and the scale models. They were then asked to give the concepts a rating between -2 and 2, in which 0 is the original design of the Luma Gen2. This resulted in the ranking as seen in Table 17 below. The full ranking per wish can be seen in Appendix N.

	1 Repairability Concept	Recyclability Concept
Overall		
Total score		

Table 17: Concept selection results per concept.

The concepts were also ranked on function level to see if a better combination of the used ideas could be made. This resulted in the ranking as seen in Table 18. The full ranking per wish can be found in Appendix N.

A combination of ideas from both concepts could potentially result in a higher score. However, the highest-ranking combination consists of ideas that are not compatible with each other and is therefore not chosen. The repairability concept was selected for further development and testing.

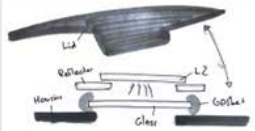
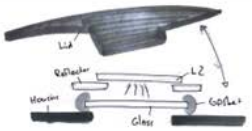
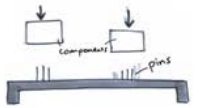
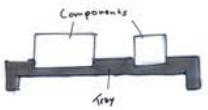
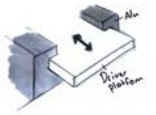
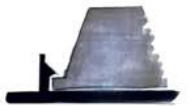
		Repairability Concept	Recyclability Concept
	1	Clamp between lid & gasket	Clamp between lid & gasket
1	Attaching the L2 to the housing		
	Total score		
	2	Pennenbed	Geartray
2	No-tool driver swap platform		
	Total score		
	3	Slide in	Clamps in between poles
3	Driver platform connection to housing		
	Total score		
	4	Snap fit	Shape features
4	Attaching the driver to the driver swap platform		
	Total score		
	5	Sideways (book)	Reversed
5	Enabling top-view access to priority components		
	Total score		
	6	Weakening the aluminum	Weakening the aluminum
6	Enabling homogeneous housing liberation		
	Total score		

Table 18: Concept selection results per function.

Chapter 8.
Final Design

The selected concept from section 7.4 was further developed and tested. This was done to see whether the improved repairability and recyclability aspects could be combined into a functional full-scale design. This chapter will present the final design, how these features have been implemented, the challenges that surfaced, and to what extend the repairability and recyclability has been improved.

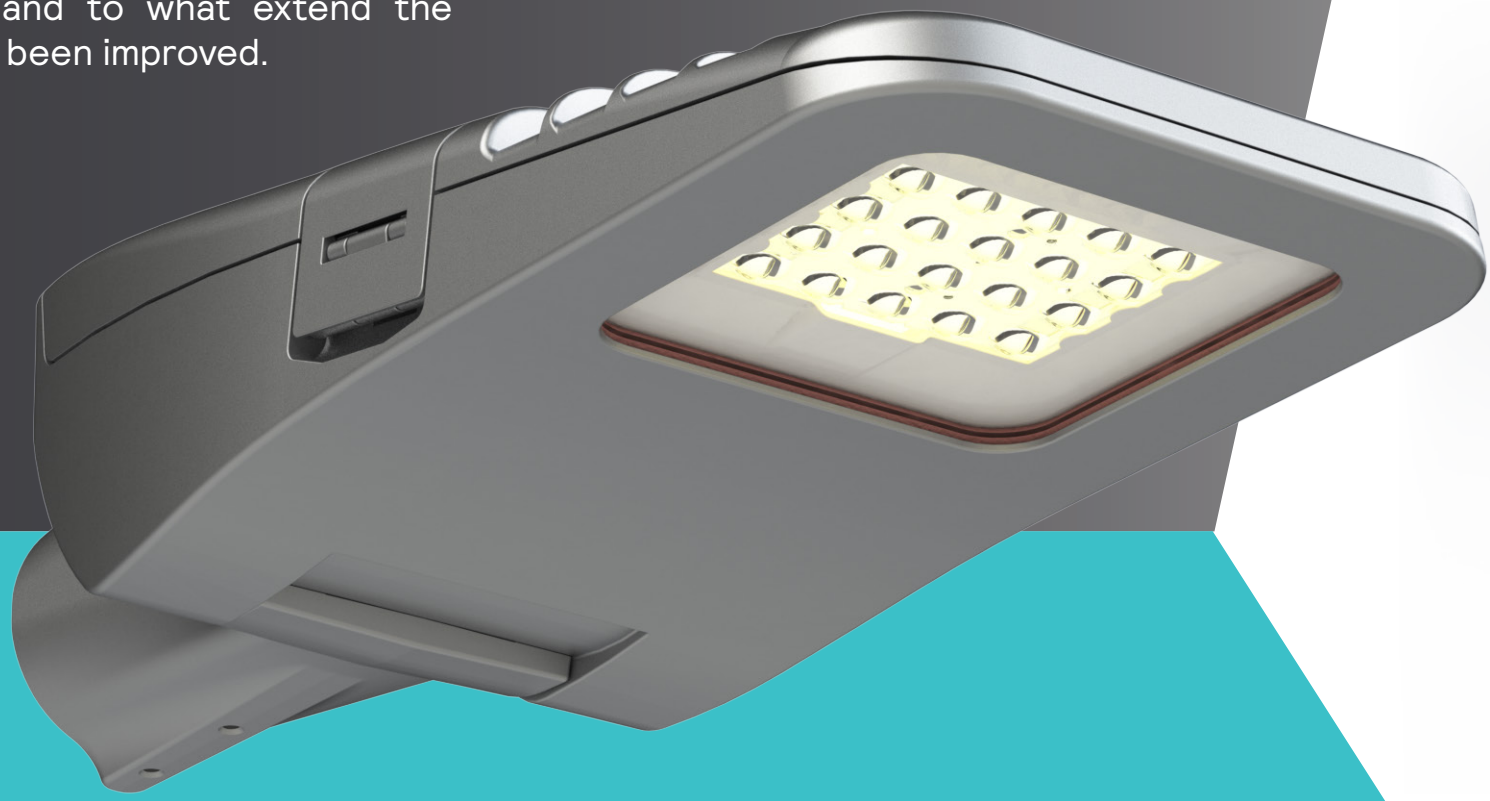


Figure 51: 3D view of the redesign from below with the L2 on.

8.1 Overview

This section will show rendered images of the final design. Feature explanation and details can be found in Sections 8.2. & 8.3.



Figure 52: 3D view of the redesign.



Figure 53: Side view of the redesign.

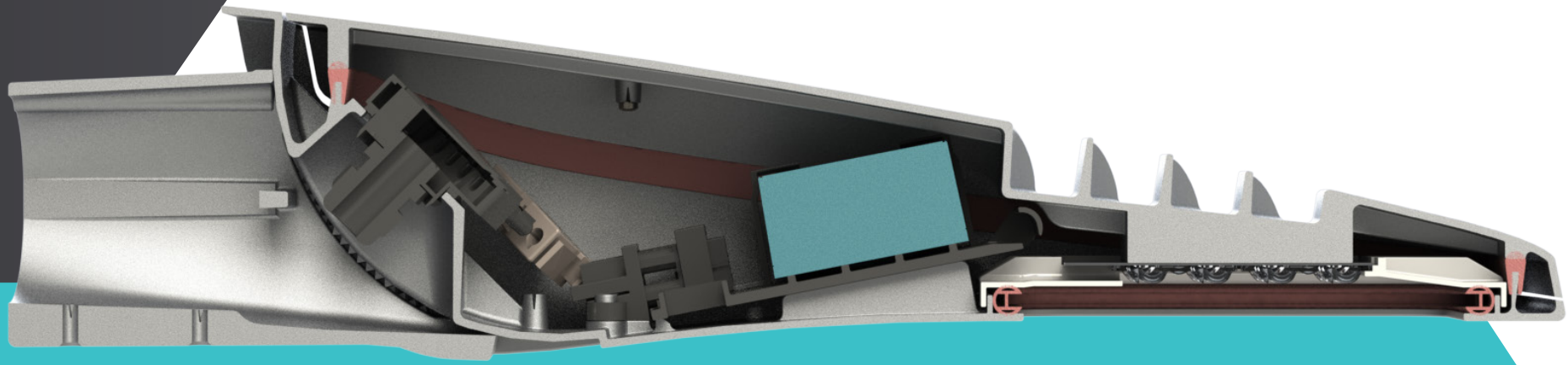


Figure 54: Side cross-section of the redesign.



Figure 55: 3D view of the redesign with the lid opened.

8.2 BoM & Exploded View

A bill of materials can be seen in Table 19. Figure 56 shows an exploded view. Note that the light blocker has not been included in this redesign as this is an optional component and no 3D model was present.

Part #	Name	Material	Pcs
1	Spigot Holders	Stainless steel	2
2	Spigot	Aluminum	2
3	Glass Panel	Glass	1
4	Glass Seal	Silicon rubber	1
5	Reflector	PC	1
6	Light Blocker	PC	0
7	Lens	PMMA	1
8	L2	Mixed/electronics	1
9	Driver	Mixed/electronics	1
10	Adapter	Mixed/wires	2
11	Driver Connectors	Mixed/wires	2
12	GearTray	PC	1
13	Driver/Power Connector Holder	PC	1
14	Driver/L2 Connector Holder	PC	1
15	Driver/L2 Connector 1	Mixed/wires	1
16	Main Power Connector	Mixed/wires	1
17	Driver/L2 Connector 2	Mixed/wires	1
18	Driver/Power Connector	Mixed/wires	1
19	Lid Seal	Silicon rubber	1
20	Lid	Aluminum	1
21	Latch	Aluminum	1
22	Latch Arm	Aluminum	1
23	Main Body	Aluminum	1
24	T20 bolt	Stainless steel	3
25	Spring Steel Pins	Stainless steel	6
26	A6 Hex Bolt	Stainless steel	2
27	A4 Hex Bolt	Stainless steel	2

Table 19: BoM of the redesign of the Luma.

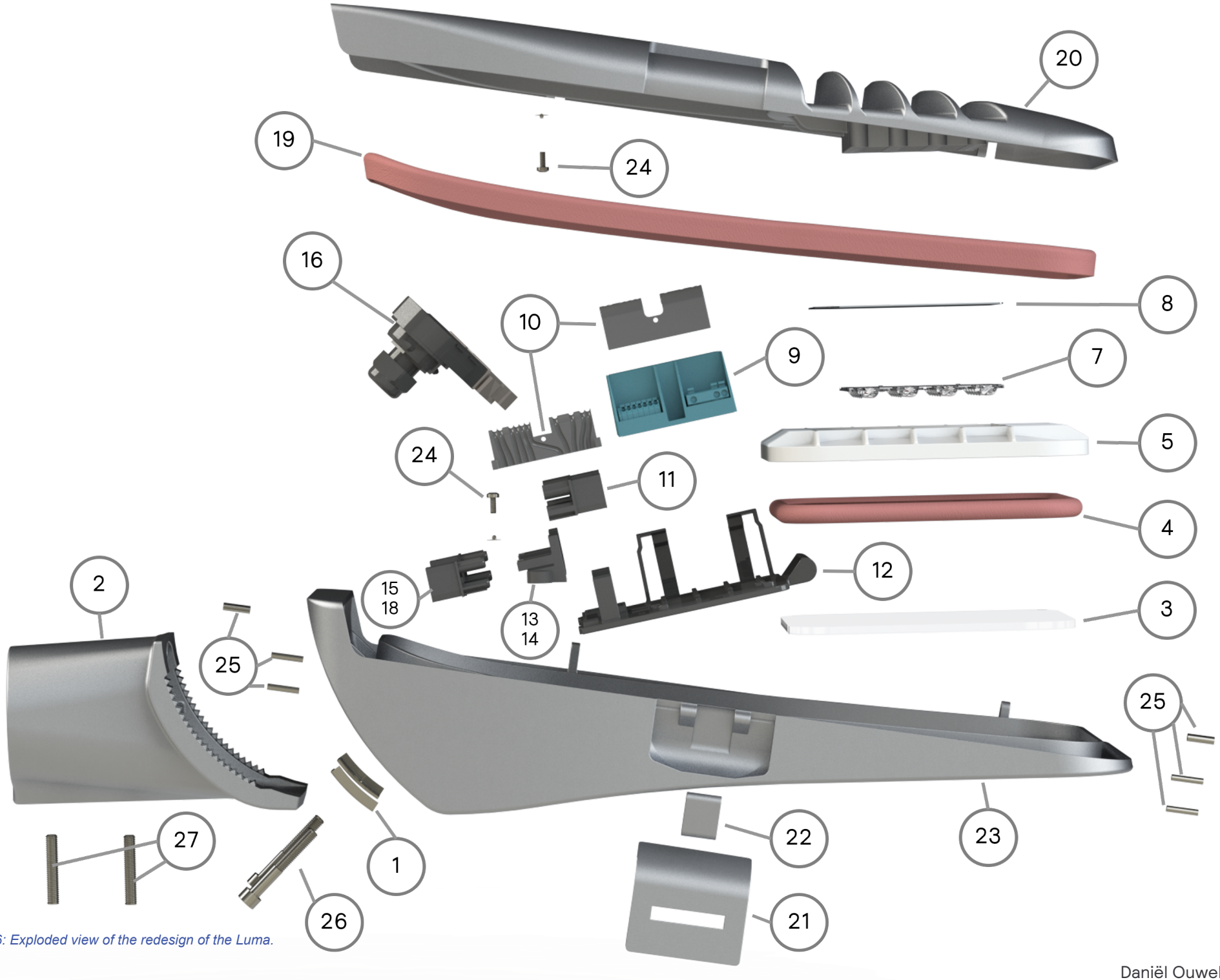


Figure 56: Exploded view of the redesign of the Luma.

