Design for Recyclability of WEEE

A case study on Signify's Coreline office luminaire

Graduation project by Marjolein Laan

Supervisors: Conny Bakker and Dorien van Dolderen
Company mentor: Bianca van der Zande

Preface

This report documents my graduation project of the Master Integrated Product Design at the faculty of Industrial Design Engineering of the TU Delft.

At the very start of my graduation journey, there were two things I knew for certain: I wanted to design a physical product and I wanted to design in line with the principles for a circular economy. The topic of my project has allowed me to do both things, and has provided me with the opportunity to learn a lot about electronics, luminaires, and the recycling industry.

Over the course of the project, Signify has been acting as a client. Collaborating with the people there - and spending three days per week at their office - has been a valuable experience for me in understanding the workings of large companies.

Ultimately, having completed this project I feel that I have learnt a lot about design for recycling, gained more experience and enthusiasm for prototyping, and now have a clearer vision of what I want the next steps in my design journey to be like.

Acknowledgements

Many people have guided and supported me throughout this project, and to those people I would like to express my gratitude.

Firstly, I want to thank my supervisors at the faculty. Thank you, Conny, for guiding me in implementing the right design tool at the right time, for all your enthusiastic and encouraging responses at all our progress meetings, and for somehow managing to always answer my e-mails within a few hours.
Dorien, thank you for your proactive attitude in planning visits to stakeholders which are at the heart of the recycling industry. Being able to start experiments already in the first week after my kick-off really gave a boost to my project. Your positive and kind personality have helped me to feel comfortable in asking for your help along the way.
Thank you, Ruud, for being my spontaneous third supervisor and jumping in when necessary. Having you to rely on when technical matters of recycling and materials became daunting has made me feel very supported.

My gratitude goes out also to the team at Signify. Thank you all for creating a warm and “gezellige“ atmosphere and making me feel part of the team.
Special thanks to Victoria, Simon, Marc and Peter for helping me explore solutions during the redesign stage. Marc, I really appreciate you helping out with the thermal aspects of the redesign, and being so approachable in the labs so that I felt comfortable to ask for help. And Peter, thank you for sharing your knowledge and experiences on manufacturing, for joining me to the thermoformer all those times and showing me relevant prior projects with an inspiring amount of enthousiasm.
Finally, Bianca, it has been great having you as my company mentor. Thank you for putting so much energy in connecting me to the right people, going “shopping“ for me for knowledge and components, for helping me keep focus on the essence of the project, for flipping my cup from half empty to half full and for all the chats and laughs. It has made my first experiences in the “working world“ all the better.

Table of Content

1. Introduction

This graduation project is concerned with (Waste of) Electrical and Electronic Equipment (WEEE or EEE). Due to electronification of people's work and private lives, global amounts of EEE and WEEE are growing fast (Global E-waste Monitor 2024, p. 26).

A circular approach to EEE is important for multiple reasons. For one, this product category contains scarce and valuable materials (Okwu & Onyeje, 2014). Also, primary production of materials for EEE comes with negative environmental and health impacts, such as air and water pollution, damage to land, loss of biodiversity, respiratory diseases and child labour (Global E-waste Monitor 2024, p. 50).

A series of strategies exist for more circular handling of products. They are summarized in the R-ladder (see Figure 1). Within this project, focus will be on the strategy of recycling. This strategy is low on the ladder, but nevertheless crucial because virtually all products will eventually reach end-of-life and - for a circular economy - their constituent materials must then be recovered.

Currently, recovery of materials from recycled WEEE is suboptimal (Global E-waste Monitor 2024, p.44), (Parajuly et al., 2016). Valuable materials are thus lost in incineration or landfill. In order to address this issue, and create a truly circular economy, we need design practices that allow for proper recycling of products. The aim of this graduation project is to contribute to such design practices.

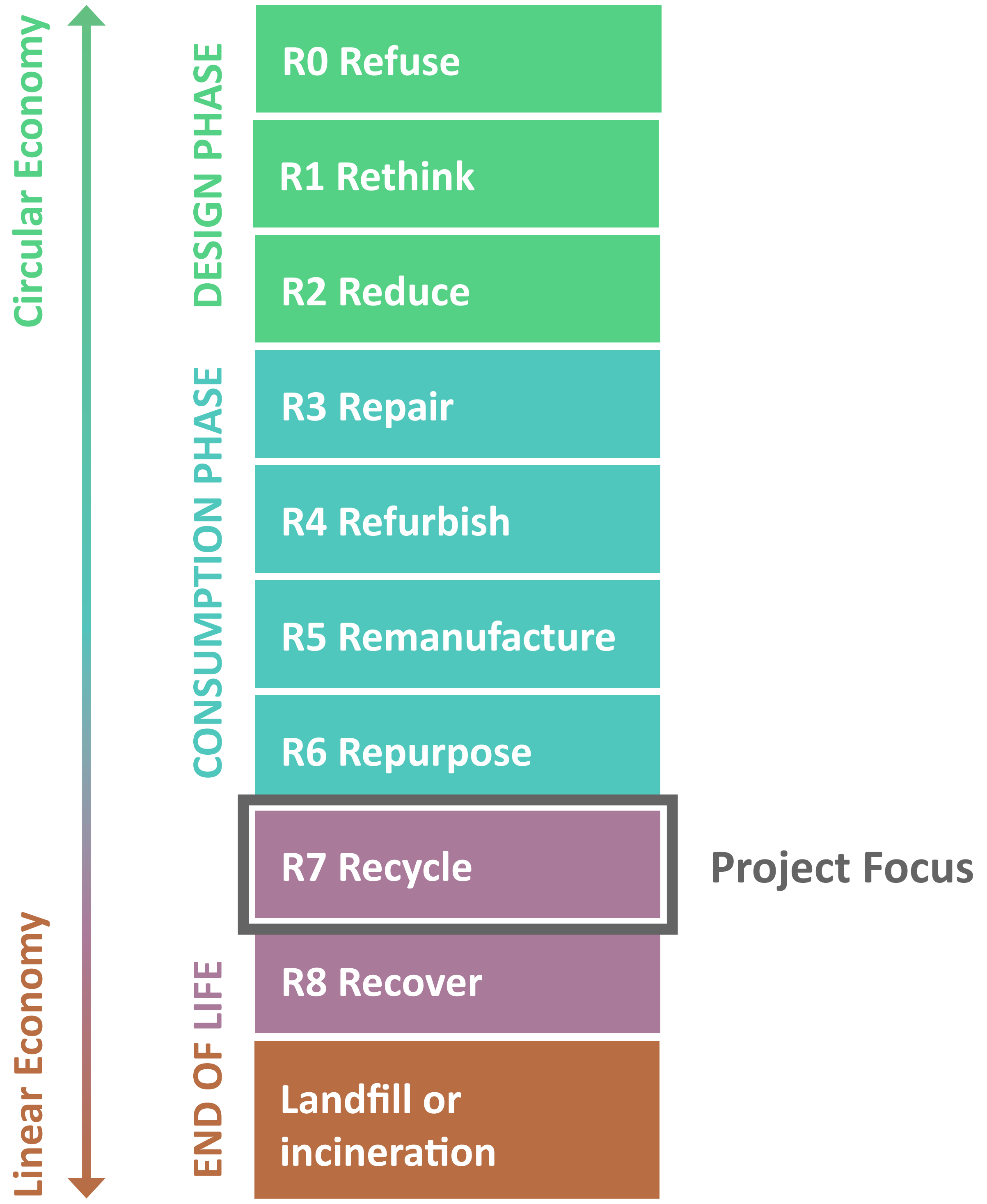


Figure 1. Circular strategies for limiting resource use and environmental impact of products. Adapted from (Malooly et al., 2023).

1.1 Circular Circuits

The current project is affiliated with the NWO research programme Circular Circuits: design of next generation electronics for a circular economy. Within this project, researchers investigate lifespan extension, reuse, repair and recycling of EEE (NWO, n.d.).

Part of this research programme is a Ph.D. research at the TU Delft IDE faculty concerning Design for Recycling of Electronics, which is meant to produce practical guidelines for designers to improve the recyclability of electronic products. This graduation project will serve as a case study to gain insight into the process of applying existing guidelines which focus on recyclability of electronic products.

One of the Circular Circuits partners is Signify, a lighting company with headquarters in Eindhoven. Signify has provided the specific design case for this graduation project.

Figure 2. Parties involved with this graduation project.

1.2 Signify

Signify is a market leader in lighting products. The company is active in more than 70 countries, made EUR 7.5 billion in revenue in 2022 and has 35,000 employees worldwide (Signify, n.d.,-a). Regarding circularity, Signify aims to double their revenue from circular sales to 32% by 2025 (Signify, n.d.-b).

1.3 Problem Definition

This project will focus on the recyclability of one of the products sold by Signify: the CoreLine Panel. This is a luminaire suited for grid ceilings in office contexts within the European market. The CoreLine is a high runner, meaning it gets sold in high volumes. For comparison, two similar yet slightly different products will also be analysed, namely the Ledinaire (also by Signify) and an office luminaire by competitor Ledvance (see Figure 3).
Table 1 includes some specifications for each luminaire type.

The recyclability of these luminaires is currently unknown. During development, optimal recyclability at end of life was not an explicit goal for Signify.
The CoreLine was selected as the subject for this study, because Signify currently views recycling as the most promising circular strategy for the product. This has two reasons. Firstly, it is a relatively cheap product in comparison to the rest of their portfolio. Secondly, it gets sold via distributers, so Signify has no direct line to end users. As a result, it would be difficult to implement circular strategies higher up on the R-Ladder while remaining profitable.

Figure 3. The CoreLine, Ledinaire and Ledvance office panels.

Table 1. Specifications per luminaire.

Luminaire type	Identification codes	Price (as on lampdirect.nl)	Luminous efficacy [lm/W]	Luminous flux [lm]	Color temperature [K]
CoreLine	EAN: 8719514950375 12NC: 911401844384	€99.24	125	3,100	4000
Ledinaire	EAN: 8718699791810 12NC: 911401885080	€37.95	100	3,400	4000
Ledvance	EAN: 4058075440234	€33.78	120	3,600	3000

1.4 Goal

This project has two main goals. The first goal is to redesign the CoreLine towards 100% recyclability within the current recycling industry, which involves shredding. To this end, a number of luminaires have been shredded at a WEEE recycler, and the shredding outputs have been evaluated on their suitability for recycling.

Desk research was conducted to gain additional insights into the current recyclability. This included an exploration of the current and future recycling industry, life cycle assessment (LCA) of the current CoreLine and existing Design for Recycling guidelines.

The issues for recyclability as identified through these activities have served as the basis for a redesign stage, resulting in a physical demonstrator. Additionally, a set of practical design guidelines was developed, with the intention to aid designers in designing recyclable luminaires.

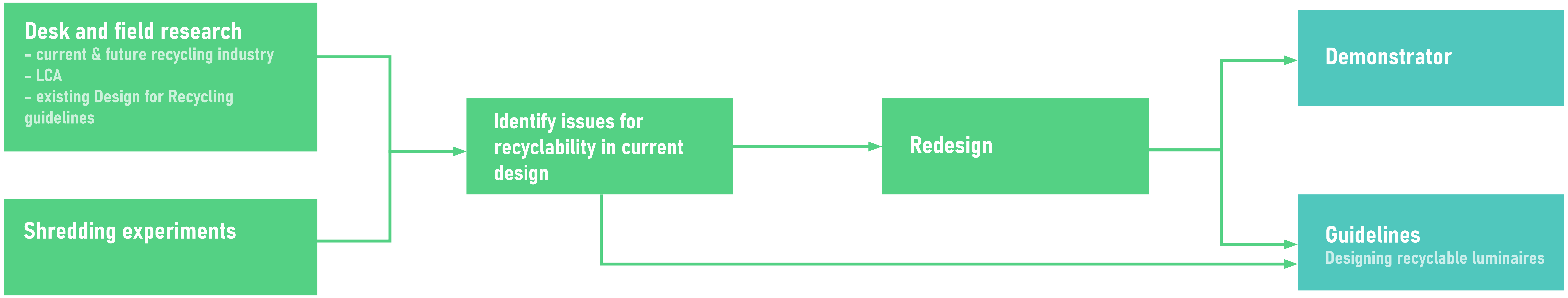


Figure 4. General approach and desired outputs of this graduation project.

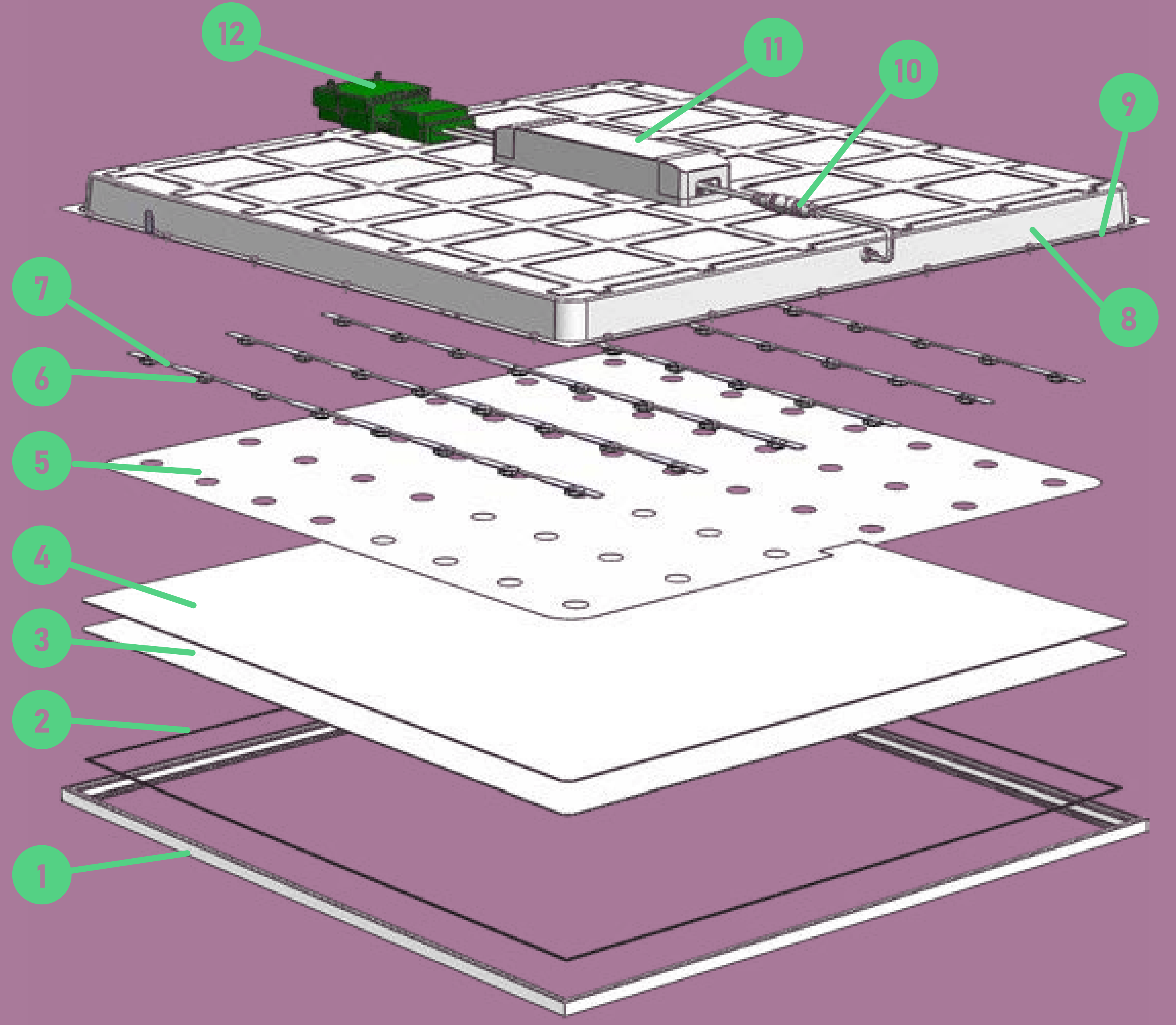


Figure 5. Exploded view of the CoreLine panel with components labeled. The numbers correspond to those in Table 2.

2. Background

This chapter first gives some further information on the CoreLine luminaire, namely on its product architecture and environmental impacts. Then, the current state of the WEEE recycling process is described, followed by an exploration of future recycling scenarios. Finally, existing guidelines concerning design for recycling are discussed.

Table 2. BoM of the CoreLine luminaire.

Nr.	Name	QTY	Material	Mass [g]
Panel				1532
1	Frame	1	Aluminum	209
2	Seal	1	Rubber	10
3	Beam shaping	1	PS	337
4	Diffuser	1	PS	
5	Reflector	1	PET	53
6	Lens	48	PMMA	34
7	L2 (light source)	6	Aluminum-based PCB + 8 LEDs	40
8	Backplate	1	Steel	835
9	Screw	24	Steel	14
Power supply				191
10	Cable	1	Copper and plastic	29
11	Driver	1	PC housing	69
			PCB	93
12	Connector	1	PA housing	72
			Electrical parts	19

2.1 Product Architecture

To investigate the product architecture, Signify shared information on component names and materials, as well as CAD files of the CoreLine. Additionally, the product was disassembled in order to identify the connections within the product, and to verify the components' weights.

Figure 5 shows an exploded view of the CoreLine luminaire. The component names and materials are listed in the Bill of Materials (see Table 2).

The product consists of two main assemblies: the panel and the power supply. The panel contains the LEDs, housing and components to optimize optical performance of the luminaire. The power supply ensures that the panel receives electricity in optimal form. The next two sections elaborate on the architecture of the panel and power supply.

2.1.1 The panel

In Figure 6, a section view is shown to highlight the different connections within the CoreLine panel. Most connections are made using glue. The frame and backplate, being heavier components, are connected via 24 steel screws. The exit windows (i.e. the beam shaping and diffuser) are not connected by means of any fastener, but is fixed into place in between the backplate and frame.

The panels of the luminaires that will be compared to the CoreLine are similar, except they lack the following components and corresponding connections:

- The Ledinaire does not contain a reflector.
- The Ledinaire and Ledvance do not contain a seal.
- The Ledinaire and Ledvance do not have a beam shaping.

As shown, the panel contains the L2s, which consist of PCB and LEDs (see Figure 7). These are especially important to recycle because they contain precious metals - gold and silver - as well as critical raw materials as defined by the European Union - gallium and copper.

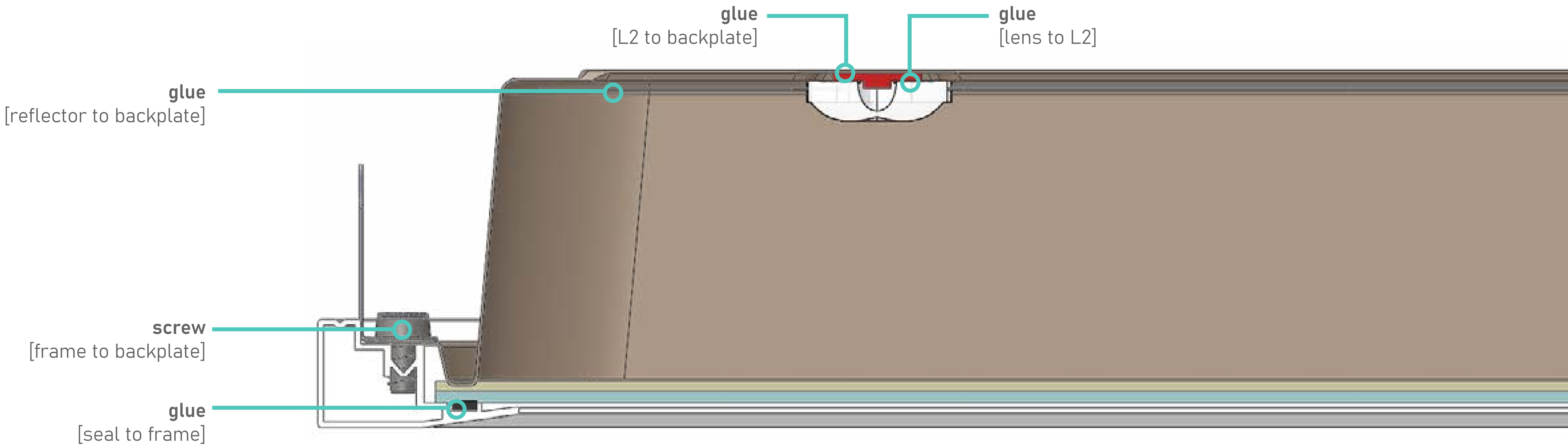


Figure 6. Section view of the CoreLine panel with connections labeled. Components have been coloured for easier distinction.