8.3 Design Details

The following section will focus on important elements of the design, iterations, and the justification of certain design decisions.

8.3.1 Latch Design

Neither of the concepts from Section 7.3. had a latch included, as it was not part of the to be tested design functions. However, for the final design, the sideways opening of the lid meant that it was necessary to redesign the latch as well.

The current latch design would have been difficult to implement, as it needs a horizontal surface to lock onto, which does not exist in the new design. Therefore, 2 options were considered. The first was derived from a toolbox latch (Figure 57). This design relies on a hook going over the side and a small arm creating leverage to keep it closed. The second option is used in the LumiStreet (Figure 58), using two separate metal brackets that are attached to the outside.



Figure 57: Toolbox latch design.



Figure 58: Lumistreet latch design.

Option 2 takes up less internal and external space and can therefore be placed almost everywhere on alongside the edge of the luminaire, resulting in a better distribution of clamping force. Option 1 however, can be designed to blend in with the exterior of the Luma as the latch can be made from the same powder coated aluminum. This can feel like a more high-end latch and would contribute to the perceived customer value, which was also the argument for the current latch design (Product Designer at Signify, personal communication, 11 June 2024). Therefore, a latch was modeled after the design of option 1.

The latch was placed in the center of the lid, blending fully in with the side profile while leaving just enough internal space for the reflector and seal. The clamping force can easily be tuned by adjusting the dimensions as shown in Figure 59. Increasing dimension 1 or decreasing dimension 2 will result in less clamping force. The needed clamping force has not been calculated and is recommended to be specified in a future design. However, a 3D-printed prototype was tested and adjusted until functional.

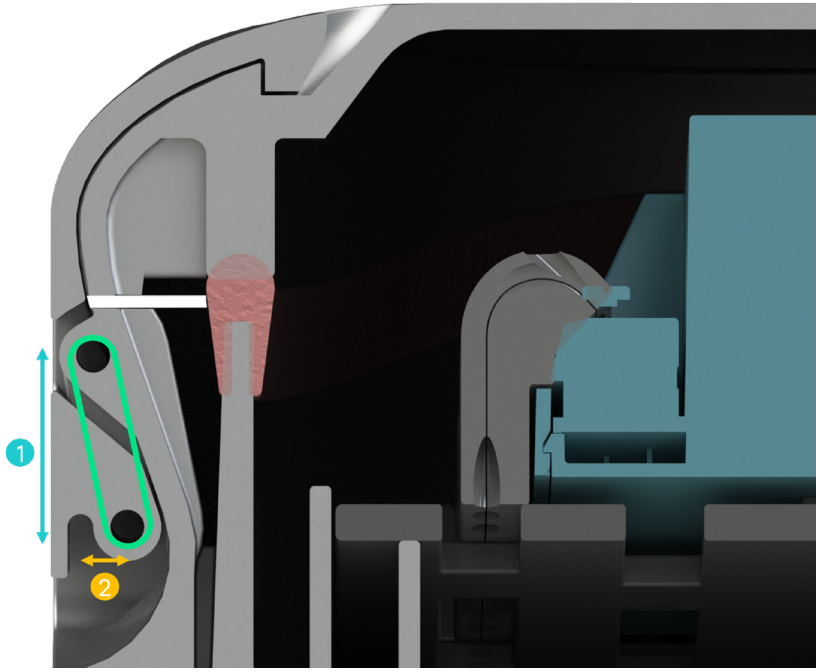


Figure 59: Latch design. The green shape represents the latch arm.



Figure 60: Lid accessibility of the redesign.

8.3.2 Improved Lid

The lid opens towards the side of the luminaire (Figure 55) and spans across the entire topside, giving the installer easier access to the priority components. All priority components are reachable from the top (Figure 60) and can be removed as such.

When opened, the side of the lid rests on the side of the main body, eliminating the need for the lid support rod. Figure 61 shows the angle of the lid in a fully opened position.



Figure 61: Opening angle of the lid of the redesign.

The cooling fins on the lid have changed direction and are now pointing downwards (Figure 62), making sure that any rain will flow off to the sides.

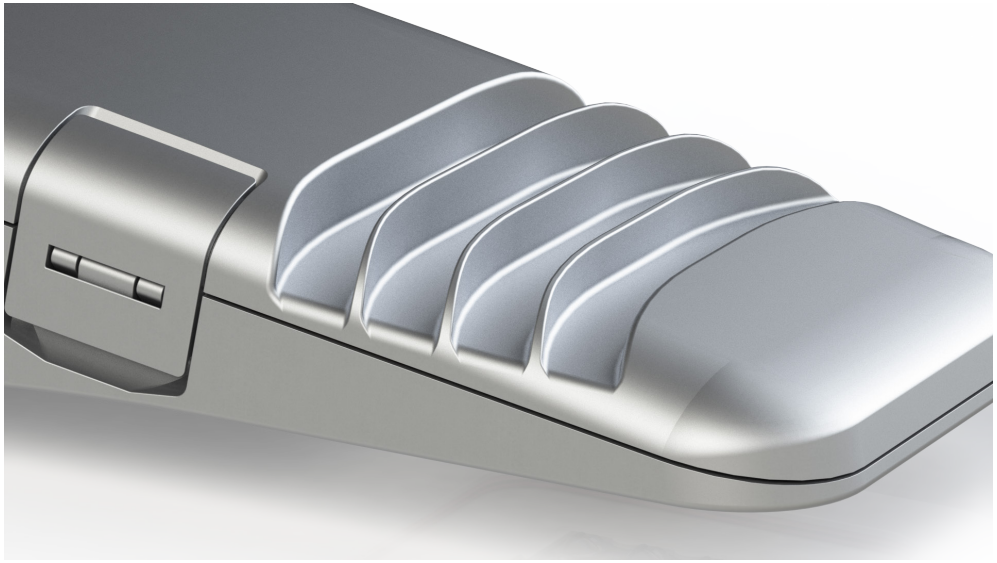


Figure 62: Detail of the reversed cooling fins on the redesign.

In the original design of the Luma, the height of the main seal location decreases as soon as it passed the spigot area (Figure 63) to give enough clearance for the installation/removal of the main power connector.

The first iteration of the new design also featured this drop. However, in combination with the sideways opening of the lid, this resulted in a sideways closing motion of the main seal (Figure 64). This motion would push the seal out away rather than press down on it.

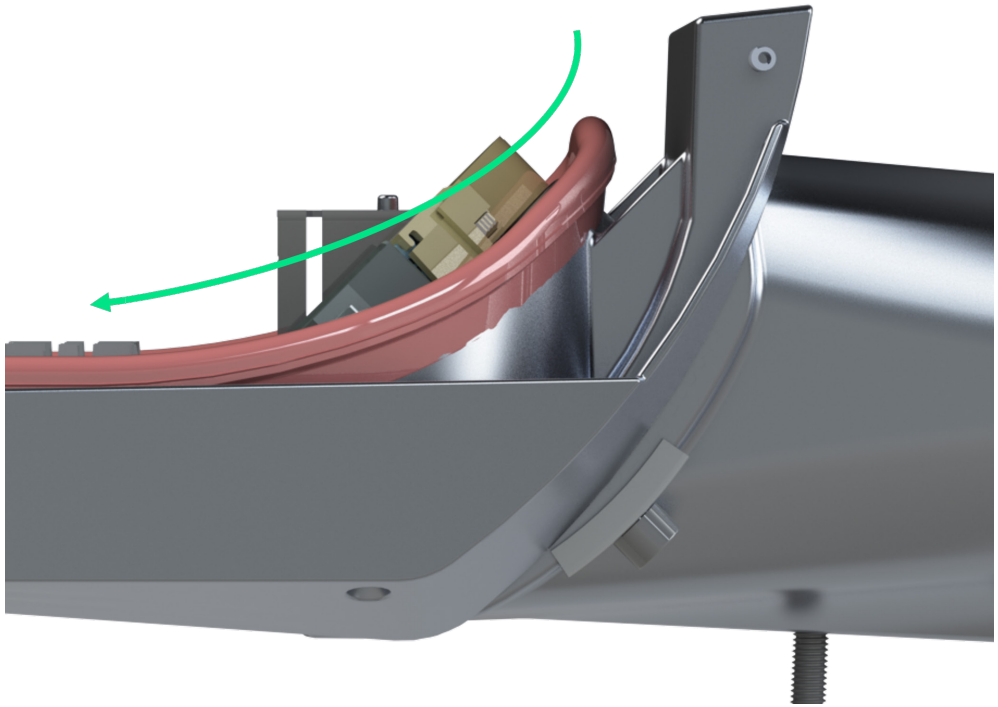


Figure 63: Original design main seal drop.

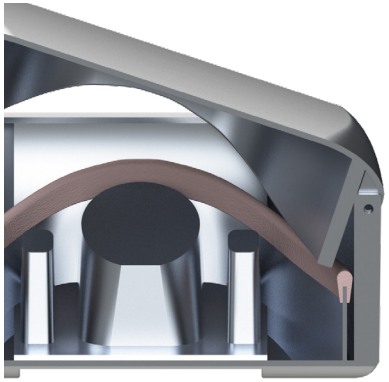


Figure 64: First iteration of main seal.

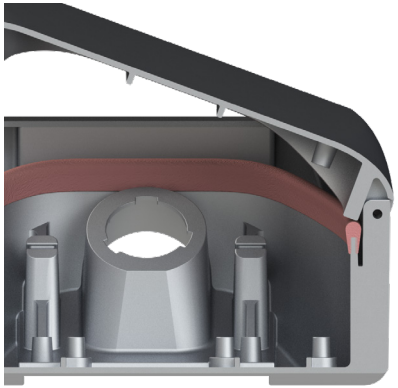


Figure 65: Second iteration of main seal.

A second iteration featured a raised main seal location (Figure 65), limiting the sideways motion. This means that the main power connector cannot be removed as a whole, but the individual connectors must be removed first (Figure 66). Ideally, the main power connector is only touched once, when installing the luminaire. Reliability of the seal has priority over a fast main connector removal.

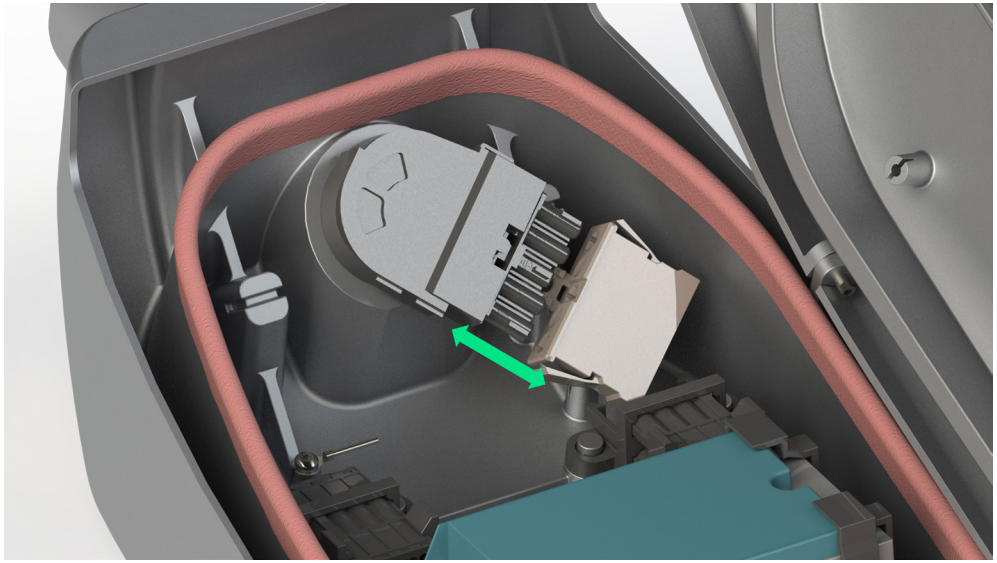


Figure 66: Removal of the power connector before disassembly.

8.3.3 L2 Cooling

The L2 can be reached from the top and is clamped between the reflector and the lid of the luminaire (Figure 67). It is constrained without the use of any bolds or friction fits, therefore making repairs faster and improving recyclability of the luminaire.

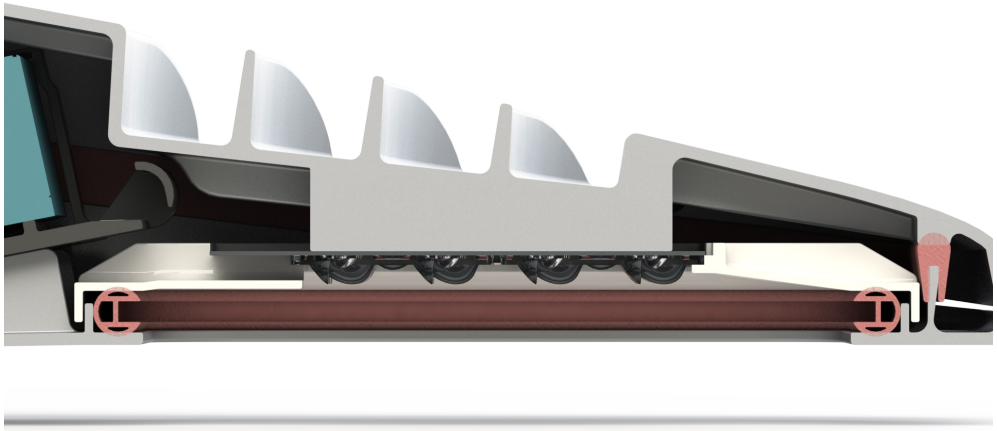


Figure 67: Side view cross section of the L2 assembly of the redesign.

An important part of the design of the luminaire is the ability for the L2 to work at its desired performance level. To maintain this level, the L2 needs to receive sufficient cooling (Requirement 5). Therefore, we determined how much cooling capacity the current design of the luminaire has and made sure that it did not decrease in the redesign.

The cooling capacity of the L2 depends largely on 3 factors:

1. Contact area surface.
2. Air gap between the L2 and the contact area.
3. Distance between the L2 and housing.

The more surface the contact area to mount the L2 to has (Figure 68), the more heat can be transferred via conduction of the aluminum. The smaller the air gap between the L2 and the contact area, the better the heat will be transferred from the L2 to the aluminum. The smaller the distance between the L2 and the housing, the better heat is transferred through convection of the trapped air, and heat radiation of the L2 to the housing.

In collaboration with a thermal expert (Thermal Engineer, personal communication, 14 October 2024), calculations were done to determine the current cooling capacity of the Luma. The calculations established the temperature difference between the ambient air temperature and the L2 temperature. For this concept, the combination of the three above factors needs to result in a delta T that is the same or less when compared to the current design.



Figure 68: Contact area surface between the L2 and the lid of the redesign.

The mounting surface area and distance between the L2 and housing are directly affected by the design of the lid and contact area fins. In the new design, the surface area has doubled, while the distance between the L2 and the housing has remained the same.

The second factor however, the air gap, is more difficult to determine, as it depends on the clamping force and deformation of the L2 under this load.

The redesign doesn't use bolts but distributes a pressure along the entire contact area. This can potentially result in a smaller air gap, depending on the deflection of the L2 within the full architecture.

Currently, the L2 contact area is straight, accounting for zero deflection. Due to time and simulation constraints, this deflection has not been tested. Deflection is assumed to be limited, as the lid enforces pressure on the sides of the L2, which is supported directly below by the reflector. However, a next step in the design could be to simulate this deflection and shape the contact area accordingly.

For this concept, the average air gap has been set to double that of the current design as a safety factor for the unknown deflection. With the increase in contact area surface and decrease in distance between the L2 and housing, this results in a delta T that is slightly lower than that of the current design, which proves this concept can provide sufficient cooling.

8.3.4 Reflector Stress

The reflector must provide sufficient strength and little deflection as it has the function of applying force onto the seal between the glass and main housing. Failure of this seal would result in possible water ingress, damaging the internal components.

The exact force needed to form a good seal depends on the hardness, diameter, and design of the seal itself (hollow, solid etc.). According to a Mechanical Engineer at Signify (personal communication, 23 October 2024), the design of the seal can, at a later stage, be adjusted to the maximum force that the reflector is able to apply.

Figure 69 shows a side view of the reflector. In this and all following images, the reflector is colored white and the seal red. The arrows indicate the forces acting on the reflector. As can be seen, the inner region of the reflector can deflect downwards by the acting forces. Three methods can be applied to decrease deflection and increase stiffness:

1. Increase the distance between the L2 and the glass plate, resulting in more vertical strength (Figure 70, 1).
2. Decrease the width of the reflector, resulting in a smaller arm (Figure 70, 2).
3. Add vertical ribs.

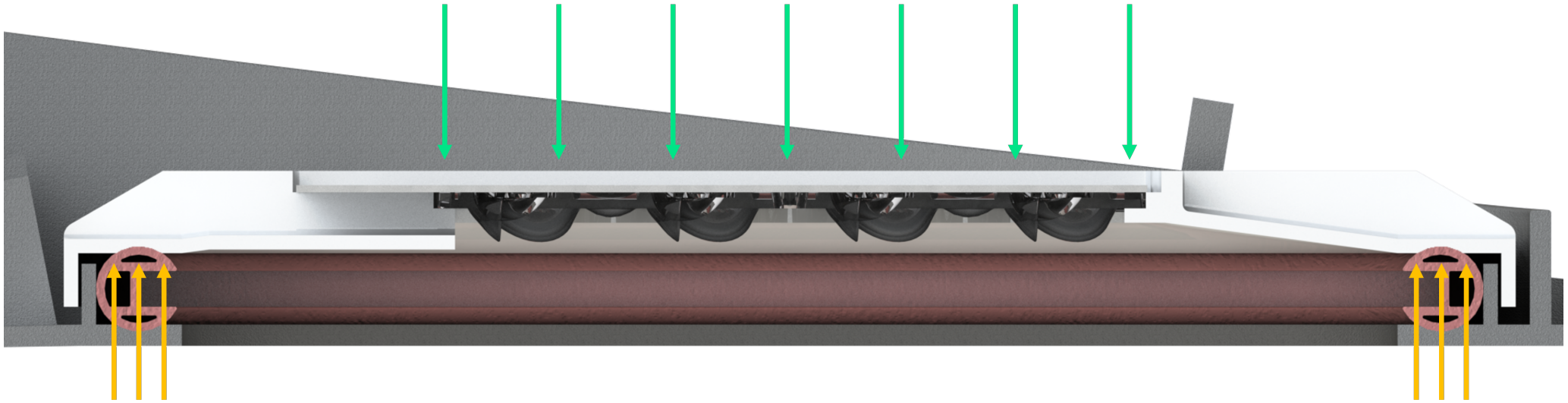


Figure 69: Side view of the reflector including the acting forces of the lens pressing down and the seal pressing up.

The first two methods are restricted by either the size of the reflector or the luminaire and can result in poor lighting performance. The third method is used in the reflector of the current design of the Luma and will be used throughout the iterations of the new design.

To set a target for the desired maximum force, an estimation was made using data of a regular solid o-ring with a Shore hardness of 50A. Full calculations can be found in Appendix P. This resulted in a target force of 221 N.

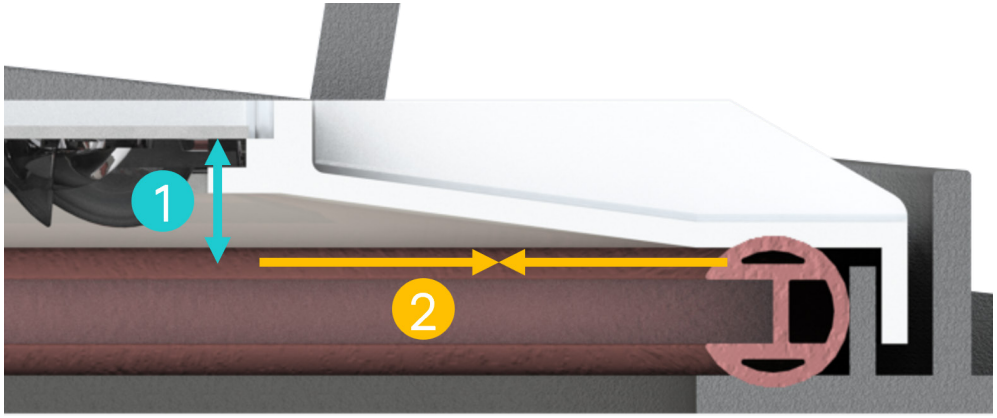


Figure 70: Geometry changes of the reflector.

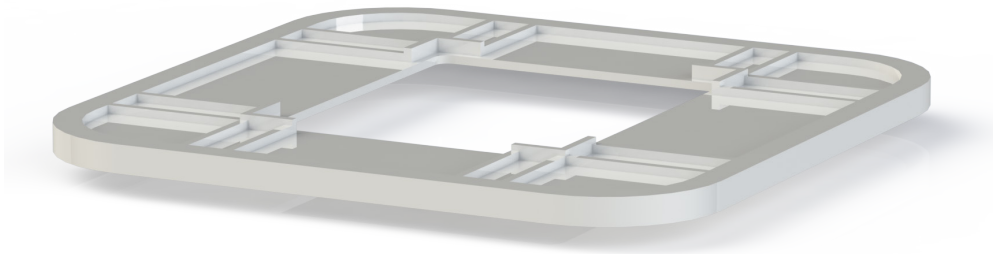


Figure 71: Reflector from the initial concept.

The reflector in the design concepts from Section 7.3 had very low ribs (Figure 71). The first iteration of the final design included higher ribs with gaps in certain places to allow for easier L2 fitment. These gaps resulted in weak points due to a low vertical edge.

The second iteration of the reflector (Figure 72) had continuous ribs, therefore transferring the force better across the whole reflector.



Figure 72: Second iteration of the reflector.

This design was able to withstand 136 N while maintaining safe stress levels (Figure 73). The highest stress occurred in the in the ribs on the front side of the reflector.