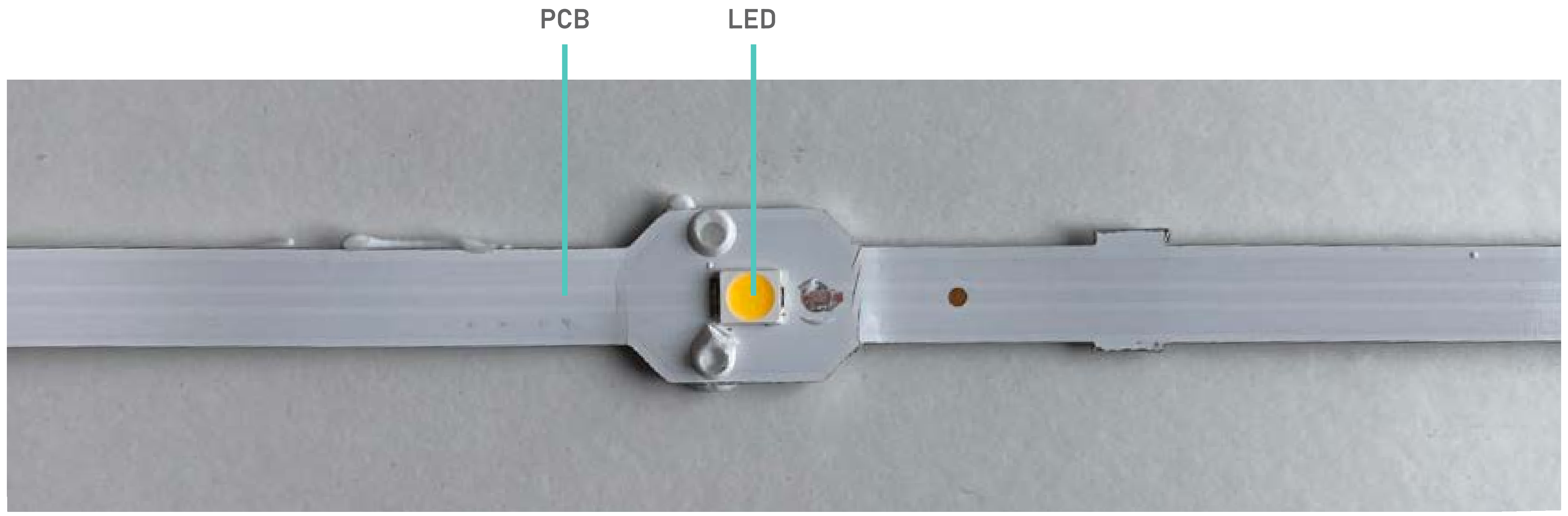


Figure 7. Zoomed in photo of a CoreLine L2. Each L2 contains 8 LEDs.

2.1.2 The power supply

Additional connections are present in the driver and connector. Figure 8 highlights these connections. It also shows the driver PCB, which is secured into the housing by the back panel with snap fits. Furthermore, a double-sided sticker is applied to the driver back panel, to allow installers to secure the driver to the luminaire after installation (see Figure 9). Lastly, several metal components (serving electrical functions) are integrated into the plastic components of the connector (see Figure 10).

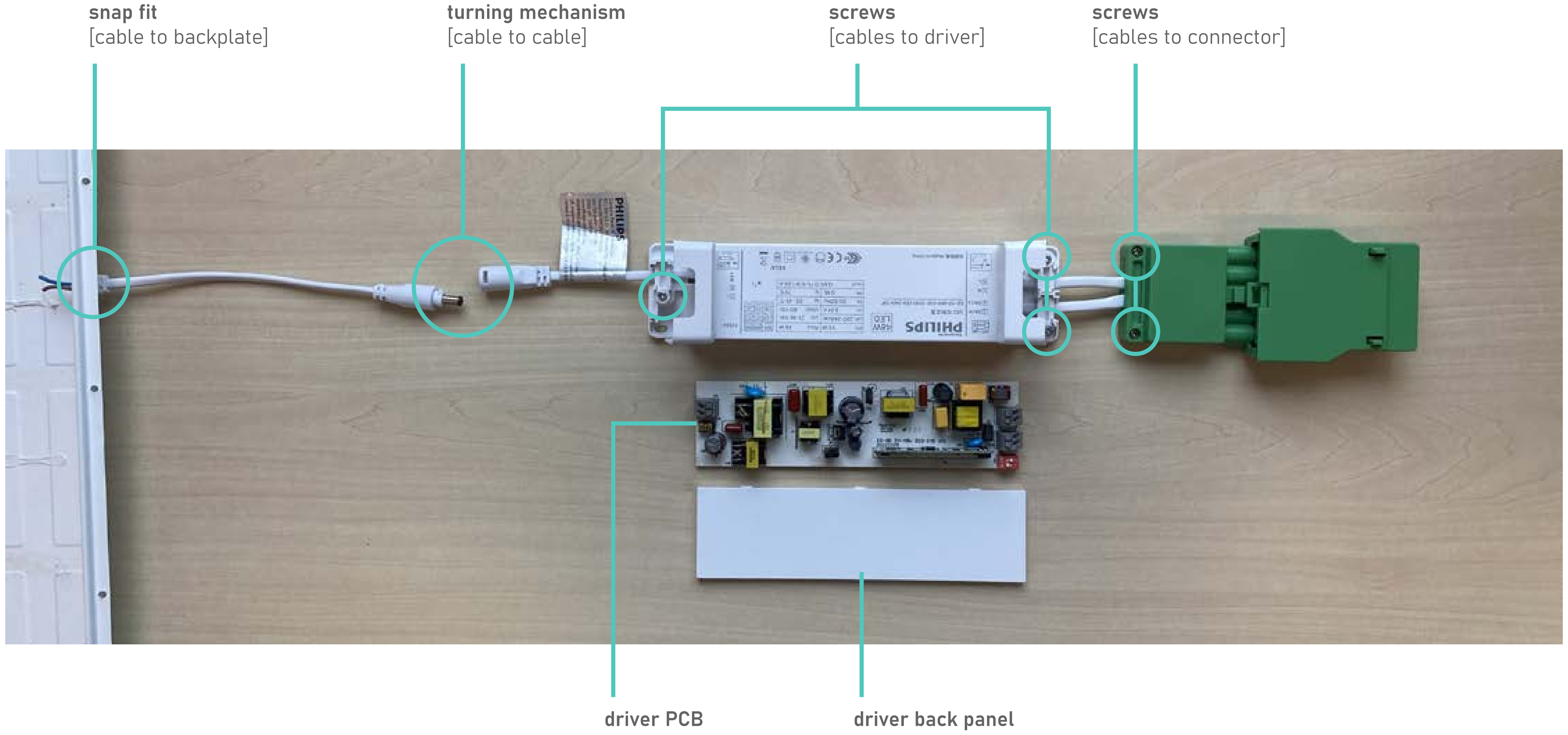


Figure 8. Connections in the CoreLine driver and connector.

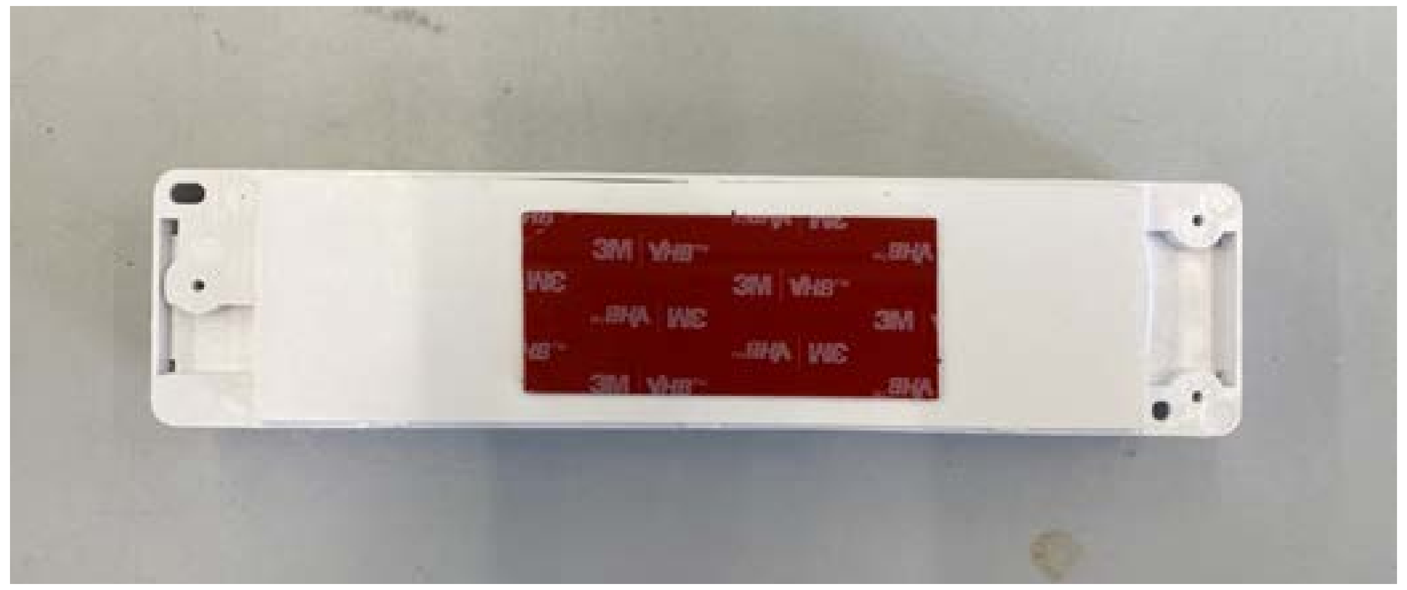


Figure 9. Double-sided sticker to secure driver to luminaire panel after installation.

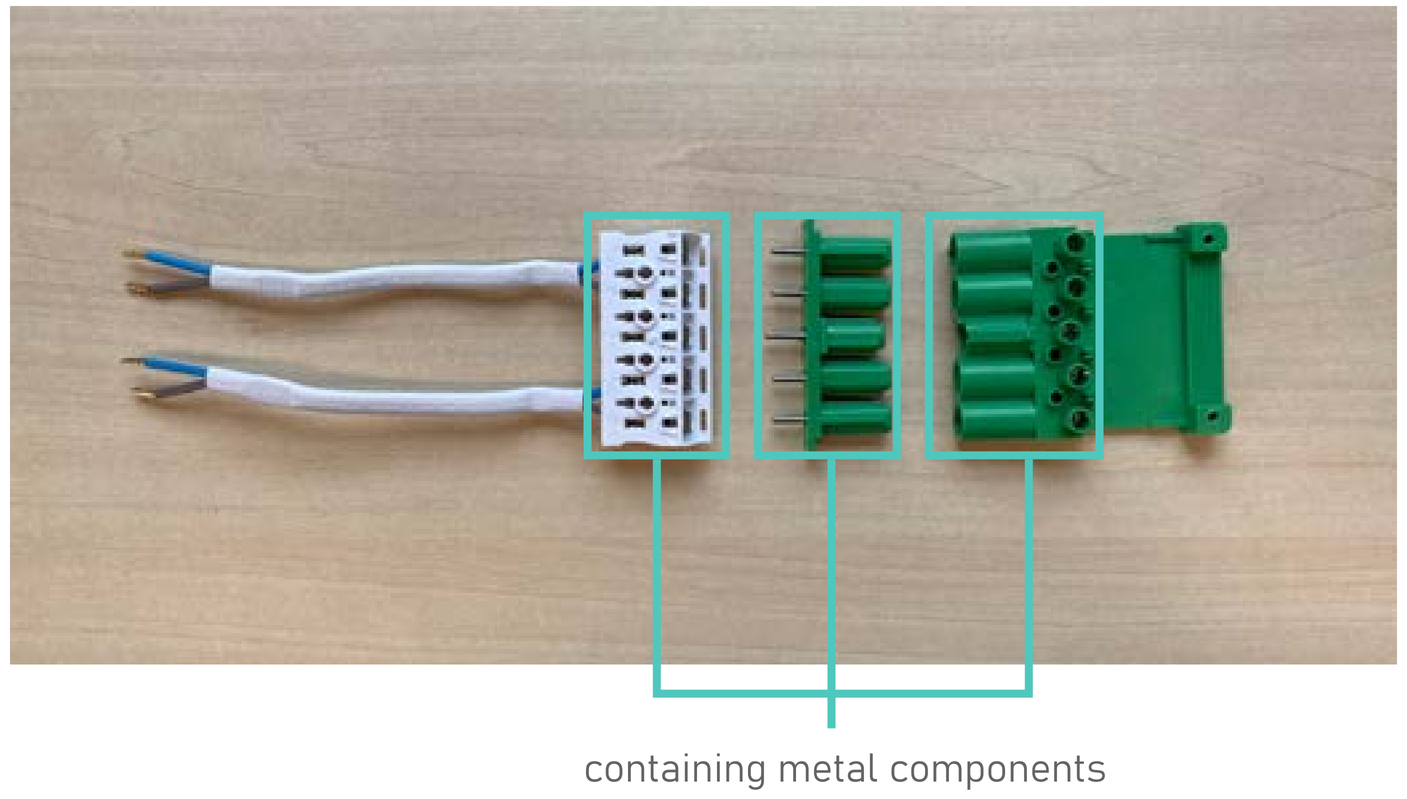


Figure 10. Metal components integrated in plastic components (in connector).

2.2 Life Cycle Assessment

Shredding experiments will help to identify any problems of the current design with respect to recyclability. Once identified, it is important to estimate the environmental impacts of these problems, so that they can be prioritized for the redesign stage. For this purpose, Life Cycle Assessment (LCA) data will be used. Figures 12 and 13 show these data for the CoreLine. The next paragraphs explain the origins of the data.

Signify has shared LCA data for the Ledinaire for all stages of its life cycle. Since the CoreLine is very similair to the Ledinaire, with only slight changes in component weights, LCA data for the CoreLine was derived from the Ledinaire LCA, according to the following formula (see Appendix A for detailed computations):
weight_coreline / weight_ledinaire * impact_ledinaire

Since recycling of materials will only reduce impacts associated with the Raw materials supply stage, only the data of this stage was considered.

Furthermore, the LCA data includes information on many impact categories, but the decision was made to use only the data on Global Warming Potential (GWP) and Abiotic Depletion Potential of Elements (ADPE). An analysis made by a Signify researcher of a series of LCAs of different luminaires, revealed that GWP correlated strongly with all other categories, except for ADPE. I assume that this holds also for the Ledinaire and CoreLine luminaires and disregard the other categories for the sake of clarity.

Some components were not included in the original LCA: the reflector (because the Ledinaire does not have one), the lenses, driver housing and connector housing. For these components, data from the Idemat2023 dataset was used (Vogtlander, n.d.). However, the Idemat2023 dataset does not contain an ADPE category in the same unit as the LCA provided by Signify. Therefore, only the GWP data is included for these components.

From Figure 13, it is clear that the GWP of the CoreLine is caused mainly by its heaviest components (the frame, backplate and diffuser) and electronic components (the L2s and driver electronics). The ADPE impacts can be contributed mainly to the electronics, as can be seen in Figure 14.

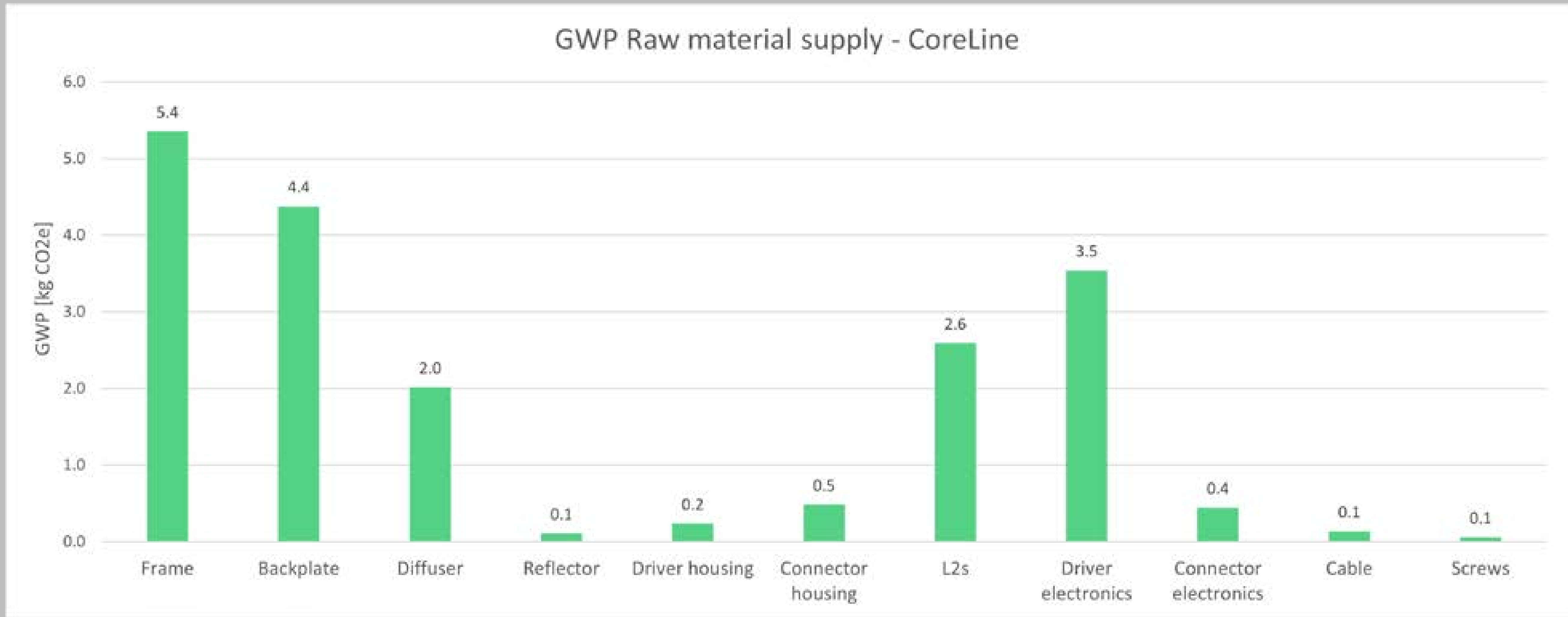


Figure 11. GWP resulting from the Raw Material Supply for the CoreLine, broken down per product component.

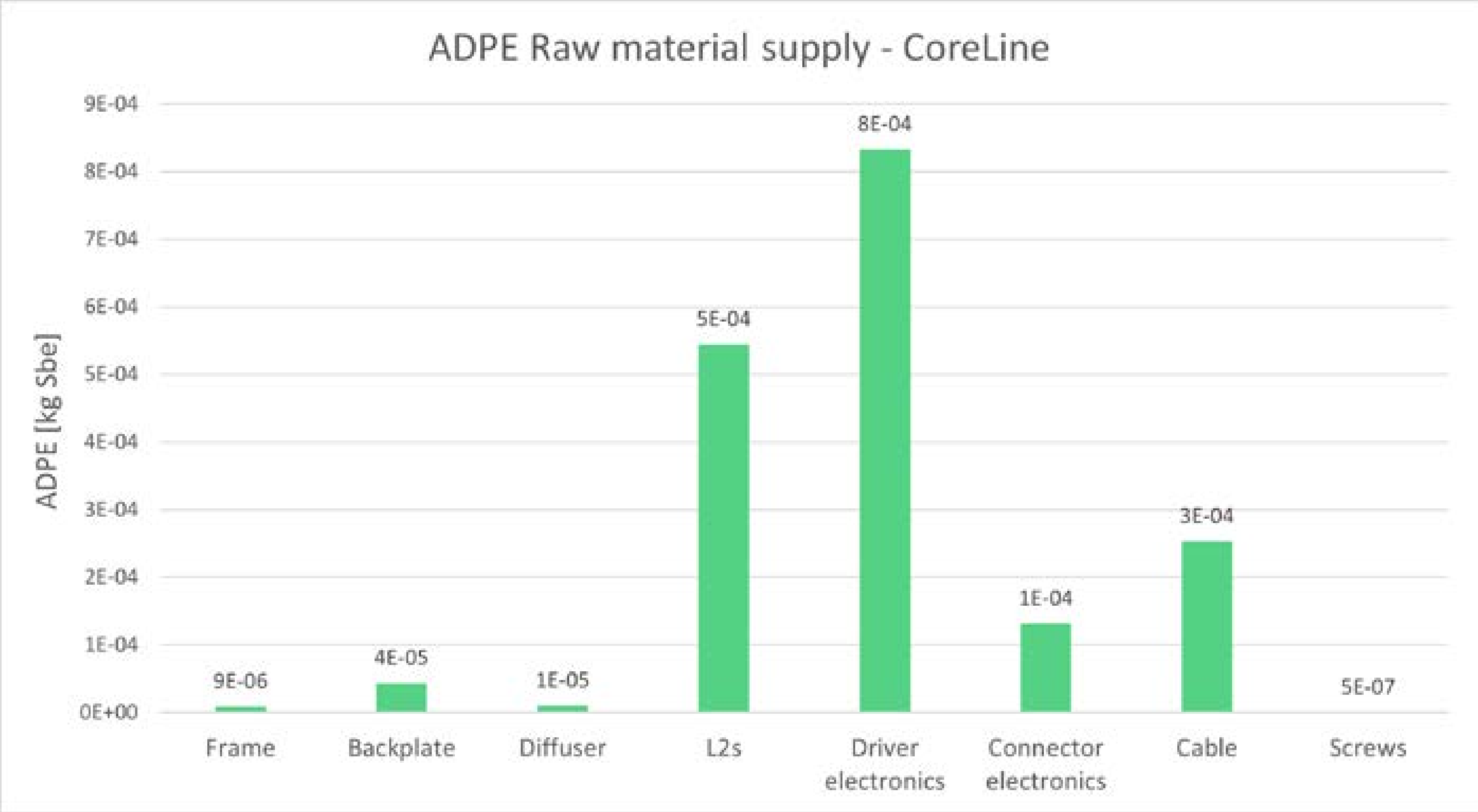


Figure 12. ADPE resulting from the Raw Material Supply for the CoreLine, broken down per product component.