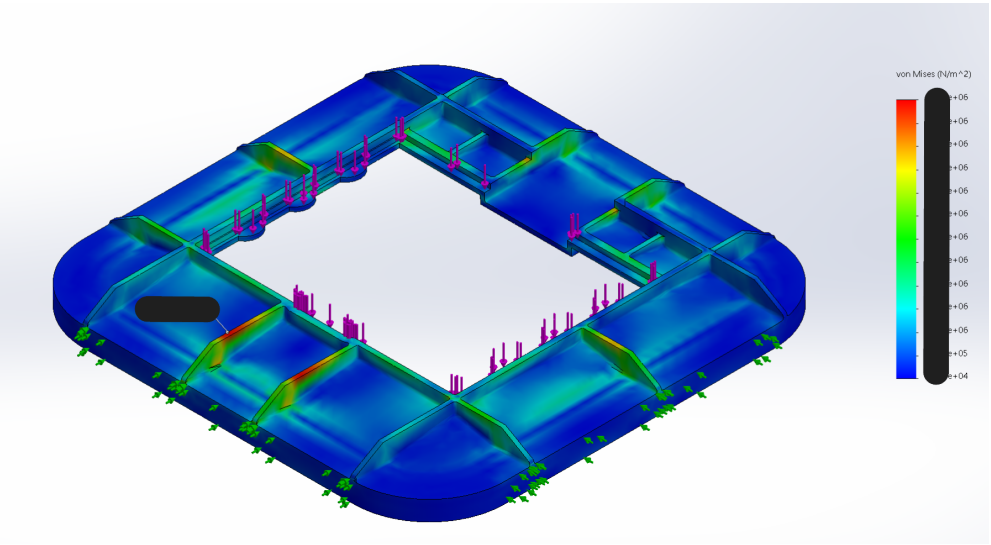


Figure 73: Stress simulation of the second iteration of the reflector at 136 N.

A final iteration was made, increasing the number of ribs to distribute the force better. This resulted in the design as seen in (Figure 74).

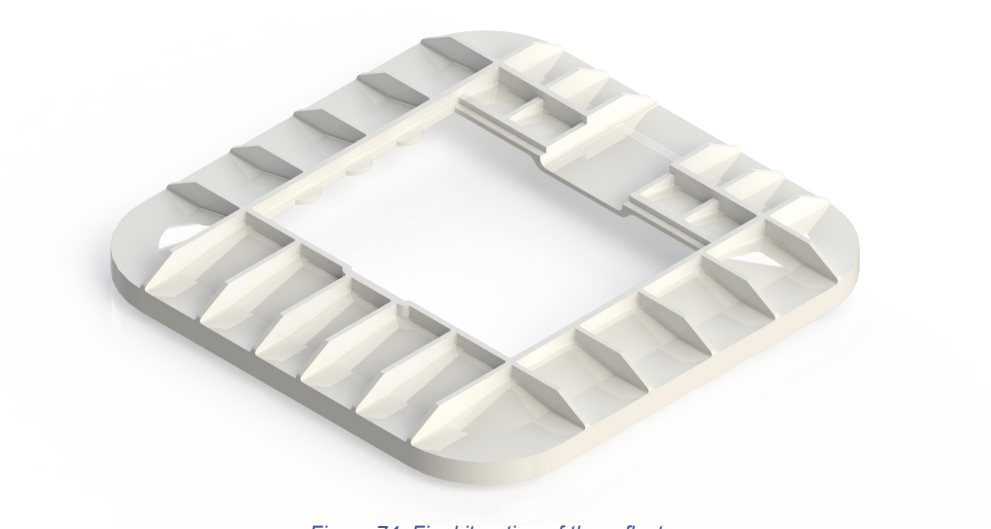


Figure 74: Final iteration of the reflector.

This design can handle 148 N of force while maintaining safe stress levels (Figure 75), a near 10% increase compared to the previous iteration.

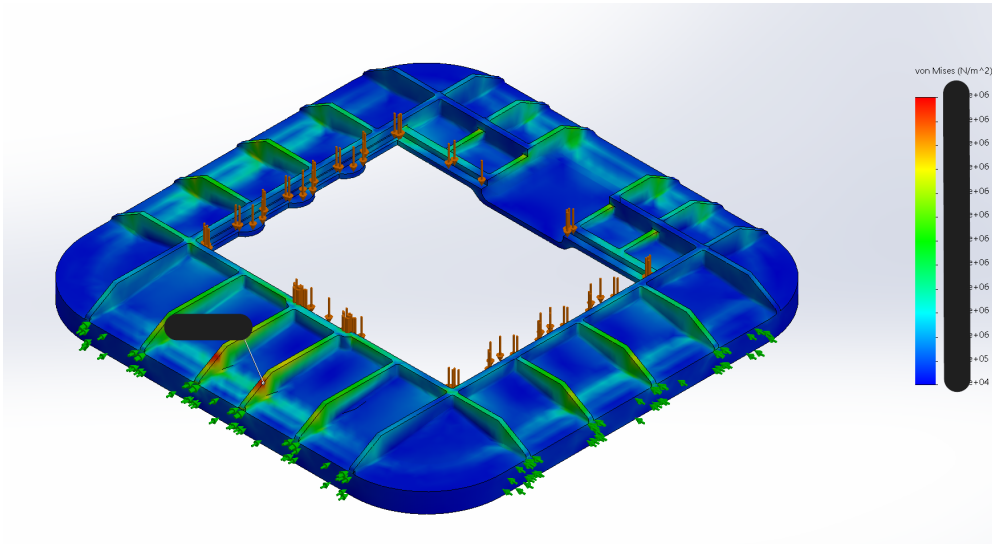


Figure 75: Stress simulation of the final iteration of the reflector at 148 N.

The 148 N is less than the target force of 221 N, however, the solid O-ring that was taken as reference, requires more force than a specially designed

seal. The target force could be decreased by implementing cavities in the seal (as seen in Figure 70), or by using a softer silicon.

In case the target force remains too high, more ribs or thicker material of the reflector could result in more strength. Furthermore, a design as presented in Figure 76 could provide a solution. This design uses poles extruded from the lid to directly push on the edge of the reflector and therefore the seal, removing any momentum on the reflector.

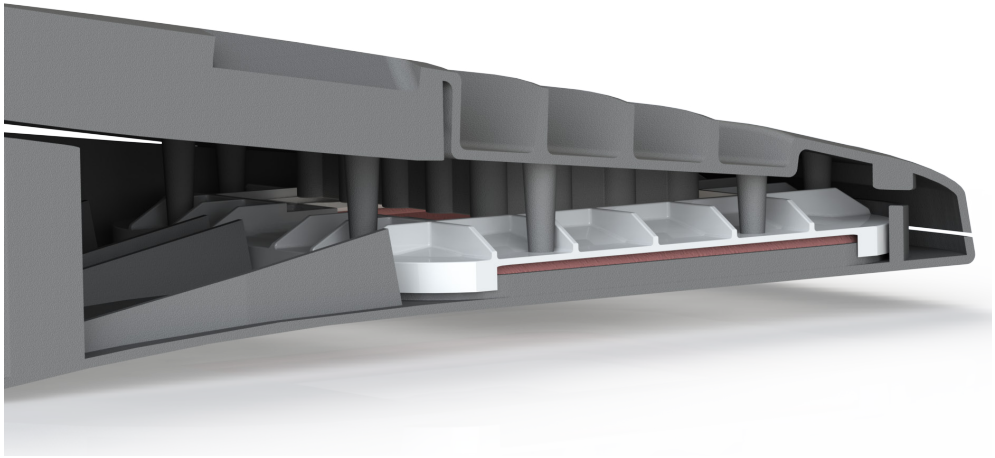


Figure 76: Lid design that enforces direct pressure on the seal.

8.3.5 Driver Assembly

The driver is placed on a GearTray instead of GearFlex box and is made to slide in and out of the luminaire for easy removal and better access (Figure 77).

It is constrained by the connectors in the back and molded guides in the body of the luminaire (Figure 78). A cutout in the lid follows the curve of the GearTray handle, making sure that it remains in place even when turned upside down (left side of Figure 67).

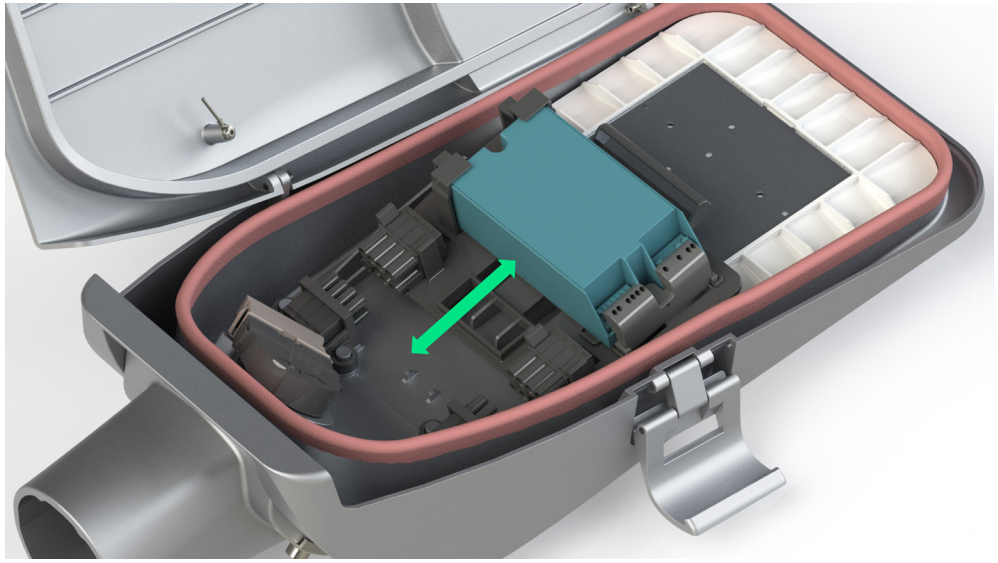


Figure 77: Sliding direction of the GearTray.

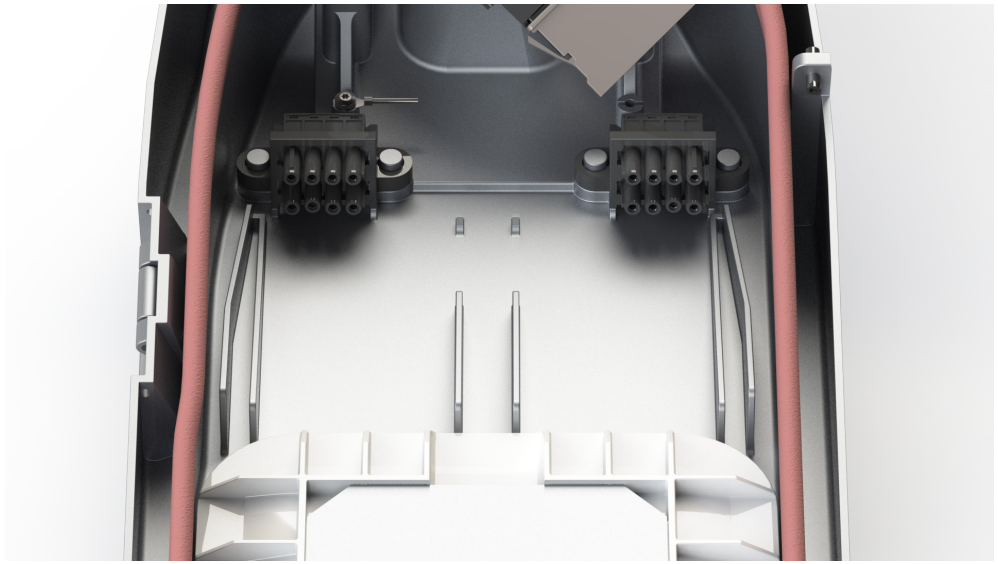


Figure 78: Frontal view of the GearTray connectors and guides.

The existing GearFlex box connectors are placed sideways using snap fits. The connector on the GearTray (Figure 79, 1) is mounted from the top, while the connector on the housing is mounted from behind (Figure

79, 2). The second method is preferred, as the force on the connectors when removing the GearTray is opposite of the mounting direction, making it difficult to accidentally break off the connectors. However, the connectors on the GearTray would interfere with the driver bracket when mounted from behind. Therefore, a vertical snap fit was used. While less reliable, with the right tolerances the snap fits can also limit the horizontal movement. The housing connectors are attached to the housing using press fitted plastic crush ribs.

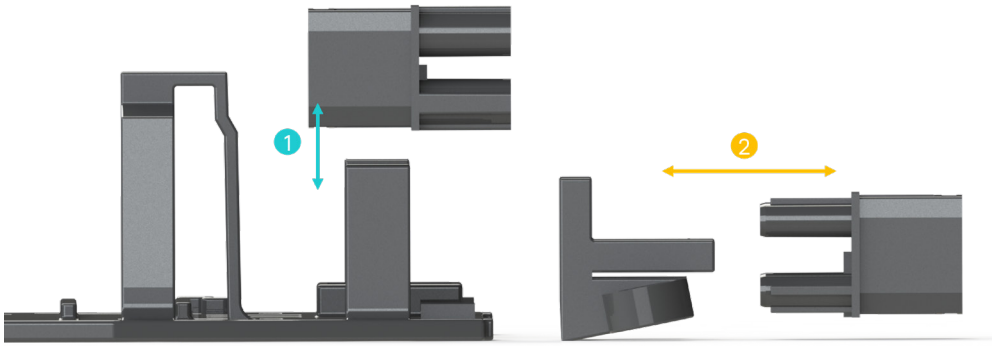


Figure 79: Side view of the GearTray connectors.

An “adapter block” is added to the driver to change the electrical interface and therefore enabling a no-tool driver swap. The adapter block as presented here is modeled with the goal of making a functional prototype. Therefore, the adapter block uses regular wires and off-the-shelf female headers to make the electrical connection. This makes the adapter block too fragile for commercial uses. In a final embodiment of the design, it is recommended to design specific electrical connectors to be used with the adapter block.

The adapter is made from two parts with cutouts for wires (Figure 80 & Figure 81). It attaches to the existing electrical interface of the driver and changes the interface from sideways pointing female connectors to downwards facing male connectors. This results in a driver that can be “clicked” in and out of the GearTray in just 2 movements and without the use of any tools. Once the adapter is installed to the driver, removal is difficult. Therefore, new drivers should be sold with the inclusion of a new adapter.

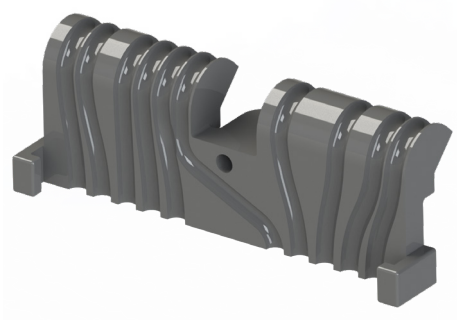


Figure 80: Inner part of the driver adapter.

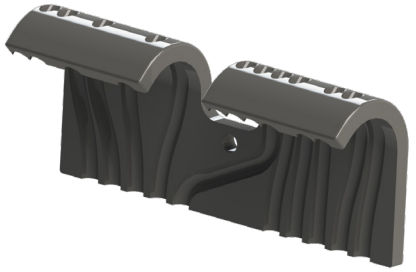


Figure 81: Outer part of the driver adapter.

The adapter has holes on top that provide access to the individual wires, allowing an installer to make electrical measurements if needed. It enables driver-only repairs and therefore minimizing the need for GearTray stock, improving repairability.

The adapter block sticks out from underneath the driver to be able to clamp on the existing mounting hole of the driver from 2 sides (Figure 82). This makes the mechanical connection between the adapter block and driver more secure and therefore reducing the risk of stressing the electrical connection. This required the driver to be raised slightly above the GearTray. To achieve this, 4 ribs have been added (Figure 83).

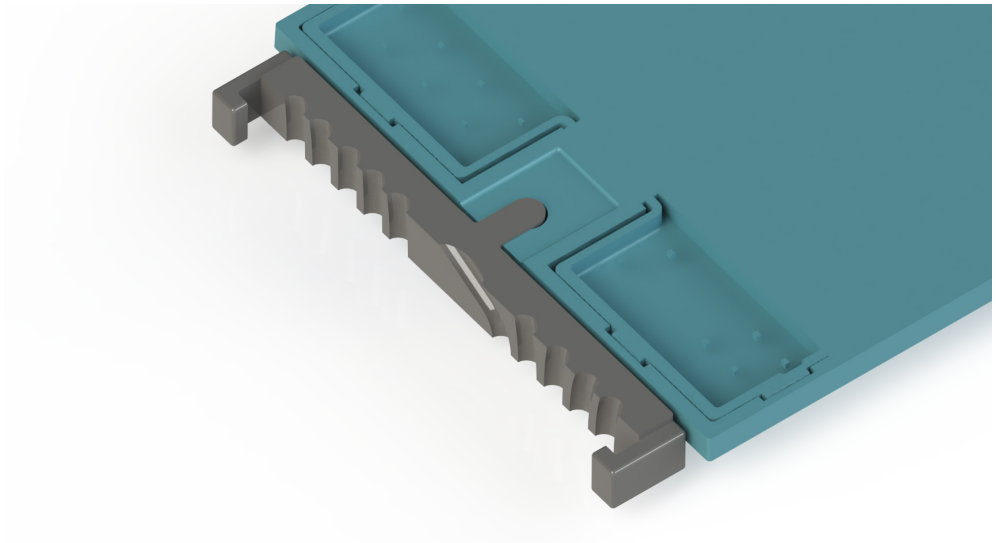


Figure 82: Top view cross section of the adapter block and driver attachment.

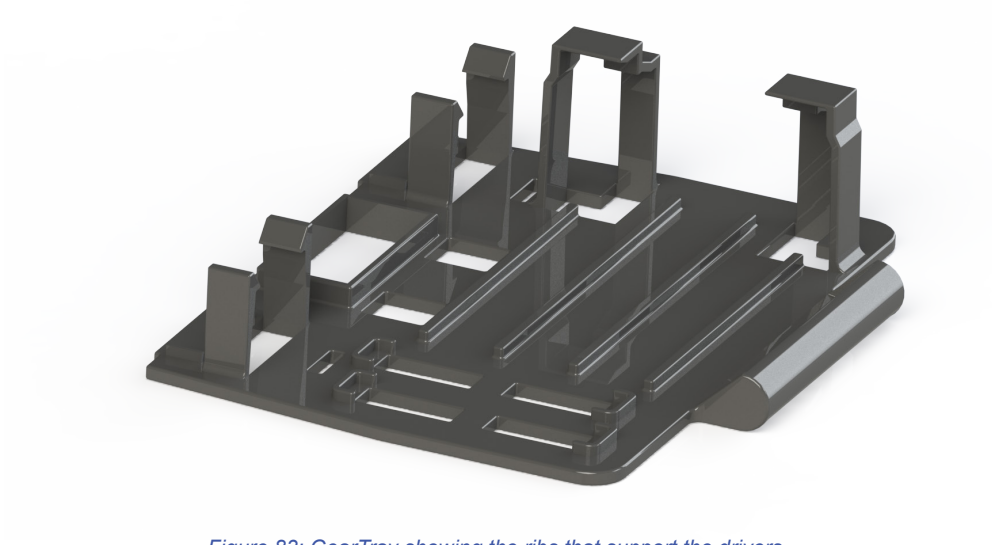


Figure 83: GearTray showing the ribs that support the drivers.

The original GearFlex box had multiple mounting holes it that would account for different driver sizes. As the goal of this design is to facilitate a toolless driver swap, this is not an option. For the Luma Nano, two driver sizes exist. The first iteration of the GearTray had snap fits that would allow both drivers to be attached with a different set of click-fingers. This design turned out to be too flimsy, as the click-fingers needed to be very long to reach over the driver. Therefore, a second design was made using brackets that would allow the driver to slide in and out, while clearing the adapter pins (Figure 84).

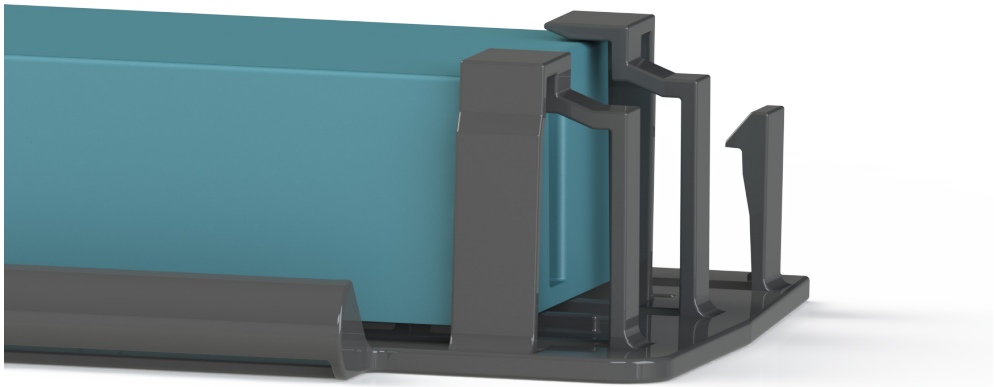


Figure 84: The brackets used to constrain the driver.

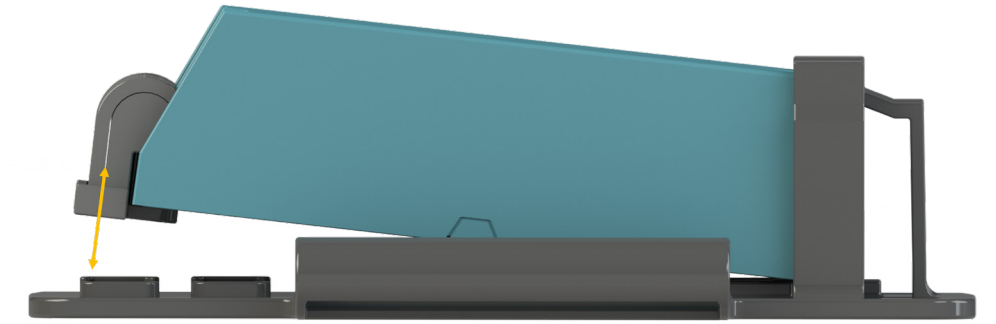


Figure 85: Adapter pins angle of attack.

This design was stronger and kept the drivers well in place. However, testing showed that the sliding movement in combination with the height of the pins, would result in an undesirable angle of attack, keeping the adapter pins from engaging with the GearTray holes (Figure 85). Therefore, a third iteration was made to allow the driver to move further back and result in the holes lining up better. This removed the horizontal limitation function of the driver brackets which became a function of the adapter block.

The driver brackets and adapter cutouts are designed to facilitate the 2 driver sizes (Figure 86 & Figure 87).

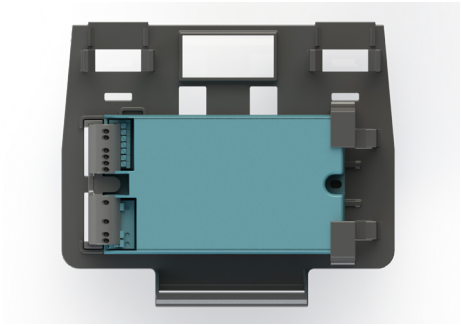


Figure 86: GearTray driver option 1.

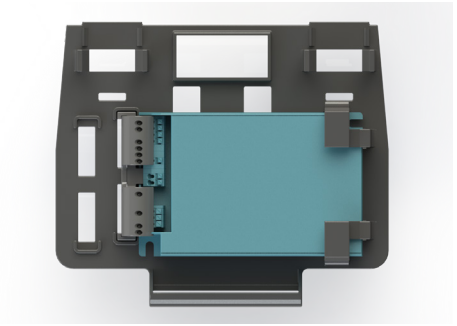


Figure 87: GearTray driver option 2.