2.3 WEEE Recycling Process

In the current WEEE recycling process, a discarded product goes through a number of steps within the recycling process. Figure 14 visualizes the high-level steps of recycling: collection, liberation, concentration and reprocessing.

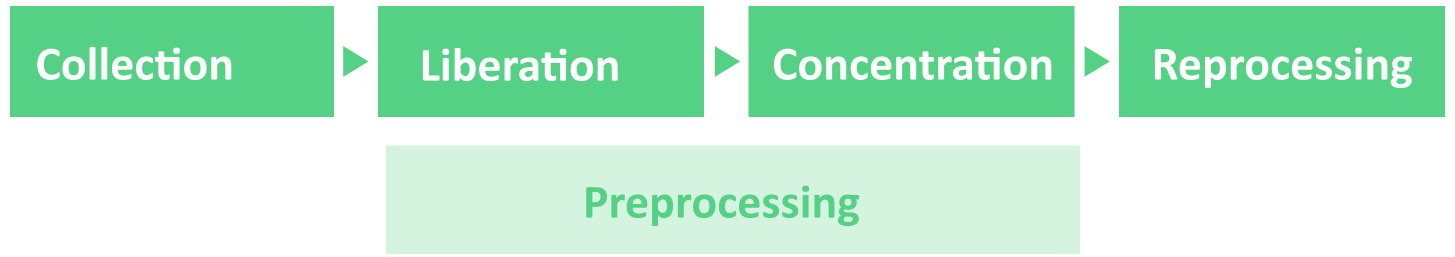


Figure 14. Steps in the recycling process (Faludi et al., n.d.). Liberation and concentration can together be referred to as preprocessing (Chancerel et al., 2009).

Collection

In the collection step, products are transported from their context of use to a recycling facility. Collection is supported by stores, municipalities and companies, who also cluster WEEE into six different categories to ease subsequent preprocessing (PolyCE, 2021). The CoreLine luminaire, having external dimensions of more than 50 cm, belongs to the category named *large equipment* (European WEEE Registers Network (EWRN), 2018). This means it enters the same recycling stream as washing machines, printing machines, electric stoves, etc.

Liberation

During liberation, connected materials are released from each other as much as possible. As a first step, some high-value or hazardous components are removed manually. For WEEE, this includes cables, batteries and Printed Circuit Boards (PCBs). Afterwards, products are typically shredded or crushed in machines (see Figure 15) (Faludi et al., n.d.). The machines break down the products under really high forces, resulting in product fragments of a few centimeters.

Concentration

The aim of concentration or separation is to obtain output fractions of high concentrations of one material, e.g. an aluminum fraction. A cascade of sorting steps, which exploit differences in material properties, enable the separation of different materials. Through interviews conducted by Dorien van Dolderen with a WEEE preprocessor, a general sequence of liberation and concentration steps was identified (see Figure 16 on the next page). Although most recyclers use comparable methods, details in their approach may vary and are typically company secret.

Figure 16 also indicates where fragments of the CoreLine components would go, when properly liberated. Fragments of electronic components (including the L2s) should go to the copper fraction. From there, the copper and other scarce and valuable metals (e.g. gold, silver) can be recovered.

Reprocessing

Finally, the separated materials are reprocessed into recycled materials, to be used for production of new goods.

Figure 15. Shredding of a product. Image taken from (Weima, n.d.)

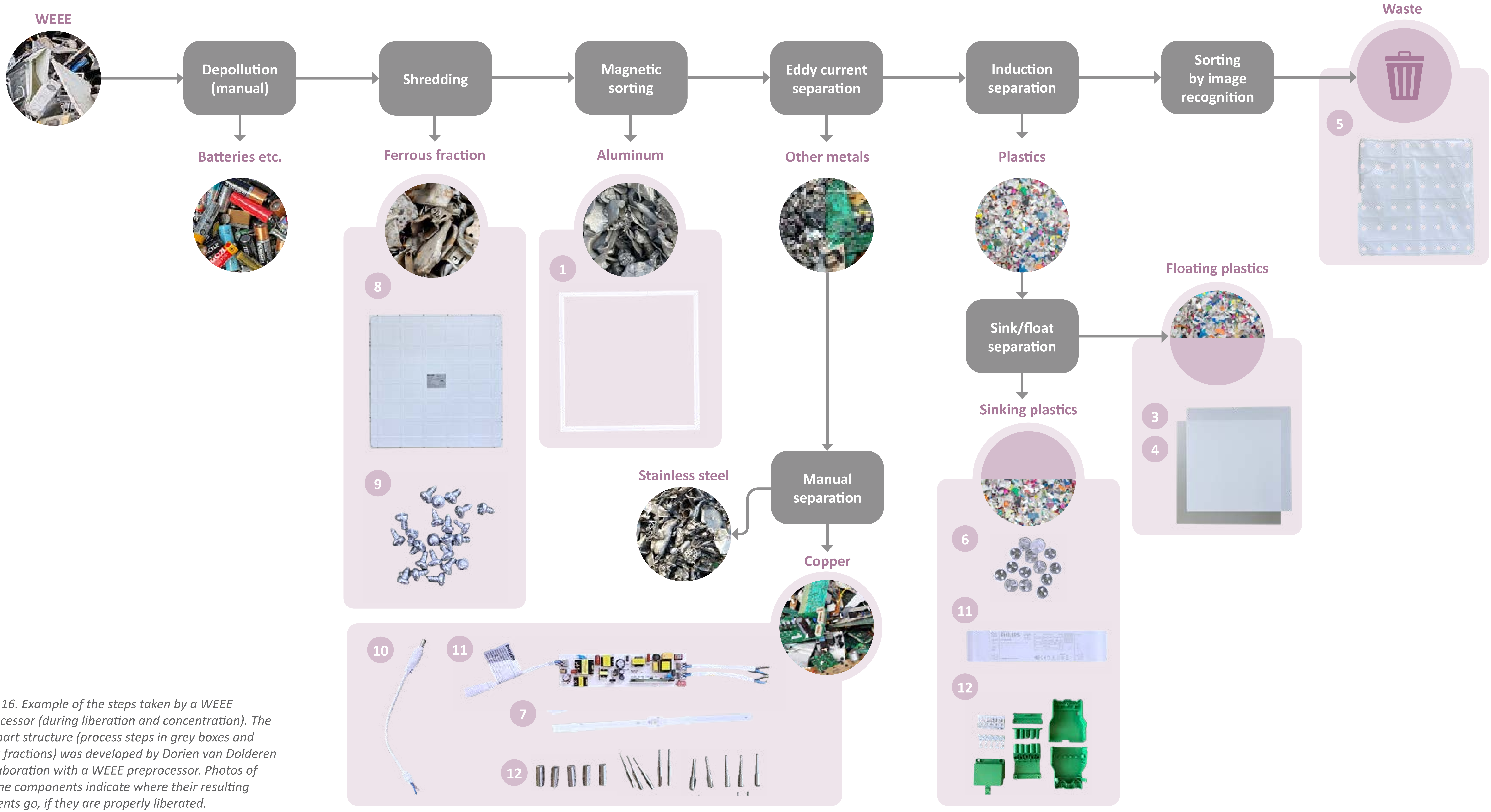


Figure 16. Example of the steps taken by a WEEE preprocessor (during liberation and concentration). The flow chart structure (process steps in grey boxes and output fractions) was developed by Dorien van Dolderen in collaboration with a WEEE preprocessor. Photos of CoreLine components indicate where their resulting fragments go, if they are properly liberated.

2.2.2 Liberation: future scenarios

At present, mechanical bulk process such as shredding or crushing are the standard approach for liberation of WEEE (Faludi et al., n.d.). A big issue resulting from shredding is that critical raw materials (CRMs) often get reduced to a very small size and are subsequently scattered into unsuitable output fractions, where they eventually get lost (Chancerel et al., 2009; Charles et al., 2020).

To increase recovery of CRMs, new liberation technologies for WEEE are being explored (Charles et al., 2020). By the time the redesigned luminaires are developed, marketed, sold and discarded, 20 years will have passed. It is therefore relevant to consider how WEEE might be liberated at that time.

Two promising innovations in liberation of WEEE are pulsed power and robotics.
In pulsed power approaches, intense shock waves are propagated in a fluid medium, which causes breakage at the interfaces of different materials (ImpulsTec, n.d.-b). Applications of such technologies are mostly in separation of composite materials (Bluhm et al., 2000) (Pestalozzi et al., 2018). However, it has also been demonstrated for disassembly of mobile phones and PCBs (ImpulsTec, n.d.-a). See Figure 17. According to ImpulsTec, their technology “allows electronic equipment to be almost perfectly separated into their main components, such as frame parts, printed circuit boards, and other plastic or metal pieces.”

Figure 17. Mobile phone disassembled through pulsed power (ImpulsTec, n.d.-a).

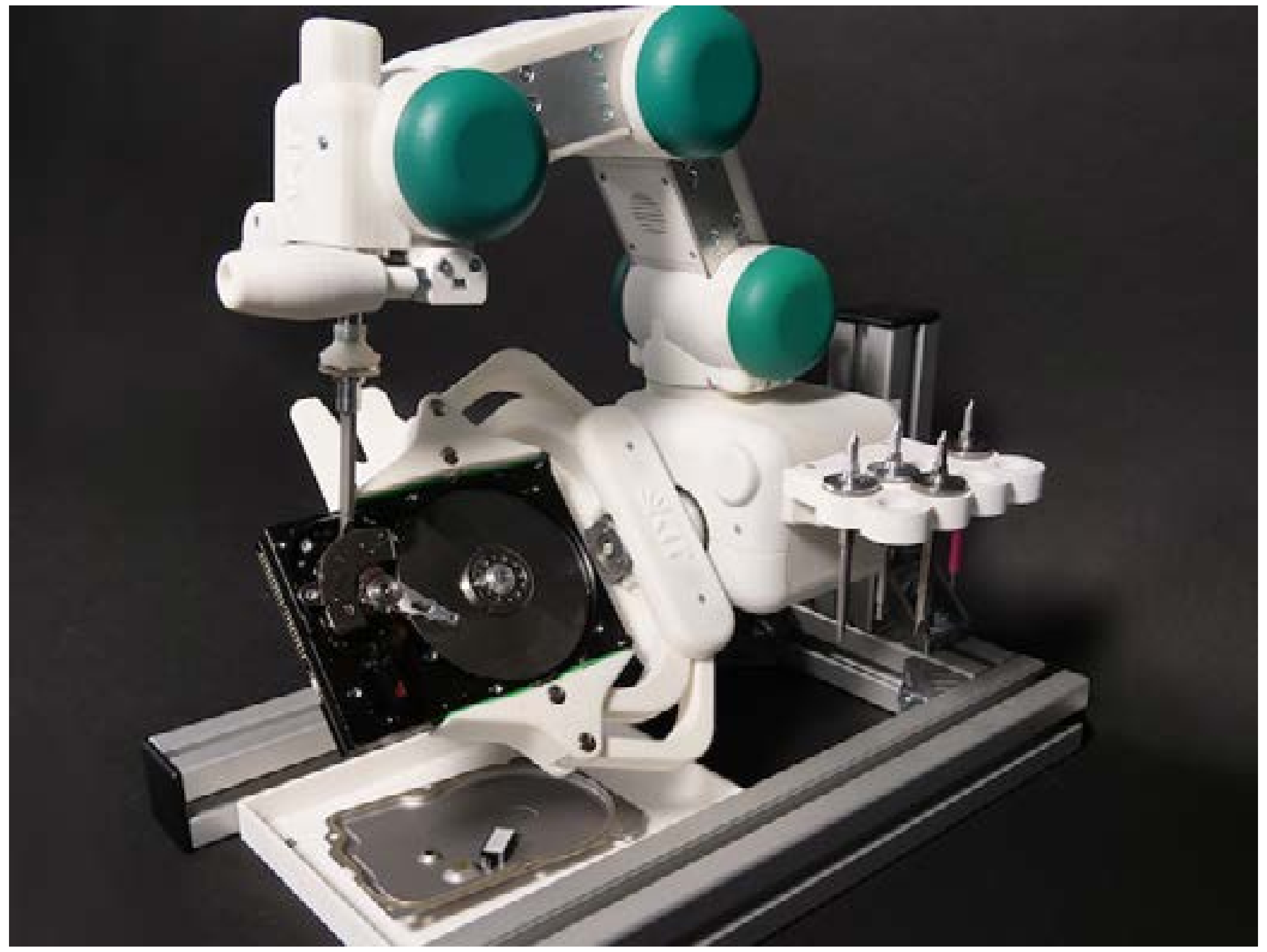


Figure 18. IMAGINE robot dismantling a hard disk drive. © Gripper_Karlsruhe Institute of Technology IAR-H2T.

Robotic disassembly is another method of material liberation which can prevent CRM dissipation. In an EU funded project named IMAGINE (IMAGINE, n.d.), an intelligent robotic system was developed which is capable of disassembling electronic devices on which it has no prior information (see Figure 18). An interview with one of the researchers from the IMAGINE project has shed light on suitability of different connections for robotic dismantling. Unscrewing and cutting cables are especially easy for robots. Snap fits can also be suitable, as long as a clear gap is provided for the robot to insert a levering tool.

The question remains whether it will be economical to use these new technologies in WEEE recycling, and more specifically in the recycling of luminaires. Although the described projects demonstrate interesting possibilites, no signs were found to indicate that these technologies are being scaled up and might be applied to end of life luminaires. It therefore seems premature to take into account these alternative liberation processes in the redesign of the CoreLine. However, these research efforts do show that WEEE liberation is under development, and it could be strategic for Signify to keep a close eye on further advancements.

2.4 Design for Recycling Guidelines

A multitude of circular design guideline sets exist in the literature. An overview of published guidelines was created by Dorien van Dolderen. This overview contains 16 sources, published between 1993 and 2021. Two of these sources present guidelines which have been developed in collaboration with recyclers (Peters et al., 2012) (Berwald et al., 2021). I assume that recyclers have the most knowledge on what is good or bad for recycling, and therefore consider guidelines which have been made with input from recyclers to be more valuable than guidelines for which this is not the case. The research done by Berward et al. (2021) is much more recent than that by Peters et al. (2012). I therefore assume the first to be more representative of current recycling practices than the latter.

For these reasons, I use the guidelines as proposed by Berward et al. (2021) to identify potential issues in the CoreLine luminaire. Table 3 and 4 present these guidelines; they are copied literally from the article by Berwald et al. The original article also includes further argumentation per guideline. Compliance of the current CoreLine design to these guidelines is considered; there are six cases of (potential) non-compliance (highlighted in orange the table):

- The L2s strips which are glued to the backplate.
- The product contains PS, PET and PMMA, which are not mentioned by the authors as plastics that will be recycled. This should be investigated further.
- The additives in the plastic components are unknown.
- The seal in the frame which is likely made of an elastomer or rubber.
- The driver sticker which is likely made of an elastomer or rubber.
- The steel screws which are applied in the aluminum frame.

These specific cases, but also the complete set of guidelines, will be taken into account during the redesign stage.

Table 3. Design for circularity guidelines on the product level by Berward et al. (2021) and compliance of the CoreLine to these guidelines.

Guidelines on the product level by Berward et al. (2021)	Compliance of current CoreLine design to guidelines
Enabling easy access and removal of hazardous or polluting parts	
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.	The L2s (also PCBs) are fixed with glue. The PCB and cables in the driver and connector are fixated according to the guideline.
Use of recyclable materials that will be recycled by WEEE recyclers	
Avoid thermosets and composites.	Plastics used in the CoreLine are PC, PA, PS, PET and PMMA. None of these are thermosets. The CoreLine contains no composites.
Do not use plating, galvanizing, and vacuum-metallization as a coating on plastics.	None of the plastics are coated.
Avoid the use of coatings on plastics.	None of the plastics are coated.
Minimise the use of thermoplastic elastomers.	The seal that is applied in the frame and the sticker on the driver housing are either elastomers or rubbers.
Avoid the use of foam.	The sticker on the driver housing may be foam based.
Minimise the use of magnets.	
Use of material combinations and connections that allow easy liberation	
Avoid moulding different material types together by multiple-K processes (different plastic materials injected into the same mould, over-moulding, or in-mould decoration).	No multiple-K processes are used for the product.
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.	None of these connections are used.
Use of recycled materials	
Consider more textured surfaces for injection moulding plastic parts. Avoid uniform high-gloss surfaces	

Table 4. Design for circularity guidelines on the part level by Berward et al. (2021) and compliance of the CoreLine to these guidelines.

Guidelines on the part level by Berward et al. (2021)	Compliance of current CoreLine design
Avoidance of hazardous substances	
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.	Signify is phasing out the use of BFRs in their products (Signify, n.d.-c)
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].	Signify adheres to REACH regulations (Signify, n.d.-c)
Avoid the use of substances that are listed on the 'SIN list' [42].	Unknown.
Do not use halogenated polymers (e.g., Polyvinyl chloride (PVC), Polytetrafluoroethylene (PTFE)).	The product contains no halogenated polymers.
Enable easy access and removal of hazardous or polluting parts	
Avoid magnetic parts on printed circuit boards (PCBs).	
Use of recyclable materials that will be recycled by WEEE recyclers	
Use common plastics in the product such as ABS, PP, PA, PC, PC/ABS, HIPS, PE (polyethylene), where possible.	The plastics in the product are: PC, PA, PS, PET and PMMA. PS, PET and PMMA are not mentioned in the guideline as plastics that will be recycled.
Avoid polymer blends.	The product contains no polymer blends.
Avoid glass fibre-filled plastics.	The product contains no glass fibre-filled plastics.
Minimise the use of thermoplastic elastomers.	The seal that is applied in the frame is either an elastomer or a rubber. The exact material is unknown. Same goes for the sticker that is applied to the driver housing.
Avoid the use of thermoset rubbers.	
Minimise additives in plastic materials.	Additives are not shared by suppliers.
Use material combinations and connections that allow easy liberation	
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 aluminum (non-ferrous).	Screws are used in the aluminum frame.
Do not permanently fix aluminum (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.	The L2s, which contain copper, are glued to the steel backplate.
Use of recycled materials	
Choose geometries for injection-moulded parts that allow easy flow paths. Avoid tight and narrow geometries.	
For injection mould plastic parts, do not use long injection paths.	
For injection mould plastic parts, consider more or wider venting ports.	

3. Shredding Experiments

To be able to assess the recyclability of the current luminaire designs, shredding experiments were conducted. This chapter details the research questions, method and results of those experiments.

3.1 Research Questions

This study has two primary research questions:

RQ1. What issues for recyclability occur from the shredding of the CoreLine luminaire?
a. Which issues are most important to solve in the redesign of the product?
b. Do these issues occur to the same extent in the Ledinaire and Ledvance luminaires? If not, what causes the difference?

Any such difference could indicate a better performing design feature, which would be valuable input for the redesign phase.

RQ2. How does prior removal of the driver influence the shredding of the CoreLine luminaire?
a. In terms of the amounts of liberated materials?

Differences in shredding results could serve as an argument for removal of the driver prior to shredding.

3.2 Method

3.2.1 Shredding

The shredding was conducted at an E-waste preprocessor (see Figure 19). Five separate batches were fed into the shredder one after another. These batches contained new, unused luminaires. No components were removed before shredding (except for the drivers and connectors, in some batches). Table 5 lists the types and quantities of products per batch.

Table 5. Product batches that were shredded in the experiment.

Batch content	Number of products shredded
CoreLines with driver	4
CoreLines without driver	4
CoreLine drivers	9
Ledinaires with driver	5
Ledvances without driver	5

Between batches, the shredder was kept running a bit longer, to allow for stuck fragments to release and thus decrease contamination between batches.
It must be noted that the shredder which was available for experiments is of a different type than the ones they use for actual recycling. As a result, the former outputs smaller fragments than the latter. Since liberation improves as fragment size decreases, this means that any issues for recyclability identified within this experiment are very likely to occur also in actual, industrial recycling processes.

Figure 19. Luminaire being shredded at the WEEE preprocessor.

3.2.2 Sorting

After shredding, fragments were sorted into several fractions, see Table 6. For each fraction mentioned in Table 6, there was a container into which the corresponding fragments were sorted (see Figure 21).

Firstly, there were fractions consisting of homogeneous fragments, i.e. fragments consisting of only one material. Additionally, fractions were assigned to different types of connections. A fraction *too small* included all fragments that were so small (roughly 1 cm and smaller) that sorting them by hand would require too much time (see Figure 20). This is a deviation from industrial sorting processes, where fragments down to 2 mm do get sorted and recycled.