8.3.6 Breaklines

Breaklines have been added around the bolts that have not been replaced by another method of connection. This has been done for the spigot bolts (Figure 88), the spigot holder bolts (Figure 89) and the ground wire bolts (Figure 90).

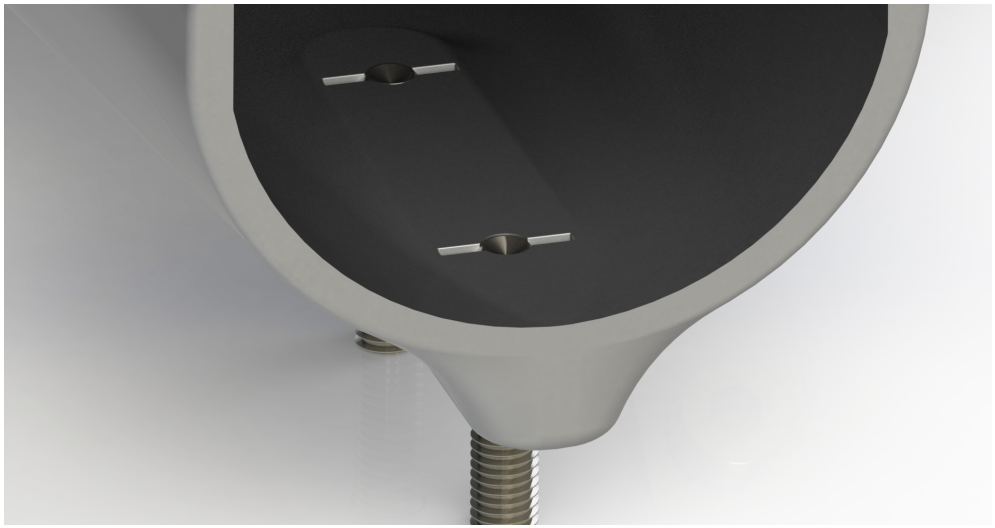


Figure 88: Breaklines on the spigot bolts.

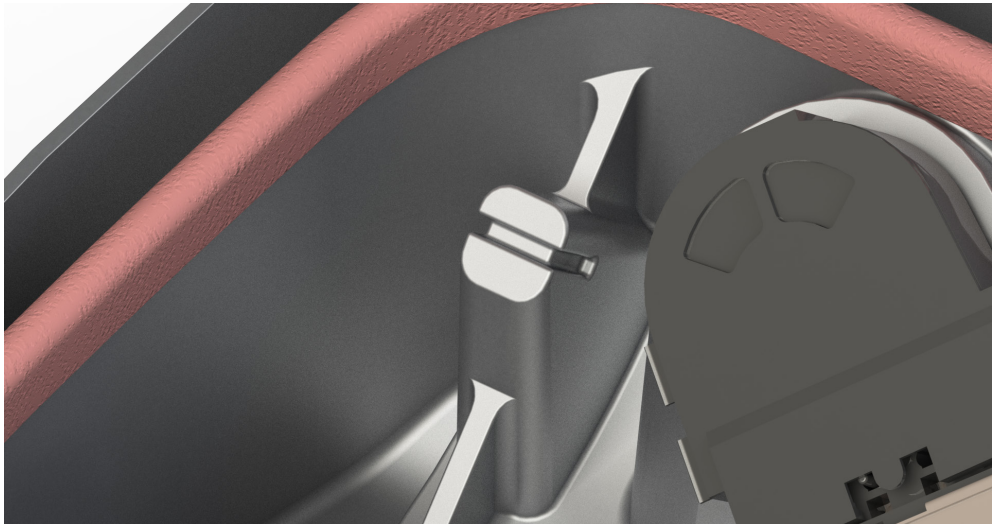


Figure 89: Breaklines on the spigot holder bolts.



Figure 90: Breaklines on the ground wire bolts.

Research was done into the use and application of breaklines within a design, however, very little information was found. Therefore, different breakline options were modeled and simulated to understand their effect. Figure 91 & Figure 92 show 2 options for breakline designs of the spigot.

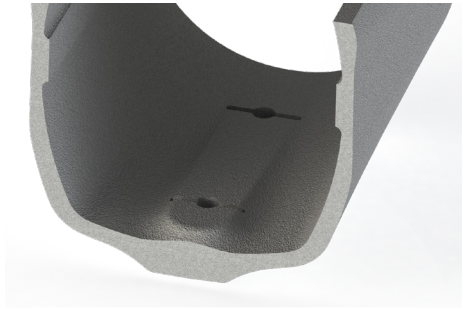


Figure 91: First breakline design of the spigot.

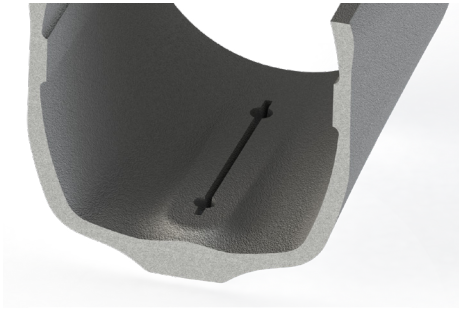


Figure 92: Second breakline design of the spigot.

When used as intended, the threaded holes should provide enough axial strength for the bolts to be torqued. However, when a directional force is applied, for example from the side, the threaded hole should snap along the breaklines. This makes the ideal breakline difficult to determine but is most likely the result of the direction and size of the breaklines. Breaklines on the outside of the spigot were not attempted as the direction of the resulting forces from tightening the bolts are likely to split the holes.

The simulations showed that the design in Figure 91 showed no significant increase in stress of the spigot when force was applied directly on the face of the holes. The stress of the design in Figure 92 almost doubled. However, it is very likely that a force applied on the threads of these holes will result in different local stresses. Unfortunately, the simulation software was unable to simulate this.

Since the design in Figure 91 maintained similar stress levels, it was used in the redesign.

8.4 Disassembly & Recyclability Map

To determine the changes in disassembly and recyclability, new maps have been made. These maps are different to the maps of the repairability concept from Section 7.3. as they have been adjusted for all architectura, instead of just the driver and L2.

The disassembly map is shown in Figure 93. Compared to the original design of the Luma, the architecture has become less complicated. The L2 and driver can be removed via less steps and the process of removing the individual wires when switching drivers has also disappeared due to the use of the adapter.

The recyclability map can be seen in Figure 94. The reduction of components and connections throughout the design is visible. The Starlock washers that were used to fasten the connector holders are now replaced by press fits. Many of the screws used for the latch and the opening of the lid have been removed as they were not necessary in the new design. The bolts to fasten the L2, glass clamps and driver are also gone. The latch design does however require an extra aluminum component and steel pins.

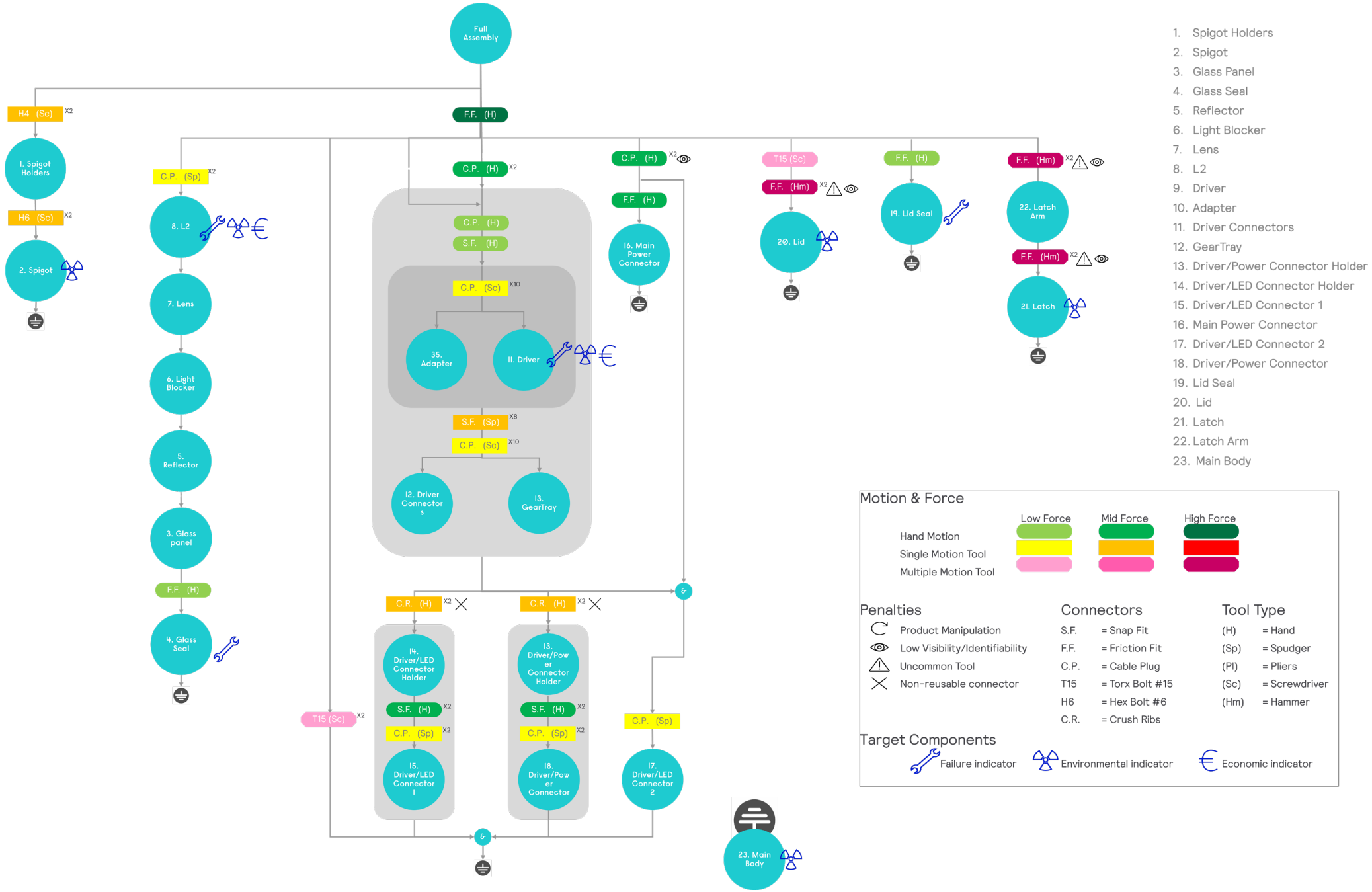


Figure 93: Full disassembly map of the redesign of the Luma.

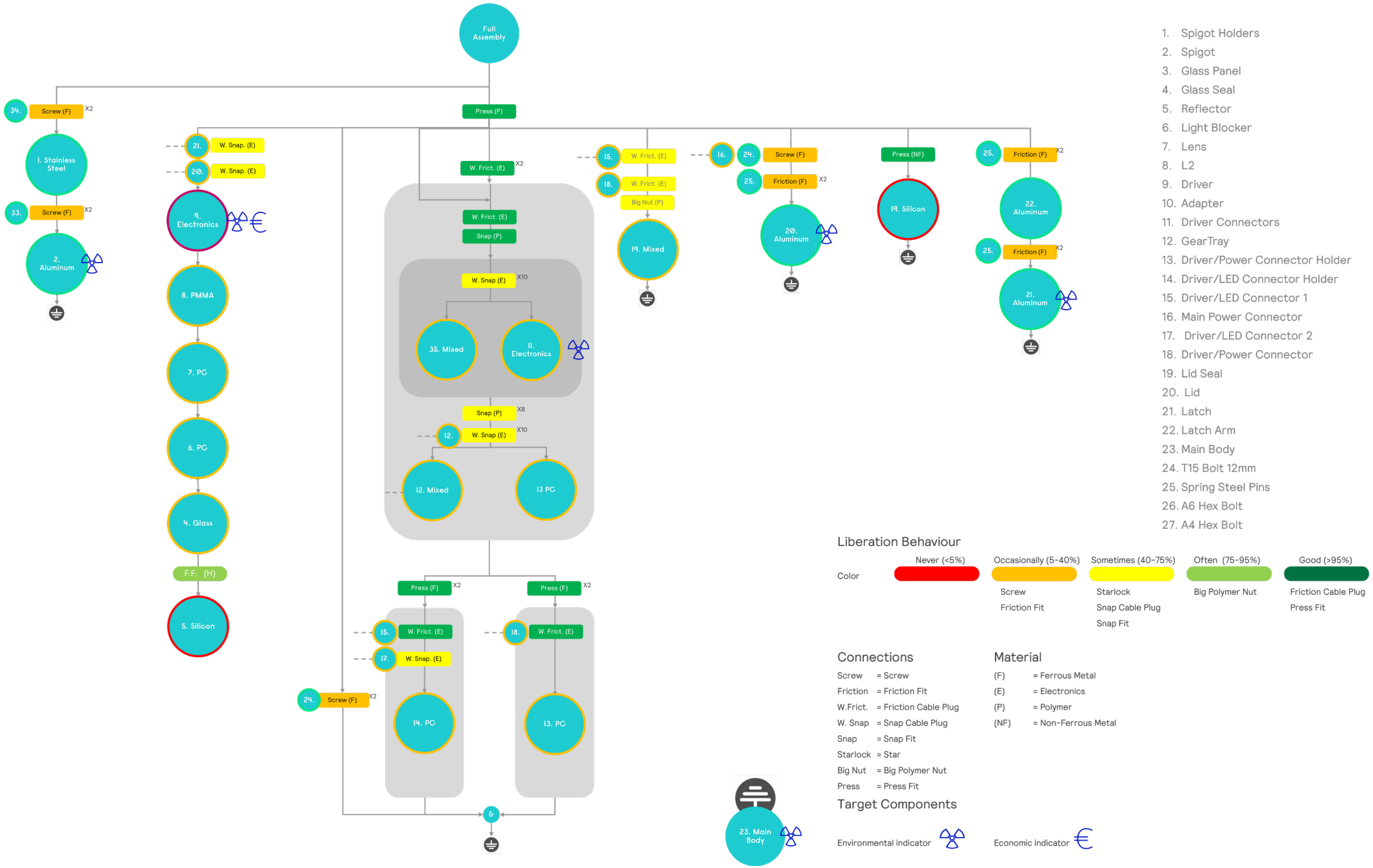


Figure 94: Full recyclability map of the redesign of the Luma

8.5 Prototype Testing

A full-scale functional 3D-printed prototype (Figure 95) was developed to test the improvements in repairability and recyclability.

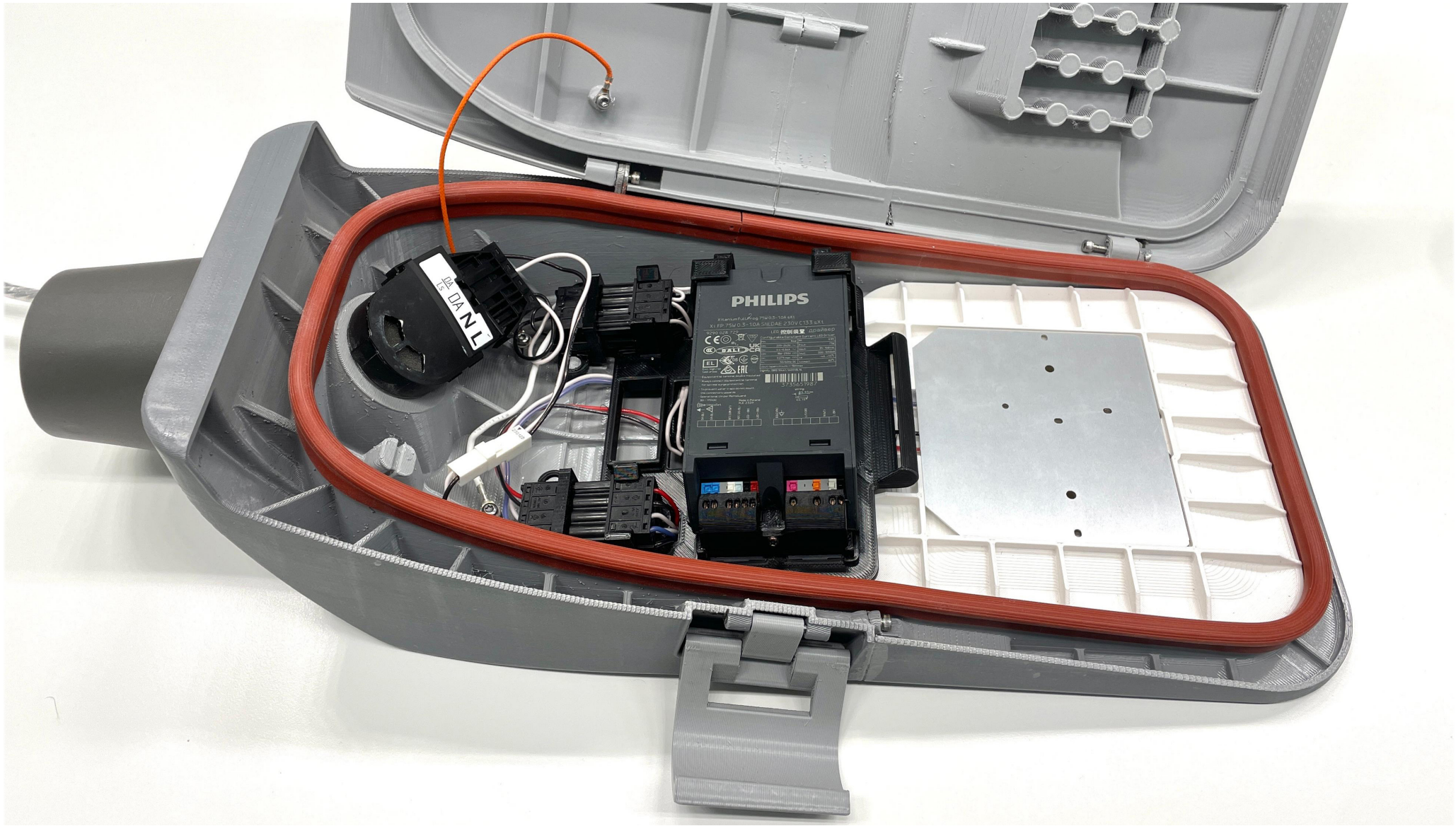


Figure 95: Functional 3D-printed prototype of the final design.

8.5.1 Repairability

To confirm the improved repairability, the prototype was presented to the repair team (personal communication, 13 November 2024).

The repair team mentioned that the accessibility of all components has been greatly improved. Both the driver and L2 are reachable from the top, as well as all connectors. This would not only improve disassembly time, but also the time for diagnosing the issue. The electrical measurement holes in the adapter further supported this goal. Everything that needs to be reached during repairs, can be reached with ease. The latch mechanism felt secure and decreased the risk of water ingress.

Furthermore, the inclusion of the adapter would make the driver swap significantly faster and simpler, as the wires cannot be connected wrongly. Therefore, on the pole repairs could be done by anyone. Therefore, a scenario in which the team that takes down the luminaires would bring a driver-adapter combo by default to see whether a quick driver change would solve the problem, is possible. This could change the current repair practices, in which all luminaires are removed from the pole before being repaired at an external location, and therefore reducing the number of movements to the pole and decreasing the down time of a luminaire.

The time to reach the priority components, the Driver and L2, was also tested and compared to the original design. Please note that these attempts were made after a couple rounds of practice to eliminate human error. Furthermore, to reach the L2 of the original luminaire, the luminaire was turned upside down. This is not possible when repairing on the spot, which makes these repairs more difficult.

It can be seen that the redesign has significantly reduced assembly and disassembly times, therefore showing an improvement in repairability. The combined repair time of the driver and L2 has been reduced from x minutes to y seconds, making the repair almost 9 times faster.

8.5.2 Recyclability

To confirm the improved recyclability, the prototype was presented to the WEEE recycler (personal communication, 13 November 2024).
According to the WEEE recycler, general recyclability of a product can be derived from 2 factors: the recyclability of materials and the sortability of resulting fragments after shredding. While the prototype does not focus on changing materials, the used connections and product architecture have been greatly altered.

He concluded that the prototype indeed shows an improvement in recyclability. The fact that the priority components are not attached with screws, will greatly improve the liberation. Click-fingers and snap fits are used to hold the driver connectors. Compared to the original design, they are expected to fully liberate as well, decreasing the amount of plastic lost in the smelter.

While the driver adapter adds a (permanently connected) connector to the assembly, it should not make a big difference, as the driver is expected to end up in the electronics fraction. The adapter will therefore be processed as such, in which the copper used for the electrical connection can be recovered. The small amount of extra plastic will be used as a fuel for the smelter.

The use of breaklines, while not proven, are also expected to improve the liberation of the A4 and A6 bolts, increasing the purity of the aluminum fraction and decreasing the amount of aluminum lost.

8.6 Design Limitations

Performance
The calculations that determined the necessary cooling of the L2 did not include the cooling fins on top of the lid. Current innovations regarding the efficiency of LED's have made the cooing fins redundant and could therefore be removed from the design. This could result in a flatter luminaire, decreasing the distance between the L2 and the outside and therefore further improving cooling capacity.

Reliability
At the beginning of the design process, the choice was made to design a shallow lid. This was done as it looked more similar to the lid of the Luma Gen2 and it provided more room for the latch. This however resulted in issues with the seal and angle of attack, as explained in Section 8.3.2. While the water tightness of the seal is most likely good enough, a lid with taller sidewalls and lower hinge attachment points could improve the reliability of the seal.

The stress calculations on the reflector were done for an ambient temperature of 20 degrees Celsius. However, if the ambient temperature increases, the temperature within the luminaire will also increase, resulting in in a lower allowable maximum stress of the reflector. The current simulations do not account for this temperature increase and could therefore result in poor long-term reliability of the reflector. This temperature increase should be considered when determining the necessary force on the glass seal.

Production
The final design was made to show the improved functionality of the core features and to give an impression of what a final product could look like. Therefore, certain design decisions had a negative impact on mass-producibility and reliability. This can be best seen in the adapter, which can be made functional with everyday materials but is too fragile for commercial use. A next iteration could focus on production and long-term part reliability.

Safety
The breaklines have been iterated on by adjusting their depth and width, while minimizing the simulated maximum stress during normal operating conditions. There are however several options to potentially improve their functionality, for example a design which has shallow but long breaklines, or breaklines that increase in depth when further away from the screw hole. These changes could allow for more/increased points of leverage during shredding, while maintaining stress levels during normal use.

Since the forces exerted by a shredder are very large and unpredictable, components should be developed and tested in real life to confirm the effectiveness of the breaklines. Currently, the breaklines are applied to the screw holes that fasten the spigot to the pole and luminaire. Liberation of these screws can result in a decrease in material losses during recycling, however, wrongly designed breaklines could also compromise the safety of the luminaire. Therefore, this tension between the recyclability and safety of the luminaire should be carefully considered if taken further.

In the new design of the Luma the adapter block of the driver has two functions: creating an electrical connection as well as a mechanical connection. The mechanical connection relies on the clutch power of the electrical connectors used. If this clutch power proves insufficient, the driver could be dislocated when undergoing heavy vibrations or during a drop test. Therefore, connectors with sufficient clutch power should be designed. If this clutch power is not enough, a redesign of the GearTray could be considered to include click fingers at the front of the driver, constraining it in multiple places.

Chapter 9.
Suggested Design Guidelines

Chapter 5 presented universal guidelines, which were not all relevant to the design of an outdoor luminaire.

Guidelines that proved to be useful throughout the redesign process of the Luma Gen2, or that have been used as background information, have been summarized in Table 21 below. Some of these guidelines have been slightly adjusted to be more relevant for the design process of outdoor luminaires.