Finally, the *rest* fraction held those fragments that did not originate from the batch being sorted. This included pieces that could be identified as belonging to a different batch, or pieces that could not have been part of any of the luminaires.

Table 6. Fractions into which fragments were sorted.

Homogeneous fractions	Mixed fractions	Other
PET	Click connections	L2
PMMA	Screw connections	Other electronics
PS	Glue connections	Too small
PA	Connected during shredding	Rest
PC		
Aluminum		
Steel		

Sorting took place at Signify and was conducted and supervised by the author, with the help of IDE students and Signify employees. After sorting, all fractions were weighed to determine how much of each material was successfully liberated during shredding.

Figure 20. Portion of one of the 'too small' fractions resulting from sorting.

Figure 21. Sorting with the team at Signify.

3.3 Shredding Results

This chapter covers the results from the shredding experiment. The first two sections discuss the reliability of the data. Then, both research questions are answered.

3.3.1 Pre- and post-shredding weights

Figure 22 shows a comparison between the batch weights before and after shredding (input weight and output weight, respectively). Exact weights can be found in Appendix B. The input weight was determined by weighing a single product and multiplying by the batch quantity. For the output weight, each batch was weighed and the mass of the container was deducted.

Based on these numbers, it can be concluded that contamination has occurred between batches. For instance, the Ledinaire batch has lost 372 grams, while the Ledvance batch has gained 47 grams. Observations made during sorting confirm this inter-batch contamination, as fragments showed up in batches that they could not have originated from. Still, there are no losses or gains larger than 5%, so it is assumed that the data is reliable enough to extract clues for the redesign stage.

3.3.2 Fraction weights

Figure 23 shows the inputs and output weights for the batch of CoreLines with drivers. The data will be used to identify which materials of the CoreLine do not liberate well during shredding, and thus where the focus should be during the redesign stage. Exact numbers and similar charts for the other batches are included in Appendix C.

A substantial amount of fragments were too small to sort; this fraction constituted roughly a kilo, i.e. 15% of the total batch weight. This observation, in addition to the fact that contamination occurred between batches, implies that computations based on the fraction weight data - which will follow in the next section - are of an approximate nature.

Relatedly, there is a large difference between input and output in the PS fraction, which is true also for the other batches. During sorting, it was clear that a large portion of the too small fraction consisted of PS (see Figure 20). Therefore, it is assumed that most of the lost PS ended up in *too small*.

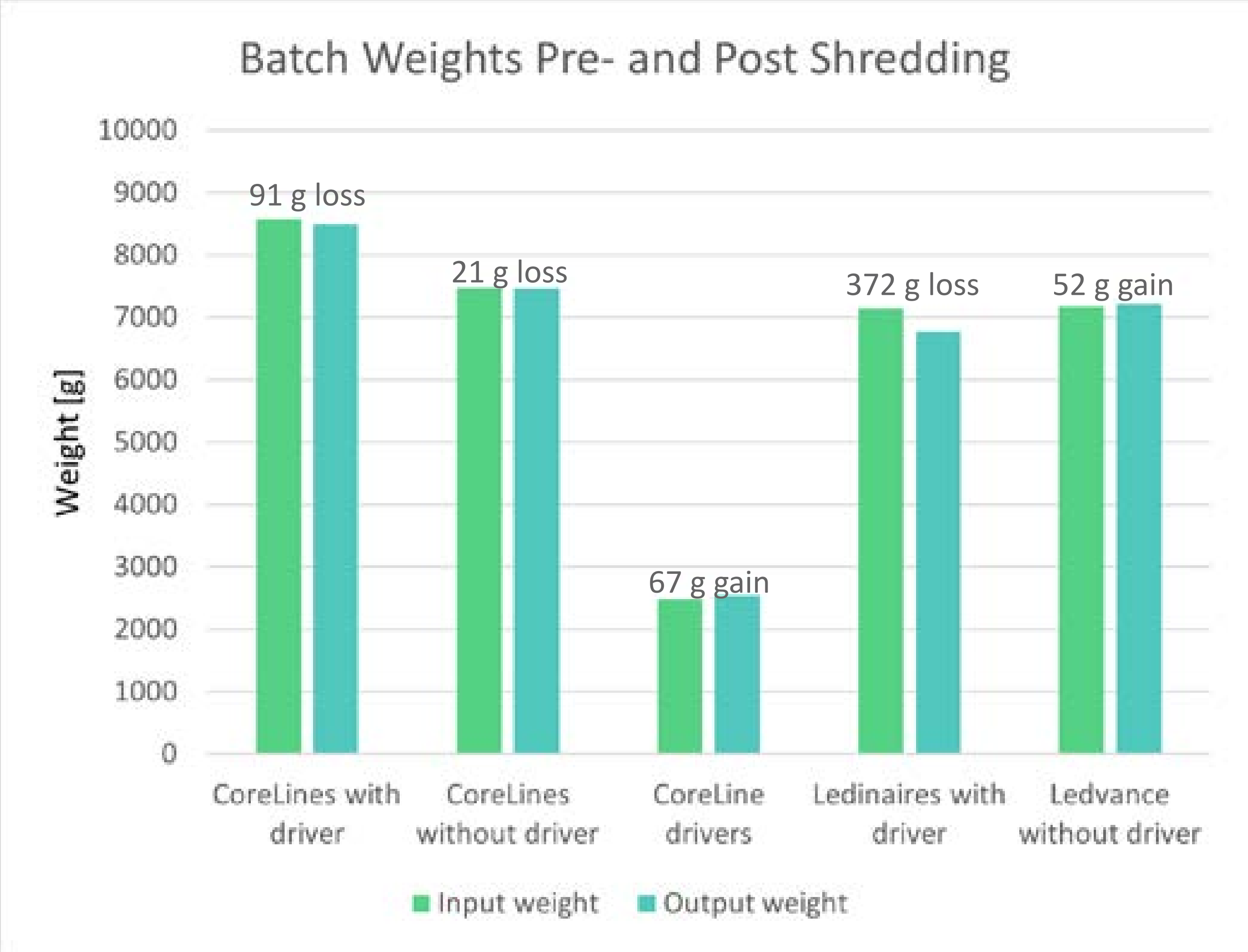


Figure 22. Weights of the batches before and after shredding.

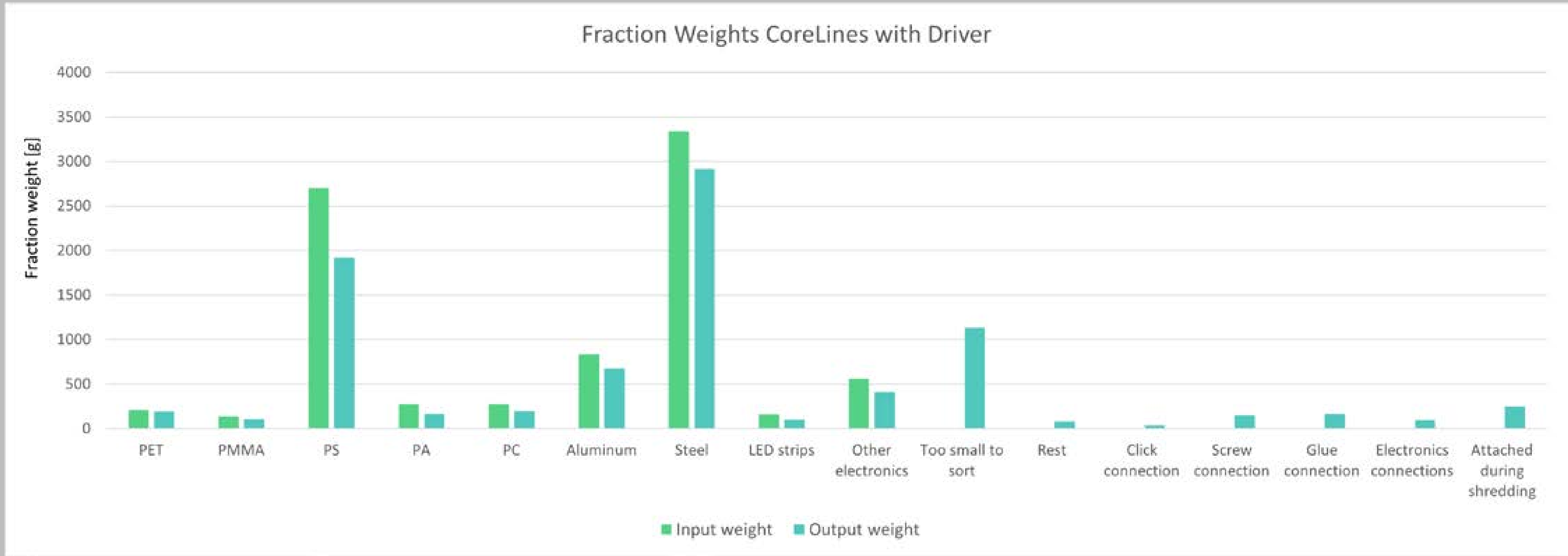


Figure 23. Input and output weights per fraction in the batch of CoreLines with driver.

3.3.3 RQ1: Recyclability issues in the CoreLine

This section will answer the first research question:

RQ1. What issues for recyclability occur from the shredding of the CoreLine luminaire?
a. Which issues are most important to solve in the redesign of the product?
b. Do these issues occur to the same extent in the Ledinaire and Ledvance luminaires? If not, what causes the difference?

Each type of mixed fragment that was found in the shredding output represents an issue for recyclability. The following sections list all problems that were discovered in the CoreLine batches and prioritizes them.

To determine the severity of each identified problem, the approach as depicted in Figure 24 was followed. The approach starts with a certain mixed fragment, and with determining which output fraction this fragment will likely enter. This was done based on interviews with a WEEE preprocessor). Then, two resulting issues are considered.

Firstly, the material within the mixed fragment that does not belong to the output fraction will not be recycled and is thus lost (left branch of the diagram). This means it must be produced again as a virgin material, with the associated environmental impacts. The higher the environmental impacts related to the lost material, the higher priority the mixed fragment has for redesign.

As a second issue, the output fraction will be polluted (right branch of the diagram). In cases where small amounts of plastic pollute metal fractions, and these fractions are processed pyrometallurgically, the pollution is not considered a problem. The plastic will be incinerated and serve as fuel to keep the process going. This was determined during interviews with the same WEEE preprocessor as mentioned in chapter 2.2.1.

In those cases where metal enters a plastic fraction or plastic enters the wrong plastic fraction, the pollution is permanent, and the final recycled material will be degraded in quality. For the sake of prioritization, it can be worthwhile to estimate the magnitude of such permanent pollution and focus first on those issues that cause the most pollution. However, it must be noted that even small amounts of pollution are undesirable for recycling, especially in a circular economy where materials are recycled indefinitely, and pollutions will accumulate over time.

Following this approach, each mixed fragment was placed in one of the following categories:

- **Problem to be addressed in redesign**: the mixed fragment corresponds to high GWP impact, high ADPE impact or a large amount of permanent pollution.
- **Problem out of scope**: same as above, but the problem occurs in the driver or connector. Within this project, design changes will only be made to the luminaire panel. Such issues will therefore not be addressed in the redesign, but are communicated to Signify as points for further development.
- **Problem of small impact**: the mixed fragment is associated with relatively low GWP and ADPE impacts, and pollution serves as fuel in the pyrometallurgical processing.

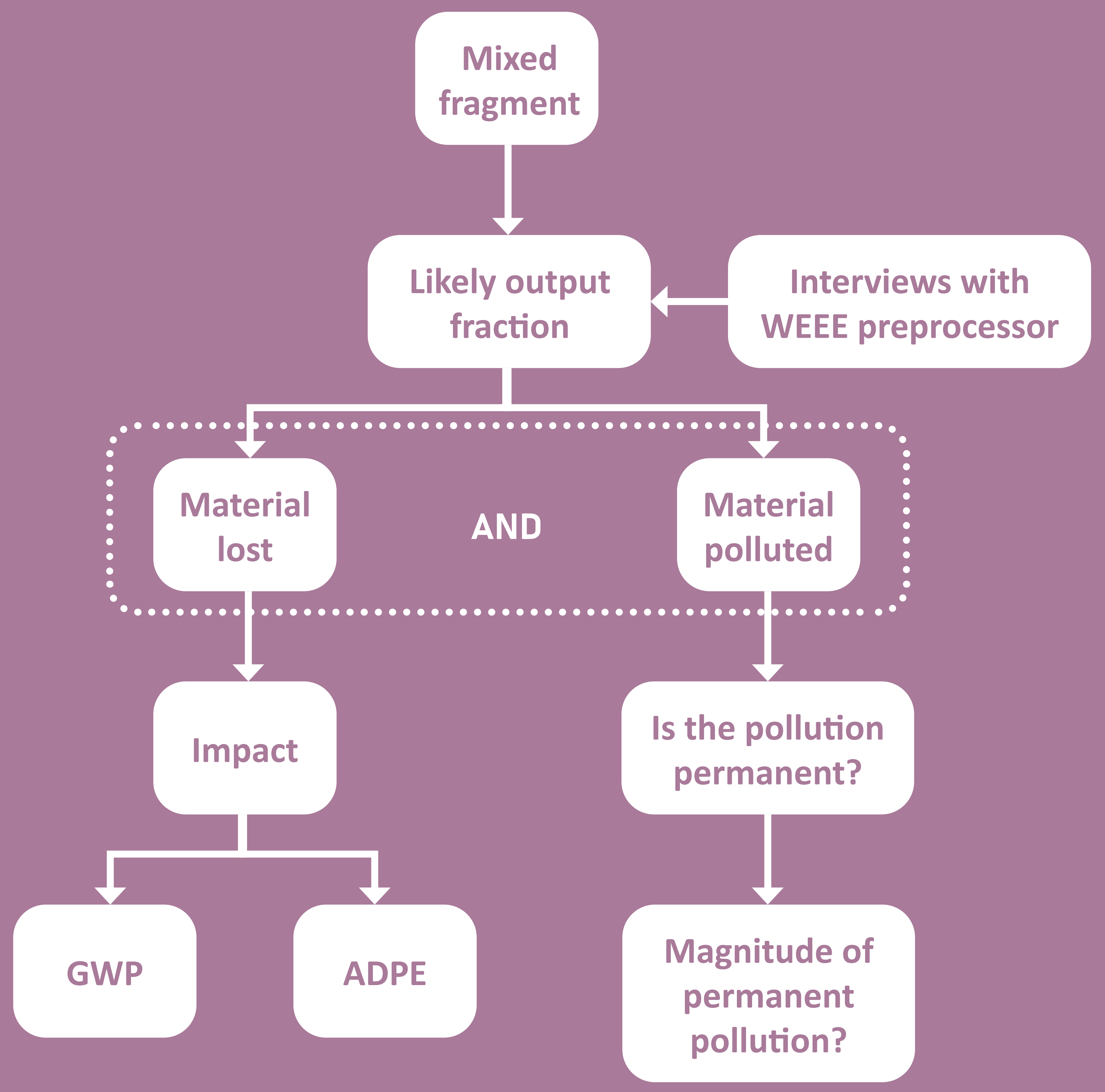


Figure 24. Approach used for prioritizing the identified recyclability issues.

In order to place each mixed fragment into a priority category, their associated GWP, ADPE and permanent pollution data were computed (see Figure 25-27). These computations are based on the LCA data from section 2.1.2 and the fraction weights as presented in 3.3.2 (see Appendix D). Once again, imperfections in the experiment have made the data somewhat imprecise, so only large differences in values are relevant. Table 7 provides an overview of the output fractions the mixed fragments are likely to go to.

Both the GWP and ADPE graphs are missing some of the identified mixed fragments because of incomplete LCA data:

- GWP graph misses: sticker on driver housing, lenses on L2s and rubber in frame.
- ADPE graph misses: sticker on driver housing, reflector on backplate, lenses on L2s, connector plastic and rubber in frame.

Since these materials are all polymers and are present in the product only in low quantities, their environmental impacts are expected not to make the corresponding mixed fragments a high priority for the redesign.

The three figures together give an overview of the most problematic mixed fragments. As becomes clear from Figure 25 and 26, the fragments consisting of L2 and steel backplate represent the biggest GWP and ADPE impacts. Based on the permanent pollution in output fractions, four more mixed fragments can be recognized as problems for recycling. These are the screws in the frame, screws in the driver housing, screws in the connector housing and the sticker on the driver housing.

The next sections each dive deeper into one of the mixed fragment types, indicate their level of priority for the redesign stage, and make comparisons with the Ledinaire and Ledvance luminaires. Issues in the panel are presented first and are followed by issues in the power supply.

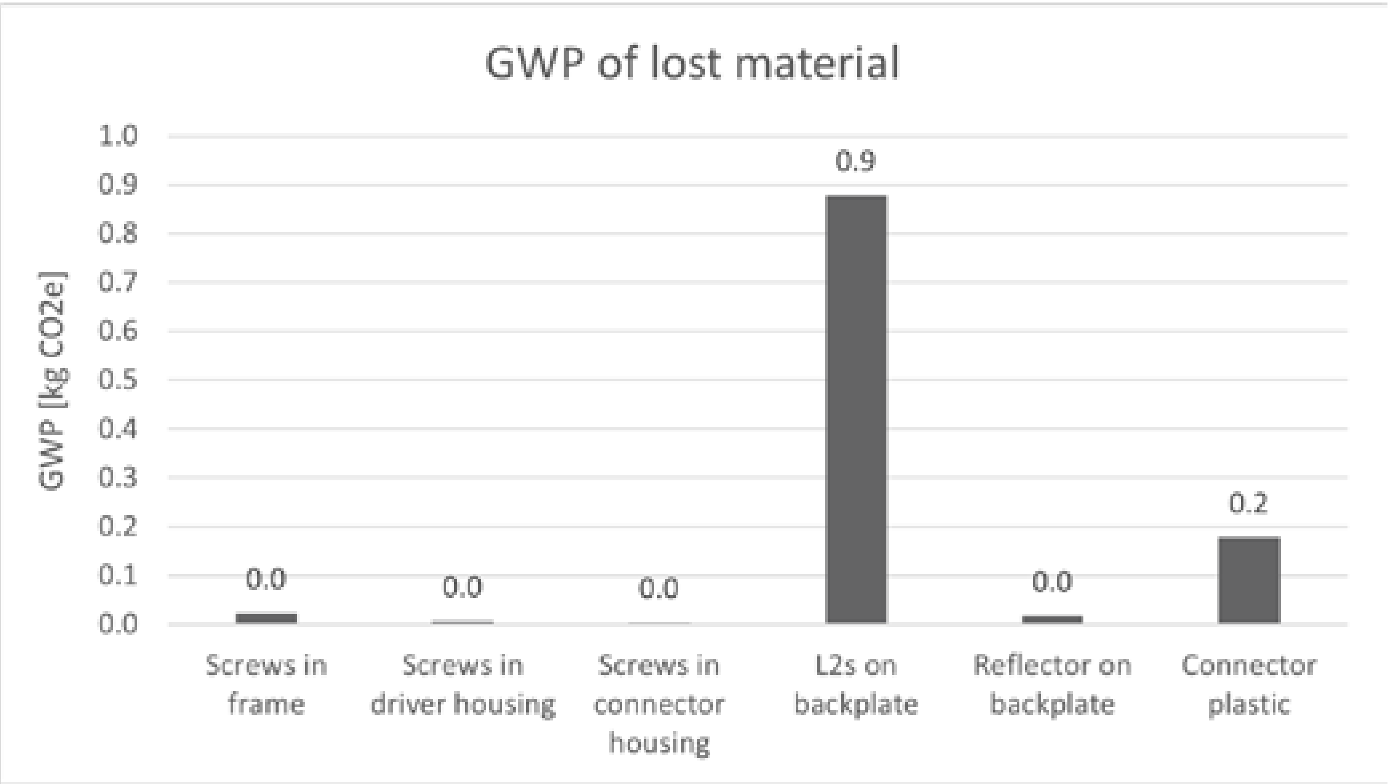


Figure 25. GWP associated with the raw material supply of the lost material in mixed fragments.

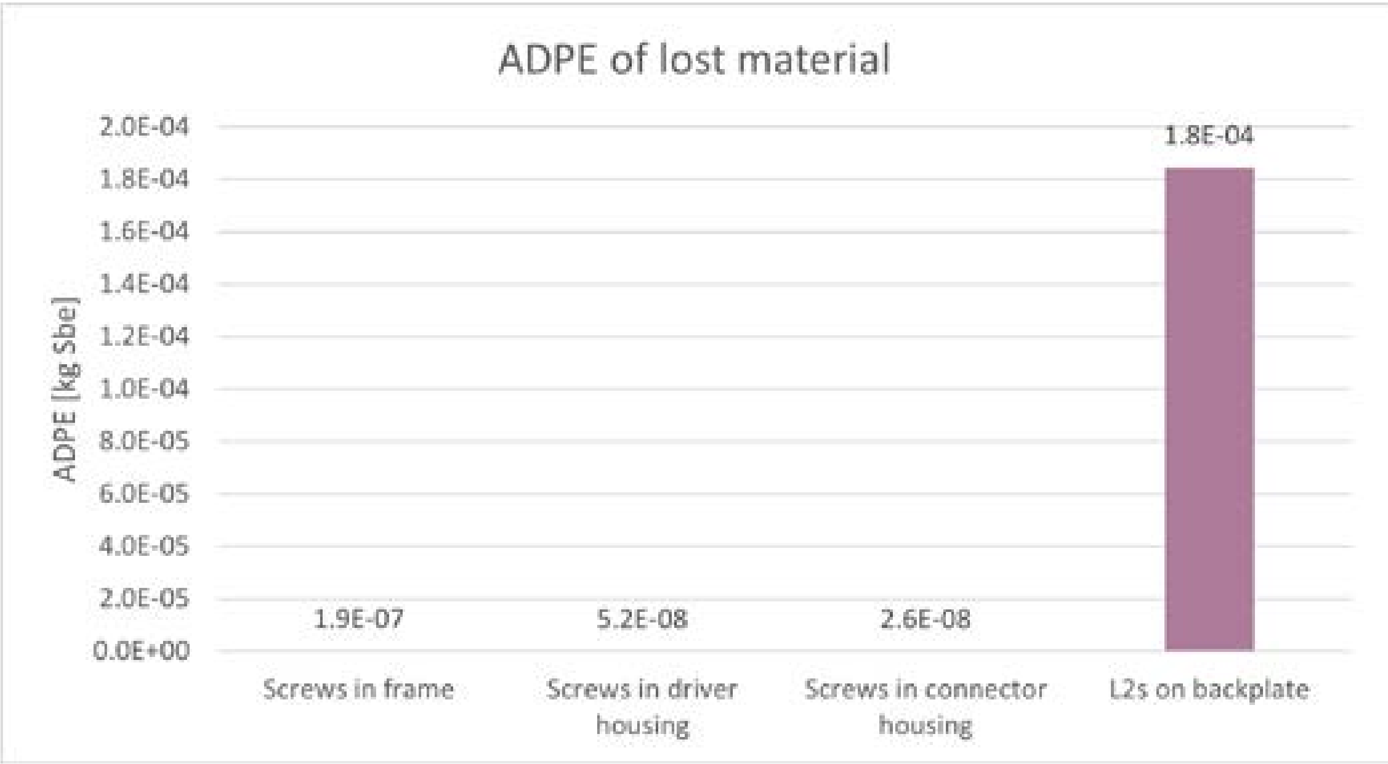


Figure 26. ADPE associated with the raw material supply of the lost material in mixed fragments.

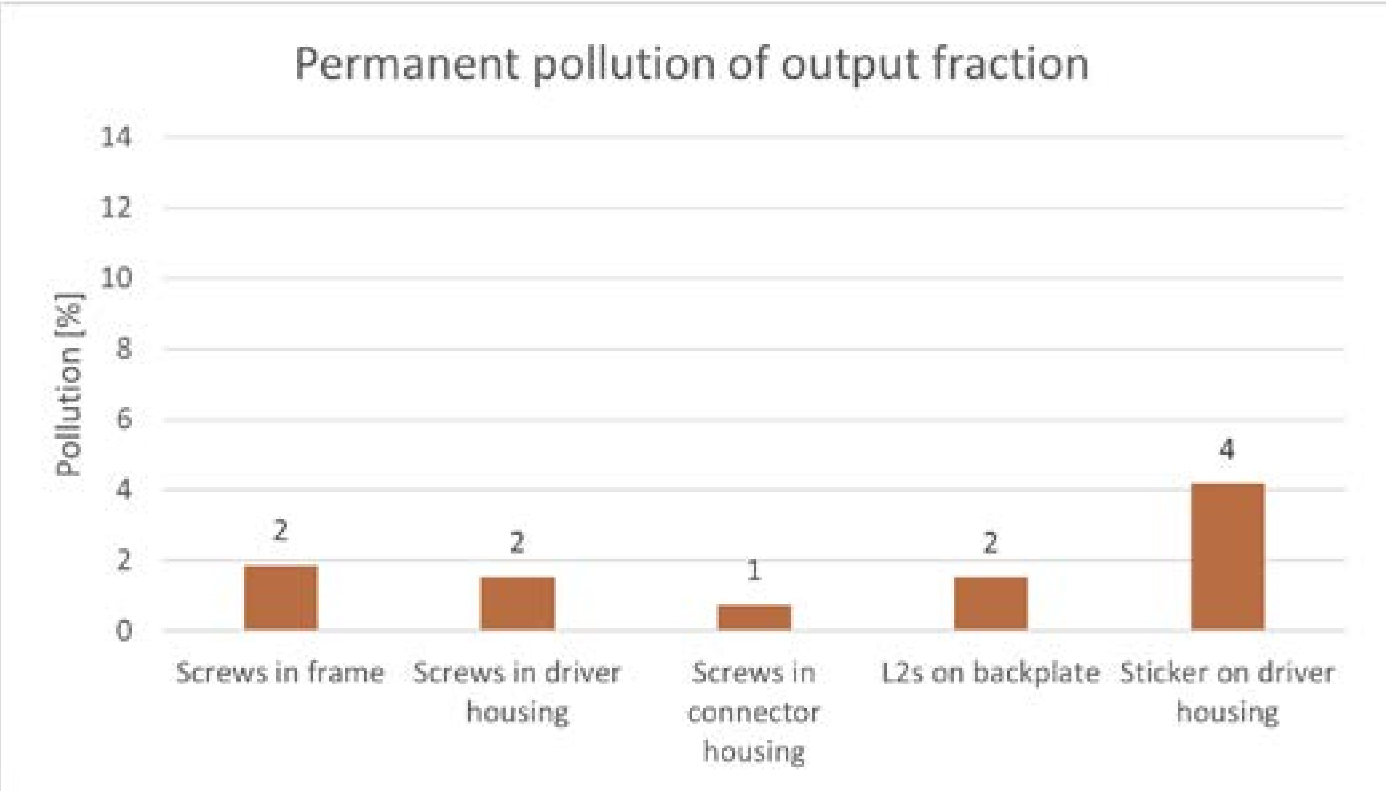


Figure 27. Degree of pullution caused by the mixed fragment in the corresponding output fraction. The likely output fraction per mixed fragment is indicated inside parentheses.

Table 7. Likely output fraction per mixed fragment, based on interviews with WEEE recycler.

Mixed fragment	Likely output fraction
Screws in frame	Aluminum
Seal in frame	Aluminum
Lenses on L2s	Aluminum
L2s on backplate	Ferrous fraction
Reflector on backplate	Ferrous fraction
Screws in driver housing	Plastics
Screws in connector housing	Plastics
Sticker on driver housing	Plastics
Connector plastic	Copper

Screws in aluminum frame

Across the eight CoreLine luminaires that were shredded, 74 out of 192 screws remained stuck to the aluminum frame (see Figure 28). Such mixed fragments will likely enter the aluminum fraction. The steel screws will thus be lost, and the aluminum stream will be polluted.

As shown in Figure 25 and 26, the associated GWP and ADPE do not indicate high priority for this fragment. However, the steel pollution in the aluminum will be permanent. The interviewed WEEE preprocessor also indicated that steel screws in non-steel fractions are very undesirable. Therefore, this issue is classified as a **problem to be addressed in redesign.**

In Figure 29, screw liberation across the different luminaires is compared. In the Ledvance, the least amount of screws remain stuck in the aluminum frame. This is probably caused by a slight difference in the Ledvance frame as: it does not have a pre-drilled screw hole. Instead, the screws are simply fixated in a gutter (see Figure 30). Apparently, and logically, the screws liberate more easily when they are not enclosed all around, but only from two sides.

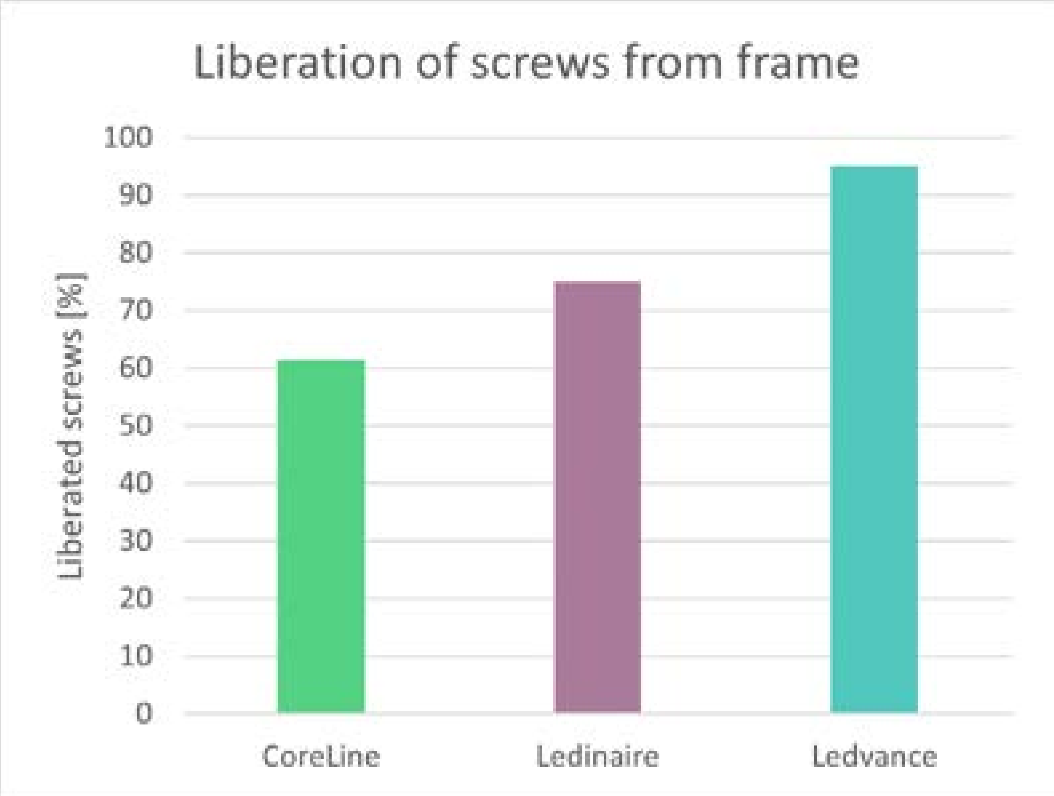


Figure 29. Liberation of screws from the aluminum frame per luminaire type.

Figure 28. Steel screw that was not liberated from the aluminum frame during shredding of the CoreLine.

Figure 30. Different approaches for screwing into the frame. Top: CoreLine frame with pre-drilled holes. Bottom: Ledvance frame where screws are fixated in a gutter.

Seal in aluminum frame

The rubber seal that is glued into the aluminum frame mostly remained stuck during shredding. The resulting mixed fragments will go into the aluminum fraction, so the rubber will be lost and the aluminum will be polluted.

The GWP and ADPE are assumed to be low, and the rubber will be incinerated in the aluminum smelter, so this is considered to be a **problem of small impact.**

The Ledinaire and Ledvance do not have this issue, because they do not include a seal. They do not include any other design feature to close off the product more securely.

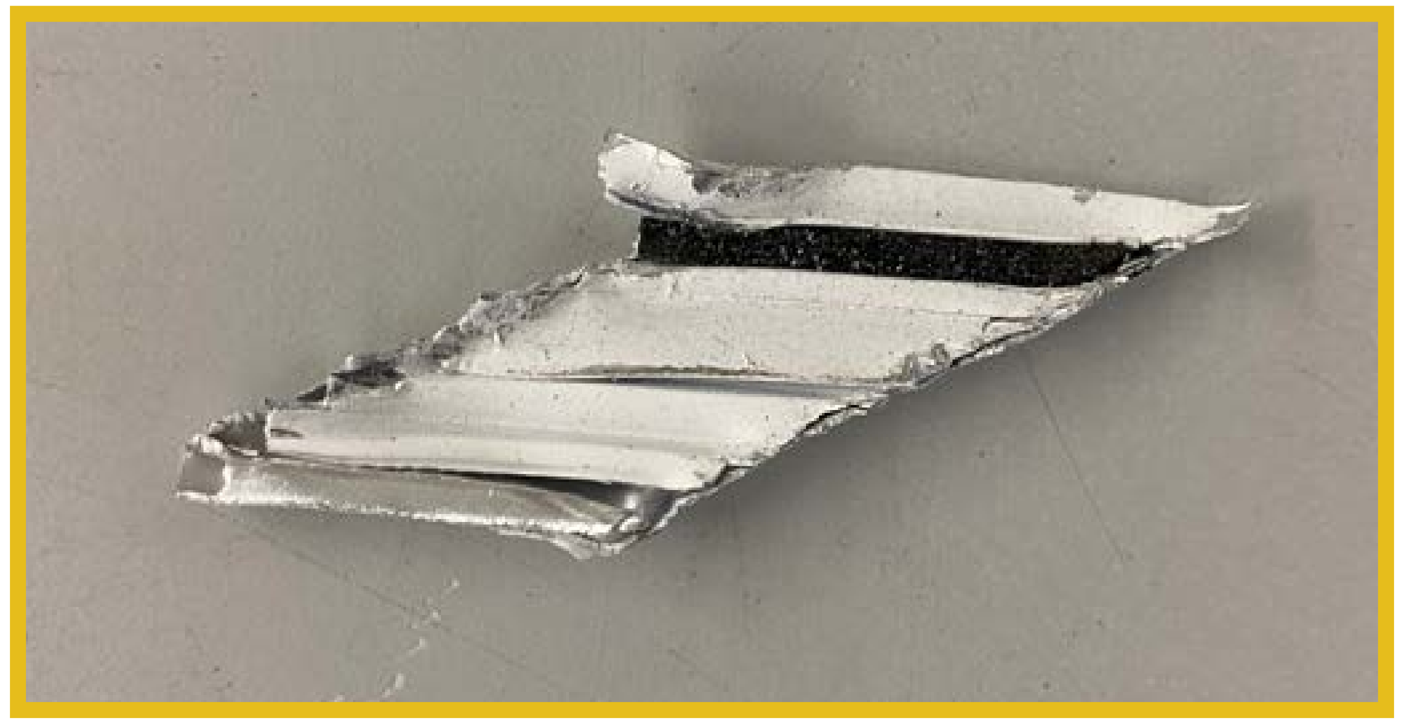


Figure 31. Rubber seal still stuck to aluminum frame in CoreLine.

Lenses on L2s

In the CoreLine, roughly 15% of the lenses that are glued to the L2s did not come off during shredding. Such pieces will enter the aluminum stream.

The GWP and ADPE impacts of the lost plastic lenses is assumed to be low, and the plastic will serve as fuel in the aluminum smelter. Therefore, this is a **problem of small impact.**

The lenses in the Ledinaire and Ledvance are attached in the same way, resulting in similar degrees of liberation (see Figure 33).

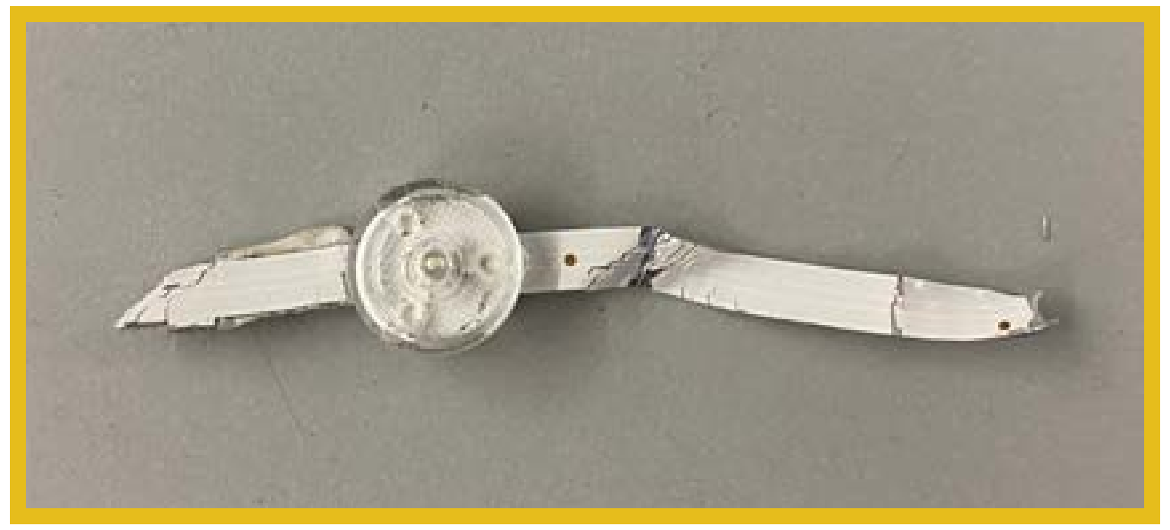


Figure 32. Lens still stuck to L2 in CoreLine.

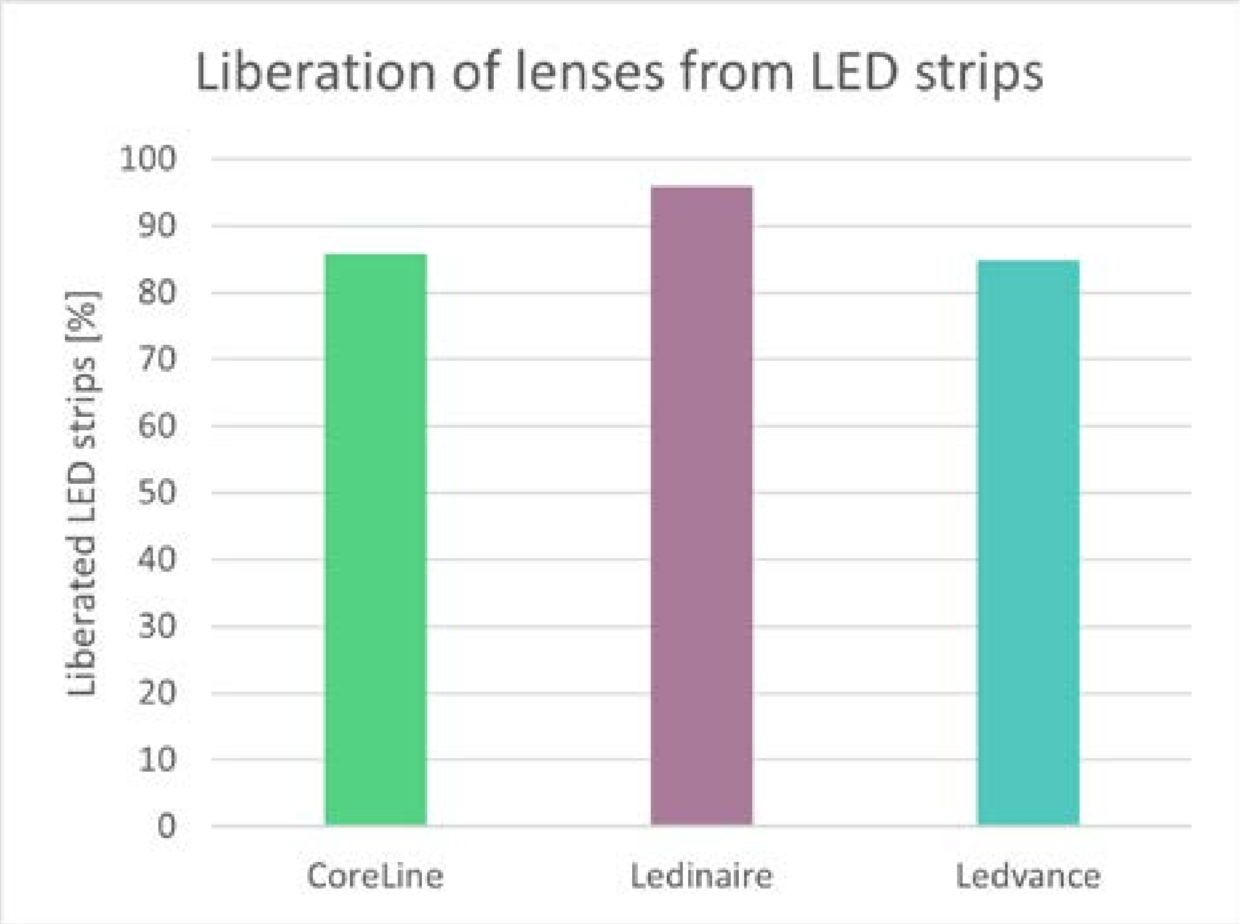


Figure 33. Liberation of lenses from L2s across luminaire types.

L2s on backplate

Roughly 40% of the L2s that are glued onto the steel backplate did not liberate during shredding (see Figure 34). Such mixed fragments will go into the steel fraction. The L2s will be lost and the steel fraction will be polluted.

Associated GWP and ADPE impacts are relatively high, and the pollution does not burn, so this is a **problem to be addressed in redesign.**

L2 liberation is comparable in the other two luminaires, except those in the Ledinaire separated slightly better (see Figure 35). This may be due to different types of glue being used. However, liberation is unsatisfactory in all three luminaires, which implies that none of these glue connections are very suitable for recycling.