These guidelines are not exhaustive or proven to be universally applicable. They can however serve as a starting point for the design of an outdoor luminaire with respect to repairability and recyclability.

Repairability Guidelines
Architecture
1. Design products such that the priority components are clustered in a sub-assembly.
2. Provide enough room to reach and remove the priority components.
3. Allow for top view disassembly.
4. Priority parts should be individually removable.
Fasteners
5. Limit the use of fasteners.
6. Allow priority parts to be removed without the use of tools.
Interface
7. Use electrical interfaces that support standardized components.
Recyclability Guidelines
Connections
1. Use click fingers, press fits or connectors to fasten priority components.
2. Limit the use of ferrous screws in a non ferrous material.
3. Limit the use of fasteners.
Material
4. Use plastics that have a density lower than 1.1.
5. Don’t use thermoset rubbers.
6. Design parts to be able to be produced with recycled materials.
7. Don’t use metal core PCB’s & potted drivers.

Table 21: Suggested design guidelines.

Chapter 10.
Reflection

This chapter reflects on the process and outcomes of this design research.

Research and analysis
At the start of the project, the repairability and recyclability of the design of the Luma Gen2 were unknown. Therefore, the Luma Gen2 was analyzed using multiple methods. The creation of a hotspot map was time consuming due to the timing of all individual steps, but was beneficial in combination with the disassembly and recyclability maps, as it showed which priority parts and connections in the design deserved extra attention. Apart from this, the hotspot map was not used further. A different use of the hotspot map in which the individual steps do not need to be timed, could already provide enough information regarding the priority parts.

The disassembly map gave a clear overview of the depth of the priority parts and, in combination with the guidelines, provided clear insights on how to improve the disassembly time. For example, it was shown that the L2 was positioned deep within the architecture and could benefit from “Surfacing”, a technique described in the guidelines as presented by Dangal et al. (2023). Comparisons of the disassembly maps of the original design and the redesign also showed clear improvements in depth of priority parts.

The Luma Gen2 was designed for easy repairability, but we learned that the real-life repair practices not always align with expectations, highlighting the importance of user testing throughout the design process. Unfortunately, we were able to speak to only 1 party that was involved in the installation and servicing process. While we got valuable insights, more sources of information could have resulted in different repair scenarios and therefore a different redesign.

The shredder experiment showed that the liberation scale as described by Versloot (2024), which showed the liberation behavior of different connections within a TV, did not match the findings from our experiment. It seemed that similar types of connections show different liberation across different product categories, and sometimes even within the same product. For example, a certain size screw used to fix the backplate of a TV to its stand will behave differently to a similar sized screw used to clamp down the glass panel of a luminaire. This is mostly due to the vast amounts of different screw types, materials that they connect, and used tightening force. Geometric design aspects, like local thickness, can also play a role. This very specific liberation behavior makes it difficult to develop a method that is applicable for multiple products. General liberation behavior can be estimated and will most likely be enough for a redesign that is more focused on recyclability, but to determine true liberation behavior of connections within a product, shredder experiments need to be done. The recyclability map could be made more accurate by investigating the connected materials instead of just the connection itself. This could give a more complete, potentially more accurate overview of the liberation behavior.

The method as described by Versloot (2024) used 2 categories for materials: recyclable and non-recyclable. During our field research we noticed that not all recycling facilities recycle the same materials, or even treat materials similar as such. Therefore, certain recycling facilities will recycle a certain material while other would consider it waste. This shows a difference between theoretical and practical recyclability of materials. To visualize this in the recyclability map, a third material category was added, showing materials that can be recycled but often are not.

Recyclability is a very broad definition that can be difficult to quantify. Some factors can be determined beforehand, such as the number of connections, type, and weight of used materials. Other factors can only be determined as a result of a shredder experiment, like the liberation, fraction purity, and material losses. These factors differ per product and depend highly on the product architecture. Shredding a product is most likely not possible for a designer, at least not during the design phase, making it hard to determine the true recyclability of a product.

Guidelines and requirements
Research into the repairability and recyclability guidelines showed that there was very little tension. Most guidelines with a positive impact on repairability also have a positive impact on recyclability. This is expected to be as most guidelines are aimed towards simplification of the design. Designing a luminaire with both improved repairability and improved recyclability was therefore a doable task. Not many design decisions had to be made that would negatively affect one or the other.

Certain requirements regarding the repairability and recyclability were difficult to quantify, as no exact numbers could be given or calculated. For the repairability, a disassembly time goal was estimated. However, this

was based on what seemed realistically achievable but would still be “as good as possible”. This requirement could only be assumed during the design process and tested afterwards when a functional prototype was developed. The same holds true for the recyclability requirement; having at least 70% liberation of components. This makes both requirements feel arbitrary to a certain extent. Furthermore, the repairability and recyclability of a product depends on multiple factors, but the used requirements focus only on two specific factors: the disassembly time and liberation. This makes sense, as these factors are directly influenced by the design. However, it is therefore difficult to make definitive claims about how much the repairability and recyclability of the redesign has been improved.

Process
While presented in the report a linear process, both the analysis and design phase are iterative. The context surrounding the reparability and recyclability practices turned out to be a complex problem, including different scenarios, practices, and outcomes. This resulted in sources not always being in line with each other and required multiple talks with the same stakeholders to get a good understanding of what was actually happening.

The design process also showed to be not linear. For example, different methods were used to combine ideas from the brainstorm. The initial methods used a ranking of ideas in the morphological chart. This however did not give an inspiring outcome but resulted in a design which felt uncreative and boring. Therefore, we stepped back, looked at the process as a whole, and adjusted the method accordingly, resulting in a more inspiring concept. **Combining the best ideas does not necessarily result in the best combination of ideas.**

This is most likely the result of using “universal” design methods. In reality, the methods are not universal and need to be adjusted to the context and the specific design project. This was done several times throughout the design process. An example of iteratively adjusting methods is the second brainstorm, as we realized that more time and detail was needed to reach concrete ideas for the concepts. The first brainstorm did not have this outcome, resulting in more abstract directions than actual ideas. Another example is the use of the morphological chart and ranking of ideas as mentioned above, which took several tries of adjusting the weights of the Pugh ranking before realizing that the Pugh ranking itself was the issue.

Knowing beforehand which exact methods are needed and how they should be applied is impossible. Most of the time, the actual outcome of a used method was the only good indicator to determine whether the method was useful.

Overall outcome
As mentioned before, the design requirements can be hard to quantify and are therefore potentially more useful as design goals rather than as hard requirements. The requirements, wishes, and guidelines gave clear direction, guidance, and boundary conditions that resulted in a final design that complied with the requirements. However, I am inclined to think that applying the knowledge gained from the experience of researching and analyzing the repairability and recyclability of the Luma Gen2 had a great influence on the outcome. The guidelines can be useful, and will most likely result in better product designs, but the hands-on experience, interviews and shredder experiment itself also gave valuable insights to use throughout the design process.

Designing for repairability and recyclability
As mentioned at the beginning of this report, designing with repairability and recyclability in mind is important for the circularity of the product and contributes to the ideology of a circular economy. It is therefore the job of a designer to implement these aspects into their design. In my personal experience, it also enriched the design phase and how you treat certain design challenges. The use of the guidelines throughout the design process would often point towards simplified solutions that would require less parts, material, or connections. This results in design that is not over engineered, but minimalistic. It also added another challenge and a clear goal for the design itself, which helped in an inspiring way when having to make decisions.

Finally, it was good to see that the redesign actually showed a decrease in disassembly time and increase in recyclability. This means that implementing repairability and recyclability at an early stage of the design process can result in a better design and will therefore contribute to a circular economy.

Chapter 11.
Recommendations

This chapter highlights possible next steps in the design or future research of this project.

Design
Certain design recommendations and limitations have already been mentioned in Sections 8.3. and 8.6. The most important ones are summarized here.

The design of the glass seal and the pressure it requires to seal properly, are unknown. Estimations have been made, but the exact force and design should be determined for future development.

More simulations regarding the stress of the reflector should be done to account for an increase in ambient temperature, which would decrease the allowed maximum stress.

The air gap between the L2 and the lid has been estimated. Future steps should include a simulation of the full L2 assembly to see whether the L2 deflects and how that affects the air gap.

The current design of the body is not ready for mass production, as the design cannot be released from a two-sided mold. Not all features are drafted and there are some overhanging edges. Future embodiment could focus on producibility of the design.

No research was found on the use of breakline/scoring in aluminum parts. Therefore, more research or testing should be done to determine a safe and useful product.

The features as presented in the design in Chapter 8 are designed for a Luma Gen2 Nano, which is the smallest available luminaire in the Luma family. It is unknown whether the designed features are possible in the bigger luminaires, as these luminaires can contain multiple drivers and L2 panels. Research should be done to see whether the features are applicable across the whole range of luminaire sizes.

In the new design, the L2 connectors have become redundant as all components are easily accessible from the top. Removing the L2 connectors and using direct wiring would result in less possible failure points and lower cost. This could be done in a future iteration.

The new design uses the original driver connectors turned sideways. These connectors have too much clutch power for the new application, resulting in bending the handle of the GearTray when trying to be removed. This high clutch power is not needed anymore as the GearTray is constrained by the lid and cannot move when closed. Therefore, connectors that are easier to disconnect are recommended.

Material
The recyclability of the Luma Gen2 could be further improved by changing the materials. As the density of the PC, PMMA, and silicon rubber is higher than 1.1, their recyclability is limited. Research into the use of better recyclable materials would be a logical step in future development.

Furthermore, it is recommended to find an alternative to the use of metal core PCB's. Currently, the entire L2 ends up in the aluminum fraction due to the printing on an aluminum core. This is undesirable, as it pollutes the aluminum and valuable materials like copper are lost.

The same can be said for the potting in the driver, making part of driver non-recyclable. The potting encapsulates the electrical components, which usually contain copper or other valuable materials. As a result, these materials are difficult to liberate in the shredder. Development of a driver that does not require potting, would result in better recovery of these materials and potentially allow for the repair of individual driver components.

Contextual
While certain components within the Luma are standardized, many different types of drivers and L2's exist. If more standardized components would be used across multiple luminaire families, production, stock, and repairs would become easier.

The redesign introduced the adapter to change the electrical interface of the driver connection. This can however be better achieved if a different interface would be implemented into the driver itself, rather than an add-on component. Changing the interface of the priority components was out of scope for this research, bit it is worth considering for a future design.

A big part of circularity is the logistical network at the end-of-life of

products. For example, the circularity of a product can be significantly improved when a product does not end up at a recycling plant but is collected and reused/refurbished, extending the lifetime without the losses of recycling. Therefore, is recommended for Signify to research the possibilities of a logistical network for the collection of broken luminaires to take ownership and control of the end-of-life of their products.

The recyclability guidelines as presented in Chapter 5 can help during the design phase but are more focused on material usage and not so much on the design itself. Guidelines that include specific product architecture and how that influences the recyclability of a product would have been more useful. It is therefore recommended to do more research into guidelines based on the shredder experiment and product architecture.

Chapter 12.
Conclusion

This design research was conducted to determine which design requirements are important for the redesign of an outdoor luminaire with regards to repairability and recyclability. Analysis of a current luminaire, interviews, and field research have been conducted, which resulted in the list of requirements as presented in Chapter 6.

Furthermore, this design researched focused on whether a redesign of an outdoor luminaire, using the defined requirements and guidelines, could result in a luminaire with improved repairability and recyclability. For this, a redesign of the Luma Gen2 was made.

With respect to the repairability, the time to replace the driver and L2 was reduced from x seconds to y seconds. The disassembly required less tools and increased the accessibility of both priority components when compared to the original design, further improving repairability and making on the pole repairs more attractive.

The redesign also showed improvements in terms of recyclability. The amount of screw connections has been reduced from x to y and the Starlock washers are no longer needed. Moreover, the suggested breaklines could result in better liberation of the bigger screws. It is therefore expected that the redesign will show an overall improved liberation, less fraction pollution and more material recovery compared to the original design.

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