It must be noted that even if the L2s are liberated from the backplate, they still will not go into the correct output fraction. Due to their aluminum base, they will enter the aluminum stream, while they should go into the copper fraction. For proper recycling, L2s with another base material should be considered.

Figure 34. L2 still stuck to steel backplate in CoreLine.

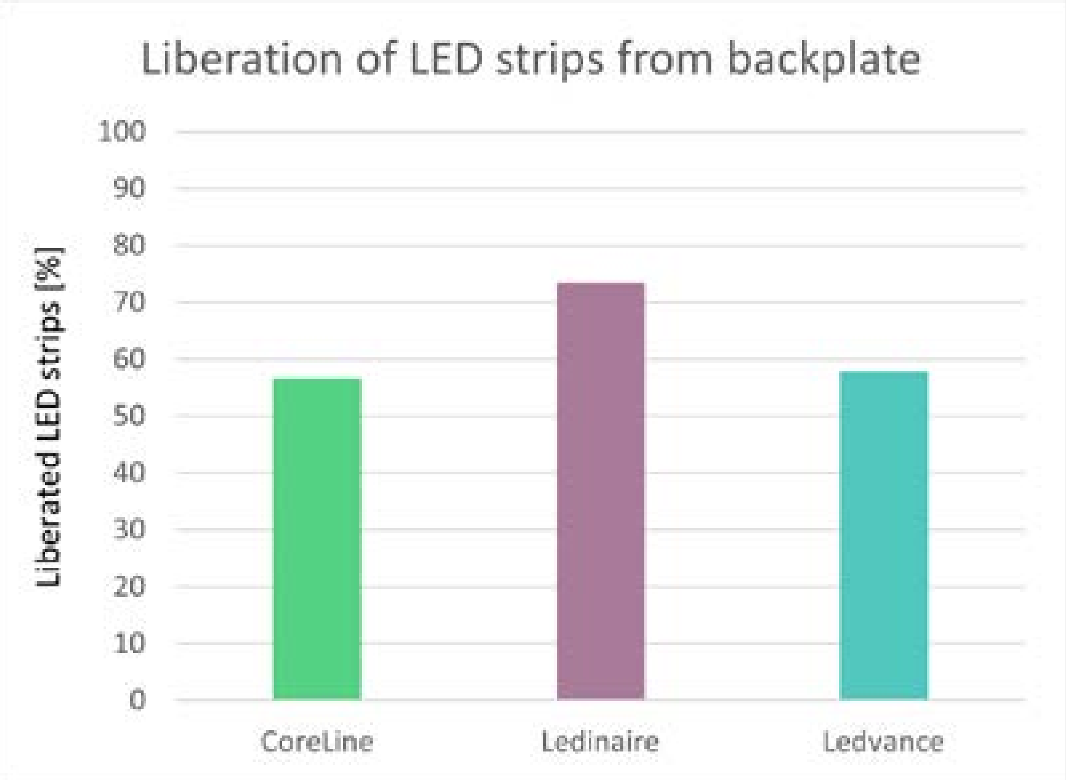


Figure 35. Liberation of L2s from the steel backplate per luminaire type.

Reflector on backplate

Some of the reflector that is glued to the backplate did not release during shredding. The resulting fragments will end up in the steel fraction, where the PET will be lost.

Corresponding GWP and ADPE impacts are assumed to be low, and the PET will burn during processing of the steel, so this is a **problem of small impact.**

Liberation of the reflector was comparable in the Ledvance (see Figure 37). The Ledinaire does not have this issue because it has no reflector, which comes at the cost of luminous efficacy.

Figure 36. Reflector still stuck to the steel backplate in the CoreLine.

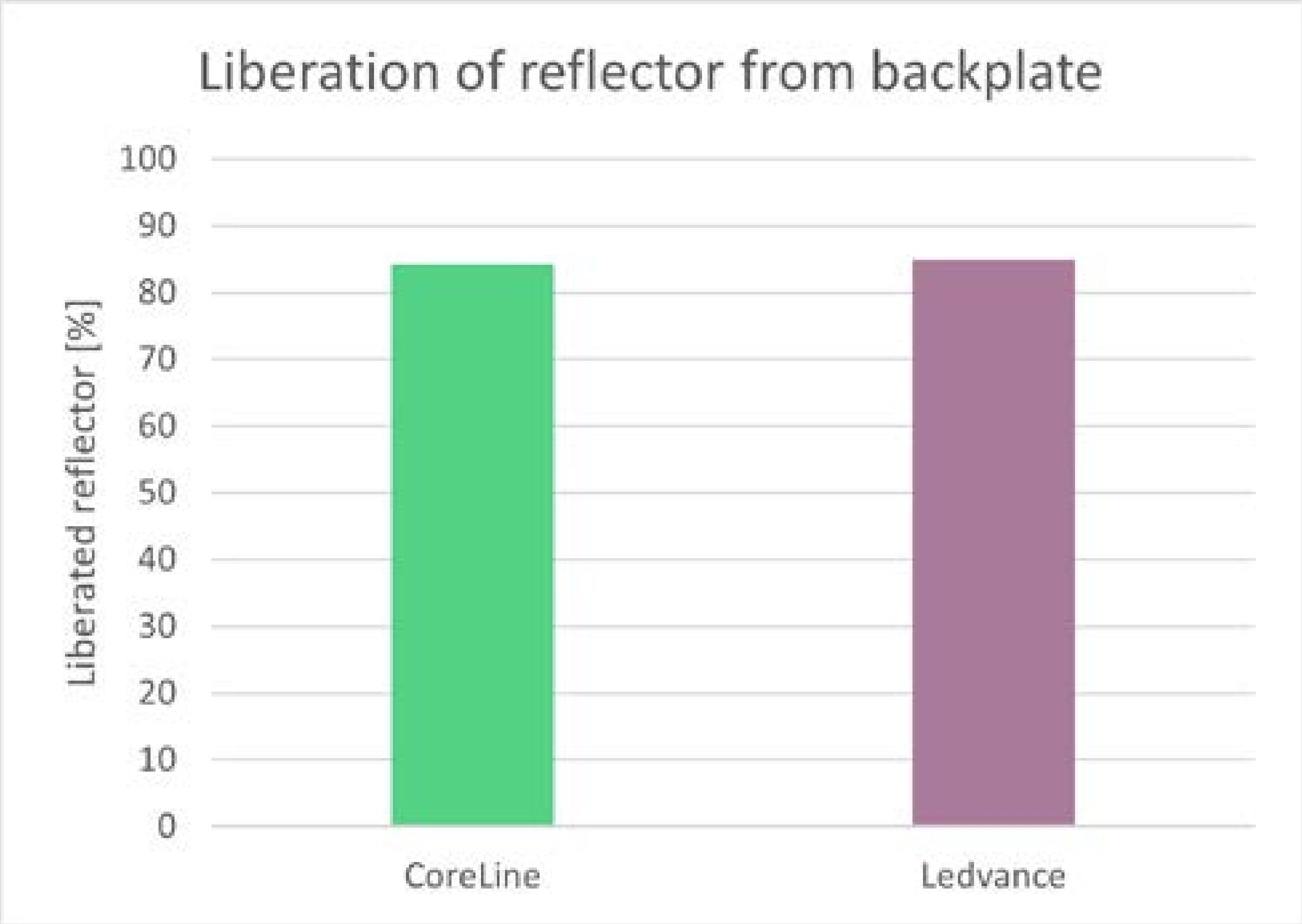


Figure 37. Liberation of reflector from the backplate compared between the CoreLine and Ledvance luminaires.

Screws in driver housing

From the 13 CoreLine drivers that were shredded, 32 out of 39 screws were not liberated from the housings. These fragments are expected to go into the plastics stream. So, the steel screws will be lost and the plastic will be polluted.

GWP and ADPE impacts are relatively low, but the pollution will not burn. For those reasons, the problem should be addressed. However, this issue occurs in the driver, so it is a **problem out of scope.**

The Ledinaire driver did not have this issue, as it is screwless. It uses a different method for keeping the cables in place, namely through a 'ladder' of snapfits combined with a teeth pattern (see Figure 39).

Figure 38. Steel screw still stuck in CoreLine driver housing.

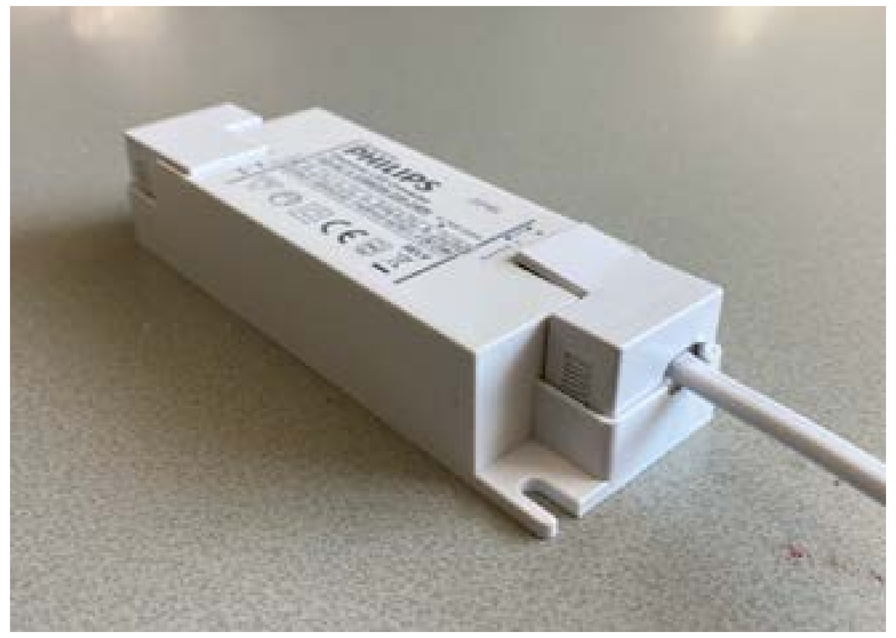


Figure 39. Screwless cable securement in Ledinaire driver.

Screws in connector housing

From the 13 CoreLine connectors that were shredded, 19 out of 26 screws were not liberated from the housings. For the same reasoning as the screws in the driver housing, the screws in the connector housing represent a **problem out of scope.**

The Ledinaire connector also contains screws and shows this same issue.

Figure 40. Steel screw still stuck in CoreLine connector housing.

Sticker on driver housing

Not surprisingly, the sticker that is applied to the PC driver housing did not release during the shredding process (see Figure 41). The resulting mixed fragments will likely go into the PC fraction, where the sticker material will be pollution.

The GWP and ADPE impacts are assumed to be low, but the pollution will not burn in downstream processing, so this is a **problem to be addressed in redesign.**

The same issue occurs in the Ledinaire, which uses a similar sticker on the driver housing.

Figure 41. Sticker still stuck to CoreLine driver housing.

Connector plastic

Shredding of the connector led to many metal-plastic mixed fragments, which are expected to go into the copper fraction. The plastic will thus be lost.

GWP and ADPE impacts are (assumed to be) low, and the plastic will serve as fuel in the copper smelter. So, this is a **problem of small impact.**

The Ledinaire connector showed this same issue.

Figure 42. Metal components still stuck in connector plastic in CoreLine.

Overview of all CoreLine issues

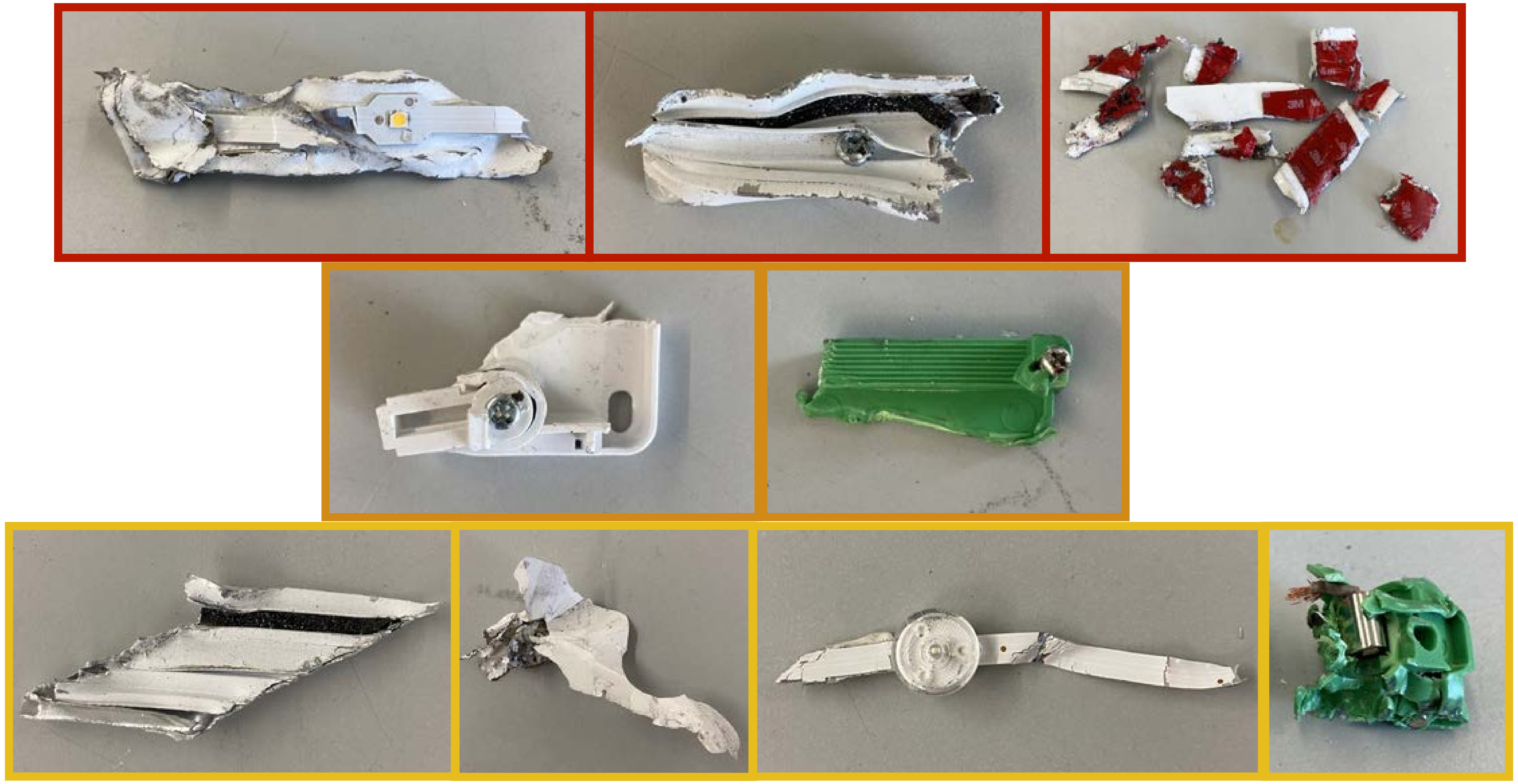
Figure 43 provides an overview of all recyclability issues identified in the CoreLine luminaire based on the shredding experiment.

In conclusion, the shredding experiments have enabled answering of the first research question:

RQ1. What issues for recyclability occur from the shredding of the CoreLine luminaire?
a. Which issues are most important to solve in the redesign of the product?
b. Do these issues occur to the same extent in the Ledinaire and Ledvance luminaires? If not, what causes the difference?

Namely, the most important issues to solve in the redesign of the CoreLine luminaire are:

- The L2s being glued to the steel backplate. This issue also occurs in the Ledinaire and Ledvance luminaires.
- The steel screws in the aluminum frame. A lot less screws remained stuck in the Ledvance's frame, because here the screws were inserted into a gutter instead of pre-drilled holes.
- The sticker that is applied to the driver housing. The Ledinaire showed the same problem, but the Ledvance did not as it does not have a sticker on its driver.



Problem to be addressed in redesign
Problem out of scope
Problem of small impact

Figure 43. All recyclability issues identified in the CoreLine luminaire based on the shredding experiment.

3.3.4 RQ2: driver removal

This section is concerned with the second research question:

RQ2. How does prior removal of the driver influence the shredding of the CoreLine luminaire?
a. In terms of the amounts of liberated materials?

Let us first take a look at the total amount of liberated material in the batches of CoreLines with driver, CoreLines without driver and CoreLine drivers (Figure 44). These amounts are very close to each other, so this zoomed out view of the data does not suggest that removing the driver prior to shredding has an effect on the shredding results.

Figure 45 zooms in on liberation of material per component. The most notable difference between batches is seen in the *Other electronics* fraction. However, the high liberation for the CoreLines without driver is only due to the fact that this was a batch without drivers or connectors.
Liberation in the other fractions is quite similar across batches. The shredding output also does not contain any mixed fragments which would suggest that components of the driver have interfered with the shredding of the panel or vice versa. In conclusion, it seems like prior removal of the driver does not influence the shredding of the CoreLine in terms of material liberation.

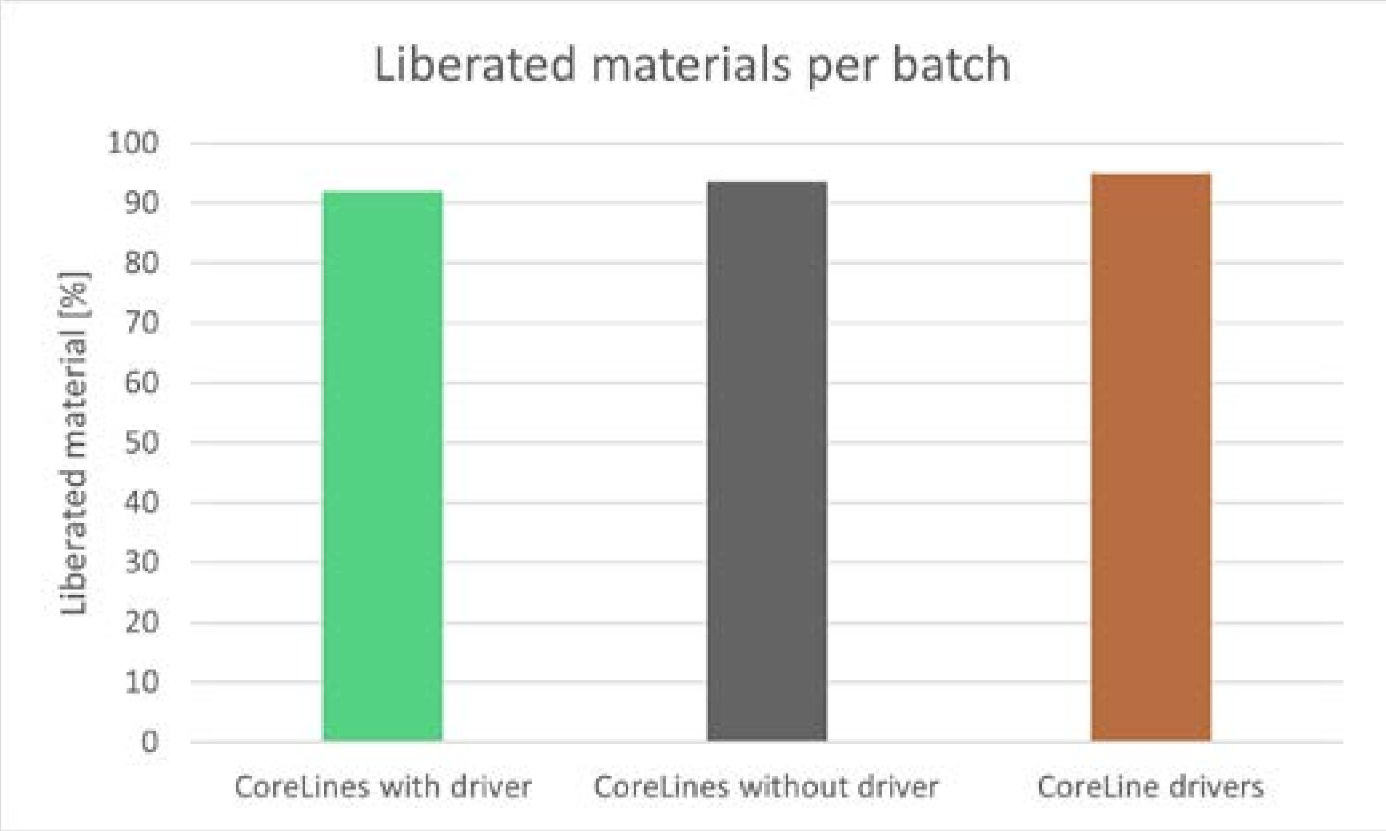


Figure 44. Total material liberation for all three CoreLine batches.

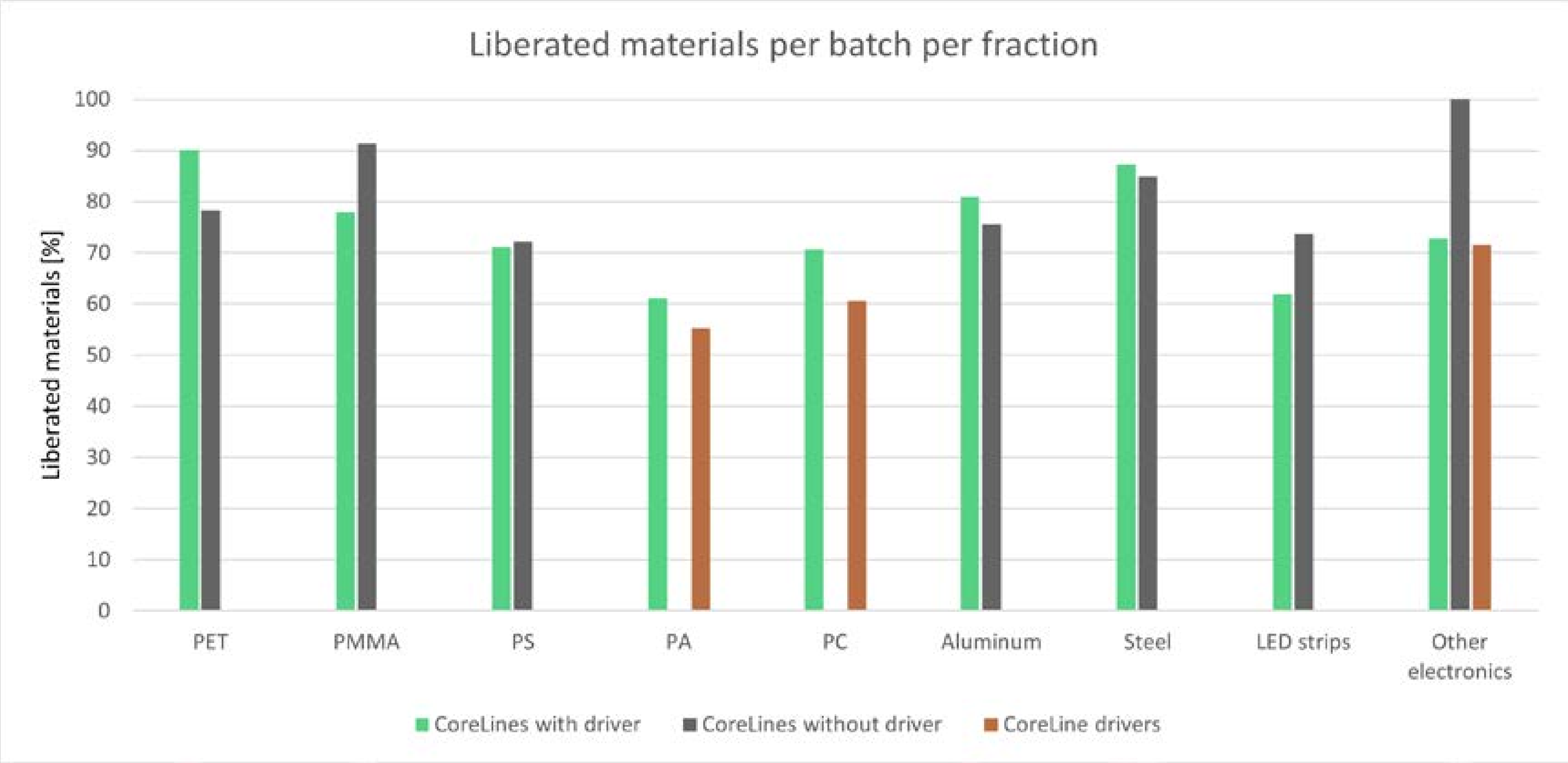


Figure 45. Liberation per fraction for all three CoreLine batches.

4. Redesign

This chapter describes where focus will lie during the redesign stage. Then, the programme of requirements is presented. Possible solutions for the selected recyclability issues are explored. A selection of solutions will be combined into one concept, and the physical demonstrator will be presented.

4.1 Redesign Focus

In the previous chapters, the recyclability of the CoreLine luminaire has been analyzed. Based Based on the recyclability guidelines by Berward et al. (2021) and the shredding experiments, a number of issues have been identified. They are summarized in Figure 46.

Two of the issues as identified through the shredding experiment were also indicated as problematic by the guidelines, namely the glued L2s and the screws in the frame.

Interestingly, the other mixed fragments would not be recognized as problematic based on the guidelines. Berward et al. do not advise against attaching plastics to metals; perhaps this reflects the assumption that the plastics will join the metal fraction and be used as fuel. Also, the guidelines say nothing about attaching stickers to plastic components. A visit to plastics recycler Galloo Plastics has revealed that the majority of stickers attached to plastic come off during a high-pressure washing step. However, the removal of stickers is not perfect, so it would be better if no stickers are present to begin with.

Then, there are some additional issues which can be derived from the guidelines, which relate to material choice. Firstly, the seal within the frame - which is made of a rubber or elastomer - is problematic because such material does not get recycled. However, since it constitutes only very little material (10 grams) and will serve as fuel in the aluminum smelter, it will not be focused on during the redesign.

Secondly, there is some unclarity regarding the presence of recycling infrastructures of different plastics types. For instance, mixed signals exist around the recycling of PC, which is used for the driver housing. While recommended by Berward et al. (2021), the plastics recyclers who have collaborated on this same paper do not seem to recycle it (MGG Polymers, n.d.), (Enva, n.d.). Plastics recycler Galloo has explained that they do not recycle PC, because it has a high density which makes is more difficult to separate from brominated plastics.

Comparable uncertainty exists around the use of additives in plastics. Berward et al. recommend to “minimise additives in plastic materials” because “additives reduce the purity of the plastic streams”. They do not specify, however, in which cases the use of additive-containing plastic is an absolute no-go and other alternatives (such as metals) should be considered.

These first uncertainties and explorations surrounding material choice have made it evident that, in order to make sound decisions concerning the use of plastic for good recyclability, much more thorough research is needed. The timeline of the current graduation project does not offer possibilities for such research. Additionally, a separate team at Signify is actively exploring potential future scenarios of recyclable and environmentally friendly materials, including plastics. The focus within this project therefore remains on the three most problematic mixed fragments that were found in the shredding experiments, and finding alternative methods of connecting the corresponding components.

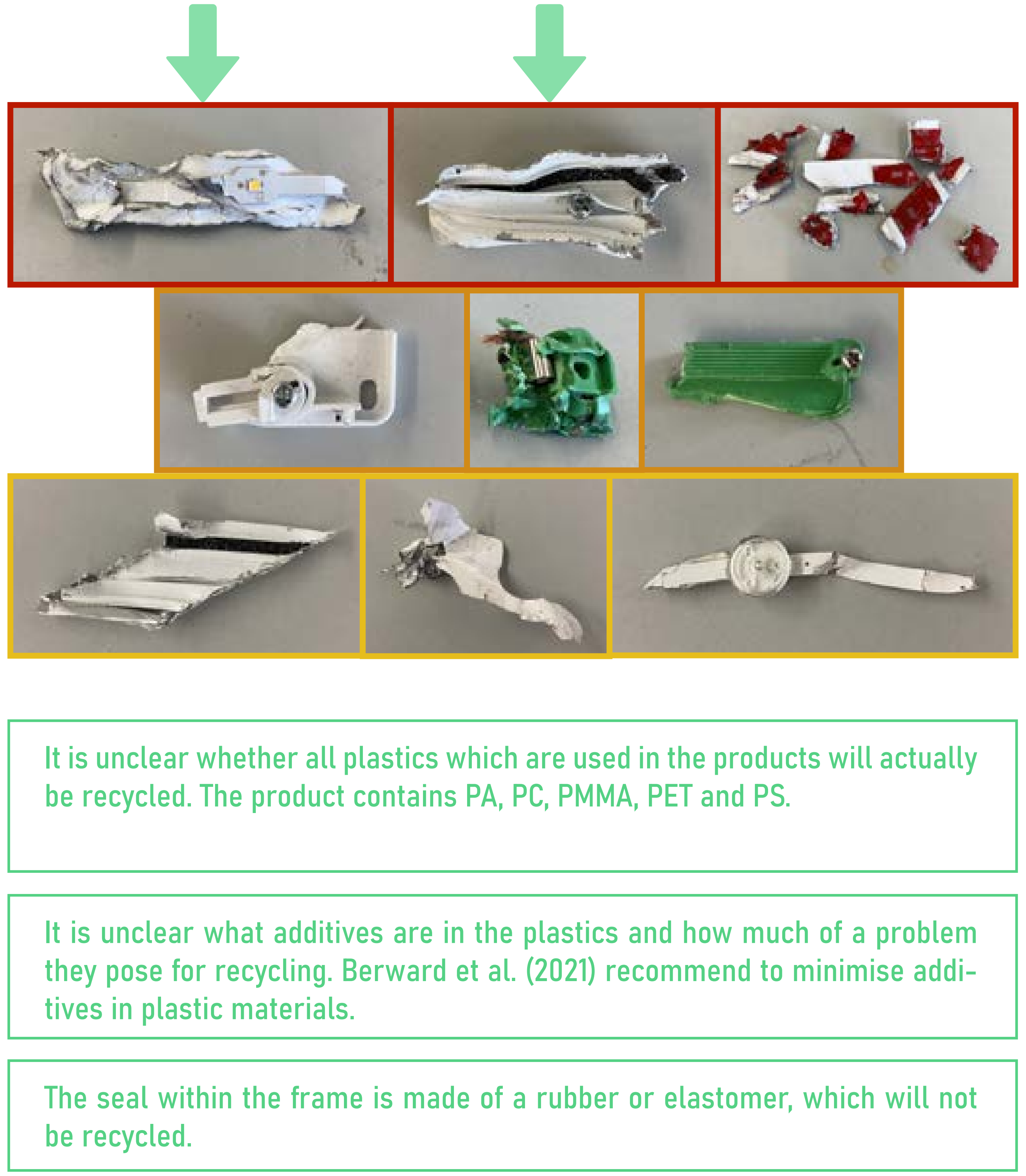


Figure 46. Overview of recyclability issues of the current CoreLine design. The photos of mixed fragments represent the issues as identified through the shredding experiment. The green text and arrows indicate the issues derived from the recyclability guidelines by Berward et al. (2021).

4.2 Programme of Requirements

The conducted research as well as discussions with Signify employees have lead to the Programme of Requirements as presented in Table 8 and 9.

Table 8. Requirements for the redesign.

nr	Requirement	Explanation
1	The outer width and length must remain as they are: 595 x 595 mm.	For proper fit into suspended ceiling.
2	Any gaps in the backplate must be smaller than a square cm.	For office compliancy.
3	An attachment option must be provided to secure the driver to the panel.	To prevent unintended disconnection of components when technicians are doing maintenance in the ceiling.
4	The L2s may not have an aluminum carrier.	If L2s have an aluminum carrier, they will enter the aluminum fraction, from where precious and scarce metals will not be recovered.
5	The L2s may not heat up to more than 90°C during operation.	This is the maximum temperature that can be handled by the solder in the LEDs. The product must allow enough heat dissipation to prevent too high temperatures.
6	The panel should not sag more than 2 cm.	Aesthetics and proper spacing of optical components.

Table 9. Wishes for the redesign.

nr	Wish	Explanation
1	Liberation of materials during shredding should be as complete as possible.	
2	The look and feel of the product should remain clean. It is preferred that the product contains no visible gaps and no severely protruding components.	Gaps can give the impression that dust can enter the product which could cause problems. Installers need to be able to handle the products easily, without getting their clothing stuck or grazing their skin.
3	The global warming potential (GWP) associated with the raw material supply for the product should be as low as possible.	
4	The abiotic depletion potential of elements (ADPE) associated with the raw material supply for the product should be as low as possible.	
5	The luminous efficacy should be as high as possible.	Light can be lost in gaps and corners of the product geometry. This is undesired. The reflector and white coatings contribute to higher luminous efficacy.
6	The light leaving the product should be as uniform as possible.	For aesthetics and comfort. The lenses and diffuser contribute to uniformity.
7	The cost price should be as low as possible.	
8	It is preferred that the redesigned product demonstrates design features which are new to the Signify portfolio.	New approaches are valuable to the company, given changing supply and manufacturing circumstances.
9	It is preferred that the product can be easily dis- and re-assembled.	For repair.

4.3 Solutions per Mixed Fragment

The initial step in the redesign stage was to explore possible solutions to each of the three mixed fragments. Signify employees have helped with this step during a brainstorm session (see Figure 47).
This chapter lists and explains the collected solutions. An overview of all these solutions is provided in a morphological chart at the end of the chapter.

Figure 47. Brainstorm session with Signify employees.

4.3.1 L2 securement

In the current CoreLine design, the L2s are glued to the backplate. This ensures the L2s remain in the correct position throughout transport and use, and facilitates good heat dissipation from the L2s, via the backplate, away from the product. In the redesign, these same functions must be fulfilled whilst preventing mixed fragments consisting of L2 and backplate (see Figure 48).

Figure 48. Mixed fragment of L2 and steel backplate as a result of glue.

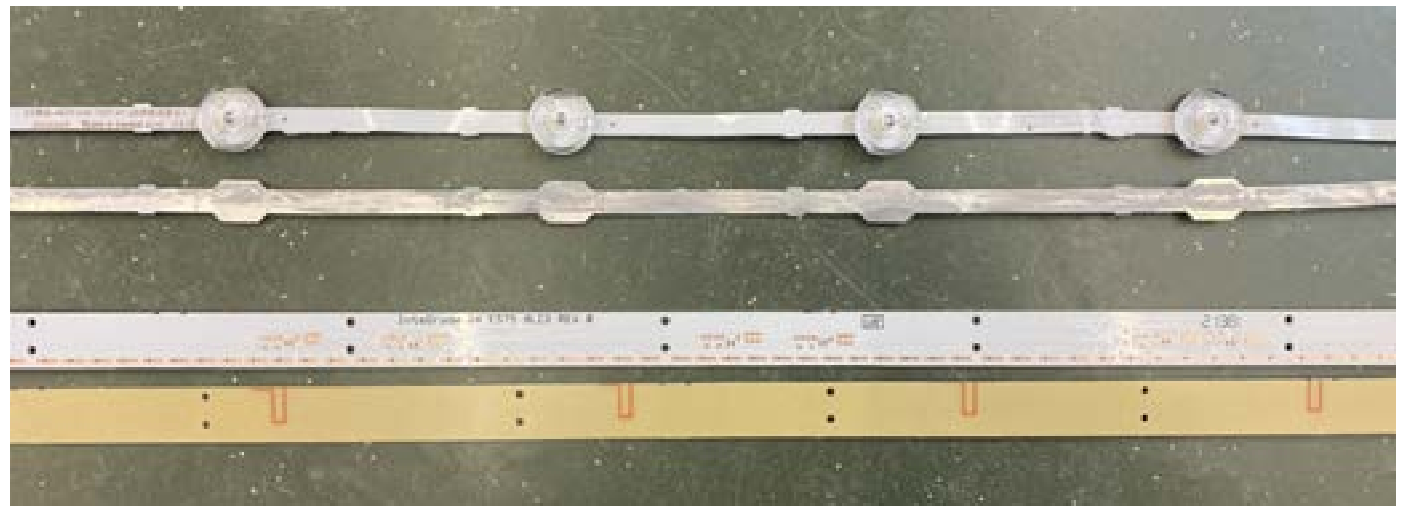


Figure 49. Aluminum based L2s (top) and epoxy based L2s (bottom).

However, as mentioned previously, even when L2s are successfully liberated from the backplate, they still will not go to the proper output fraction due to their aluminum carrier. Other L2 standards exist - and are used in other Signify products - which have fiber-reinforced epoxy carriers instead of aluminum (see Figure 49). Such epoxy-based L2s would go into the copper stream - where their precious and scarce elements can be recovered.

It was therefore investigated whether epoxy-based L2s could be applied in the CoreLine. The main concern was related to heat dissipation, because epoxy is not as good of a thermal conductor as aluminum. A Signify employee performed thermal measurements and simulations to determine the thermal performance of the CoreLine when epoxy-based L2s would be used (see Appendix E). The results indicated that epoxy-based L2s can be used instead of aluminum, while still meeting thermal requirements. Thus, the decision is made to use epoxy-based L2s in the redesigned product.

The following sections provide five possible solutions for securing the L2s within the luminaire, namely:

- Plastic snap fits;
- Integrated metal fasteners;
- Screws and fracture lines;
- Sandwich construction;
- Wire construction.

Plastic snap fits

The L2s could be secured to the backplate through snap fits. The L2s are expected to release from the snap fits in the shredder, especially if the snap fits are applied with some spacing (see Figure 50).

If plastic snap fits are chosen for the redesigned product, multiple methods are available for attaching them to the backplate (see Figure 51). The first is to integrate the snap fits into the backplate, which would require injection moulding. Signify's supply chain does not enable injection moulding plastic parts as large as the backplate. Thus, injection moulding the backplate out of plastic is considered nonviable, which makes integrated snap fits nonviable as well.
Secondly, separately produced snap fits could be glued onto the backplate. This is only acceptable for recyclability if the backplate is made out of metal; then any non-liberated plastic snap fits will serve as fuel in a metal smelter.
Thirdly, the snap fits could be produced as separate components, and be stuck through the backplate. Inserting the L2s would tighten the snap fits. This option would make for a challenging assembly; it is not straightforward to keep the snap fits in place until the L2s are attached.

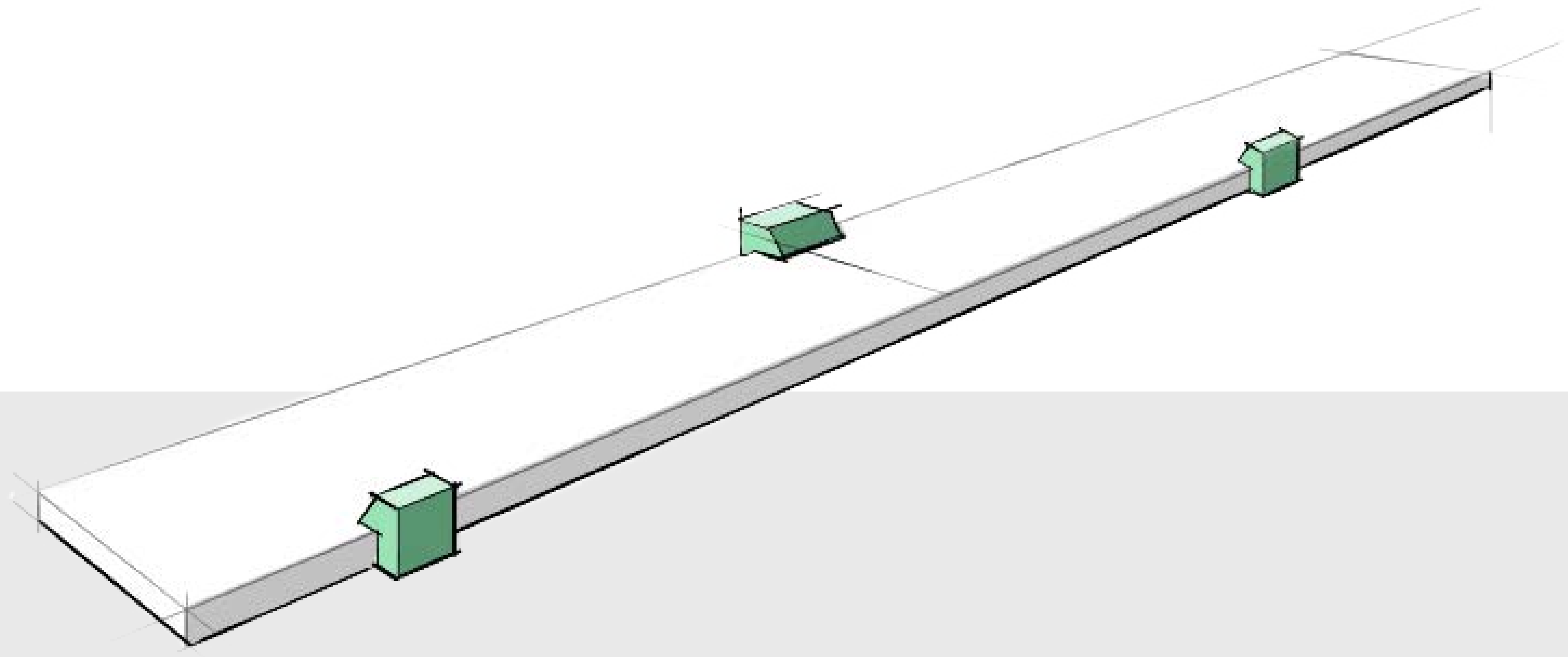


Figure 50. L2 to backplate securement by means of snap fits.

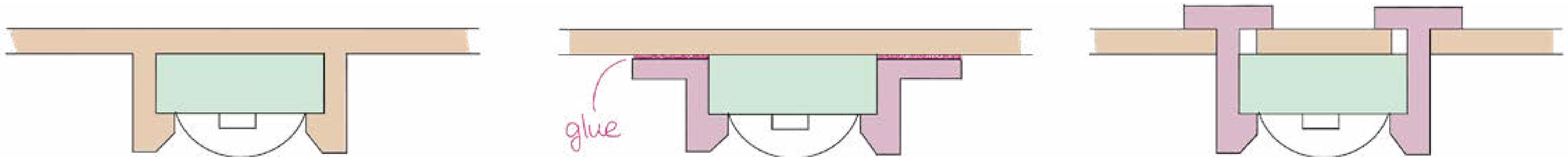


Figure 51. Various methods of attaching snap fits to the backplate. Left: integration into plastic backplate. Middle: glue to steel backplate. Right: stick the snap fits through the backside of the backplate.

Integrated metal fasteners

Cut-outs can be made during the stamping of the steel backplate, which can be bent into fasteners. The initial ideas were to make clicking features (see Figure 52) or rails (see Figure 53). The rails turned out to be impractical within the CoreLine, because the L2s would have to be bent quite a lot to be able to slide them in (see Figure 54). According to a mechanical engineer at Signify, something like the clicking features would be possible, if slight modifications are made.

The cut-outs will have an impact on the look and feel of the product. This will not be visible from the room-side, but will be visible to installers.

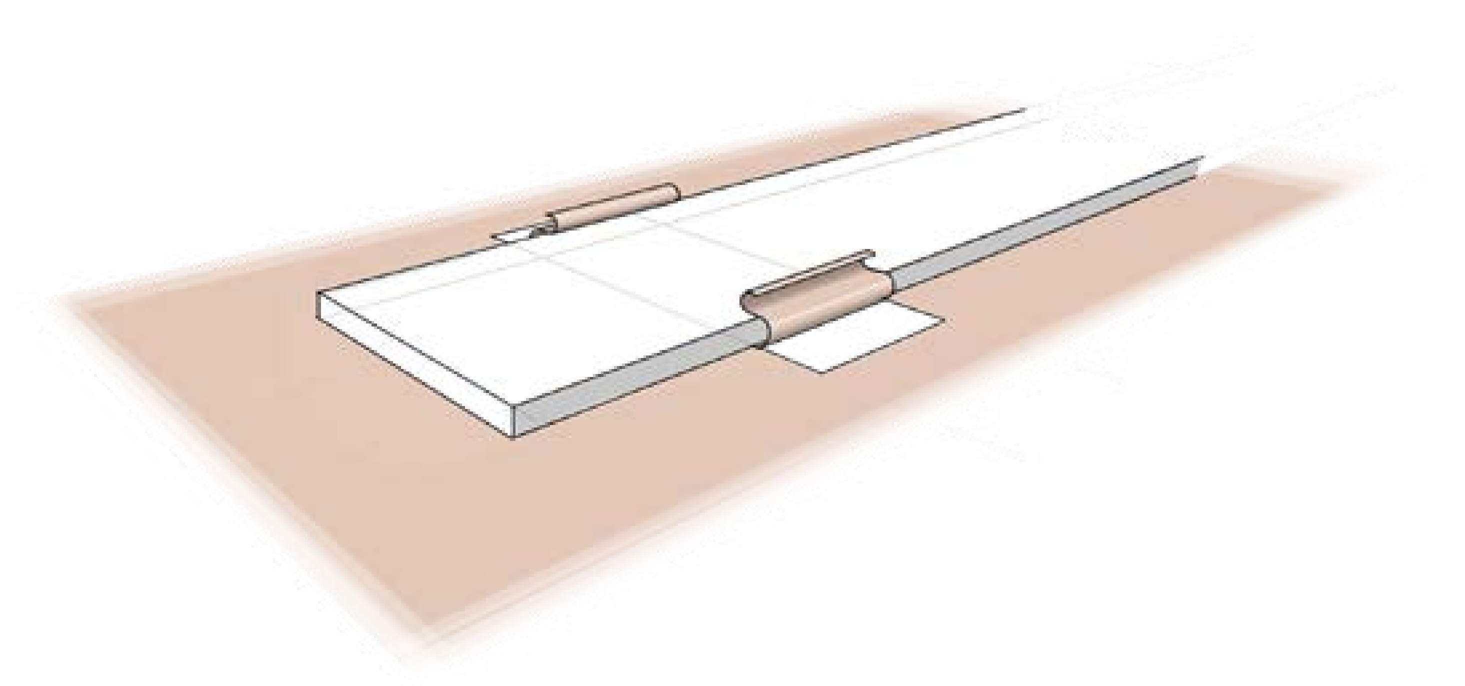


Figure 52. L2 securement by means of clicking features, integrated into a steel backplate.

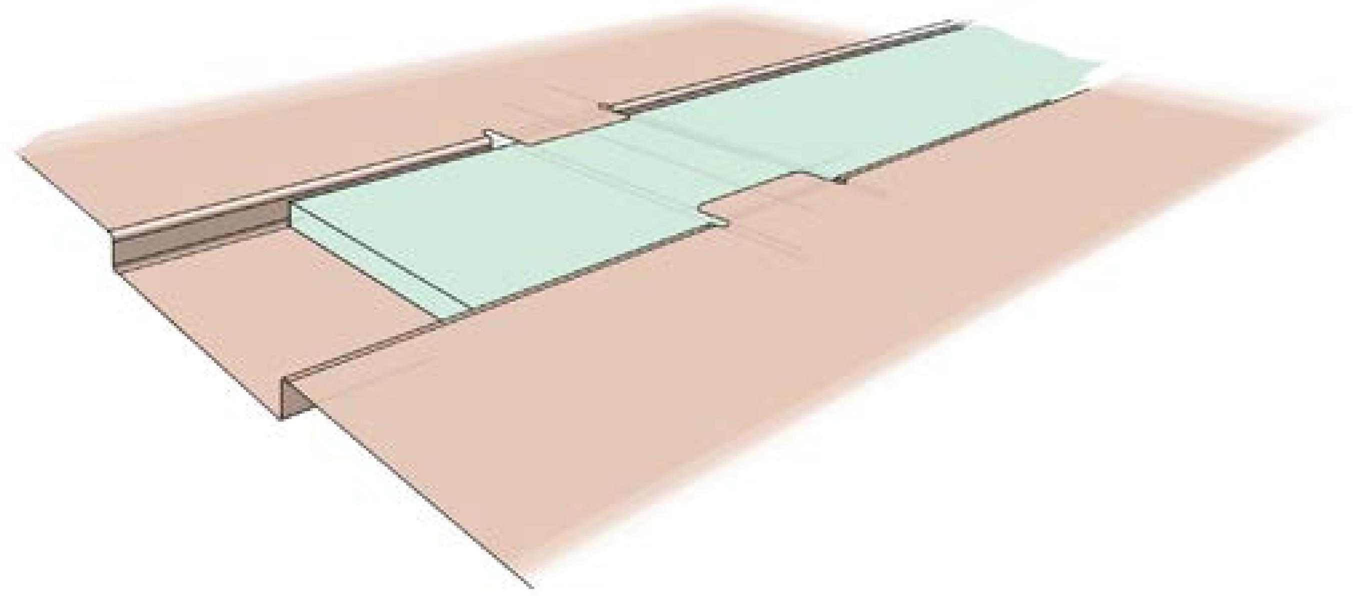


Figure 53. L2 securement by means of sliding features, integrated into a steel backplate.

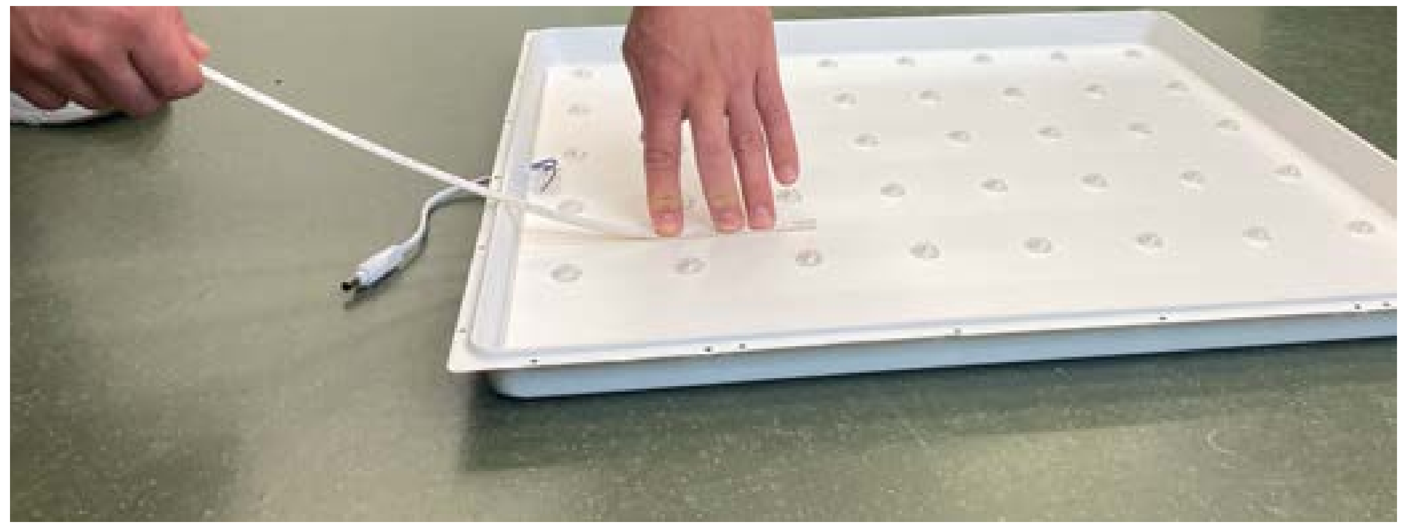


Figure 54. The L2s have to be bent quite severely if they are to be slided into the backplate.

Screws and fracture lines

The L2s could be screwed onto the backplate, if fracture lines are applied that ensure complete liberation during shredding (see Figure 55). In this scenario, the backplate should be made out of steel so that there is no recyclability problem when the screws do not liberate from the backplate.

The ends of the screws will show on the backside of the backplate.

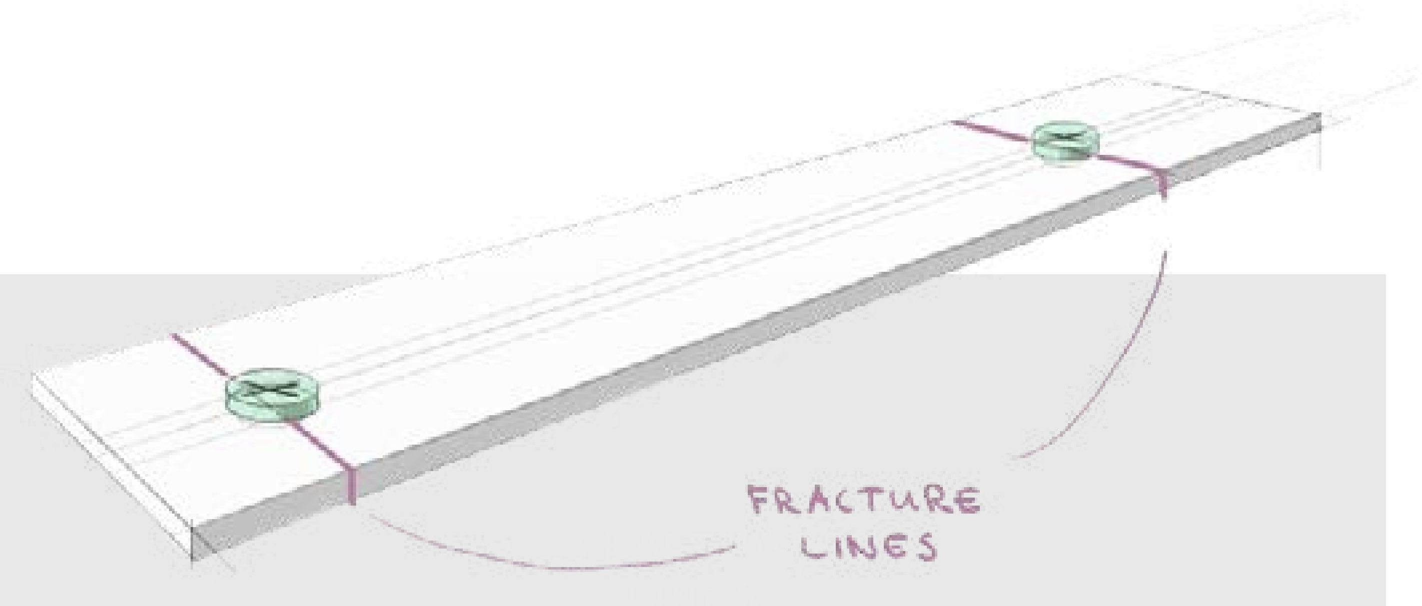


Figure 55. L2 securement via screws and fracture lines in the L2s.

Sandwich construction

The L2s could be secured by ‘sandwiching’ them in between the backplate and the reflector (see Figure 56). The backplate should then have indents to accomodate the L2s.

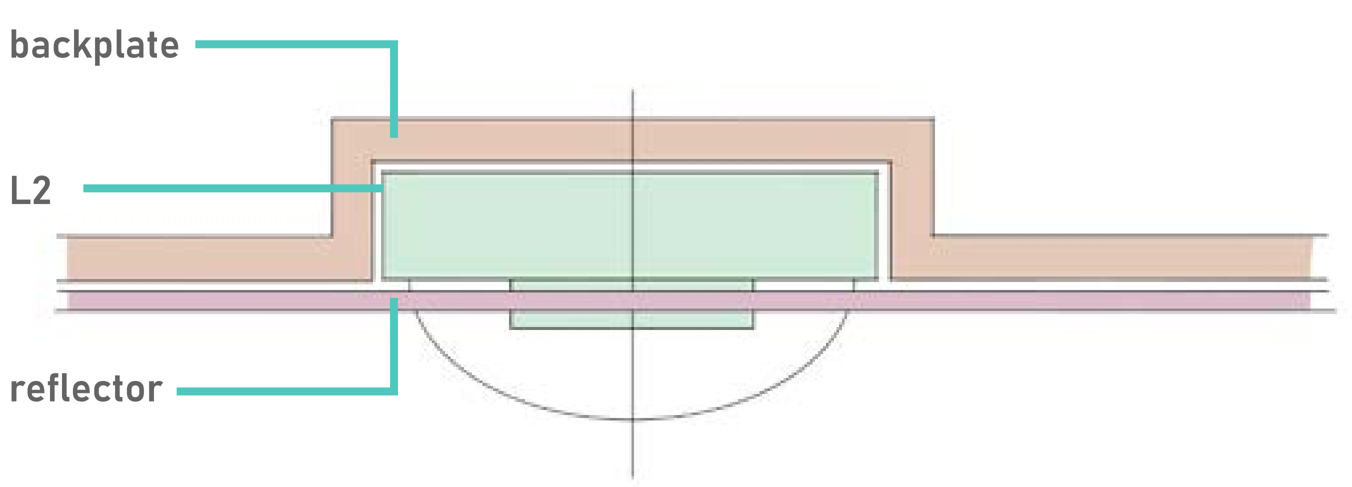


Figure 56. Principle of sandwiching the L2s between the backplate and reflector.

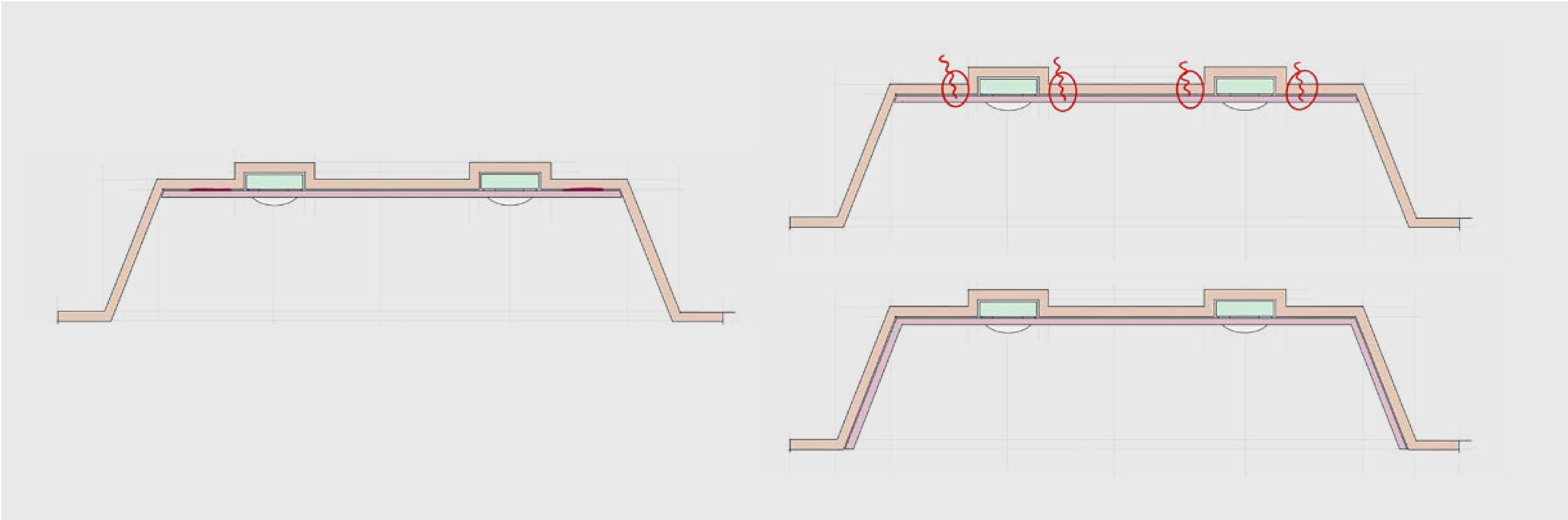


Figure 57. Three ways to implement the sandwich construction. Left: with glue. Top right: via ultrasonic welding. Bottom right: making the reflector self supportive.

Multiple versions of such a sandwich construction were considered, among which the following (see Figure 57).
Firstly, the reflector could be glued to the backplate, like it is in the current design. This option was prototyped (see Figure 58). While the L2s did not fall out of the prototype, they were not secured tightly enough to the backplate to guarantee proper optical performance. This approach therefore seems unsuitable.

Another option is to increase the reflector’s thickness and give it a shape similar to the backplate so that it can support itself.

Lastly, the reflector could be attached to the backplate via ultrasonic welding. This would require the backplate to be made out of the same plastic as the reflector, for recyclability. The L2s will be most tightly secured if the reflector is welded to the backplate along both long sides of the L2.

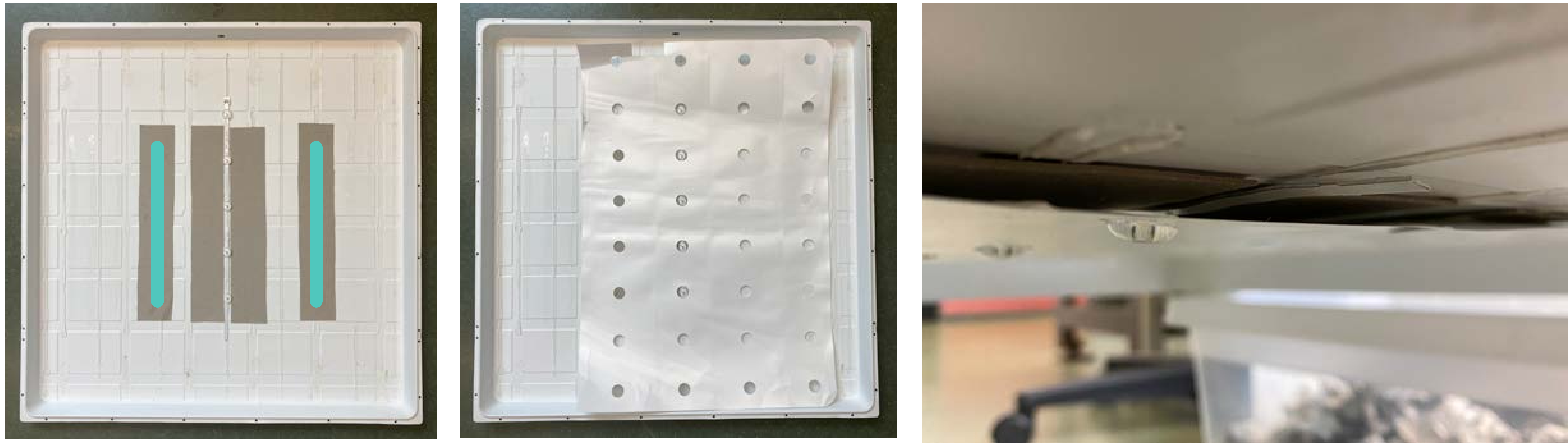


Figure 58. Prototyping the glue variant of the sandwich construction. Left: pieces of cardboard are glued to the current steel backplate to create a surface level to the L2s. The L2s are placed in a resulting gutter; they are not glued. Middle: the reflector is glued to the cardboard (along the lines indicated in blue on the left photo). Right: the glued sandwich construction does not fixate the L2s tightly enough to the backplate.

Wire construction

A construction could be made from steel wires and gaps in the backplate which would push the L2s against the backplate (see Figure 59). The gaps and protruding wires would change the appearance of the back of the product (see Figure 60).

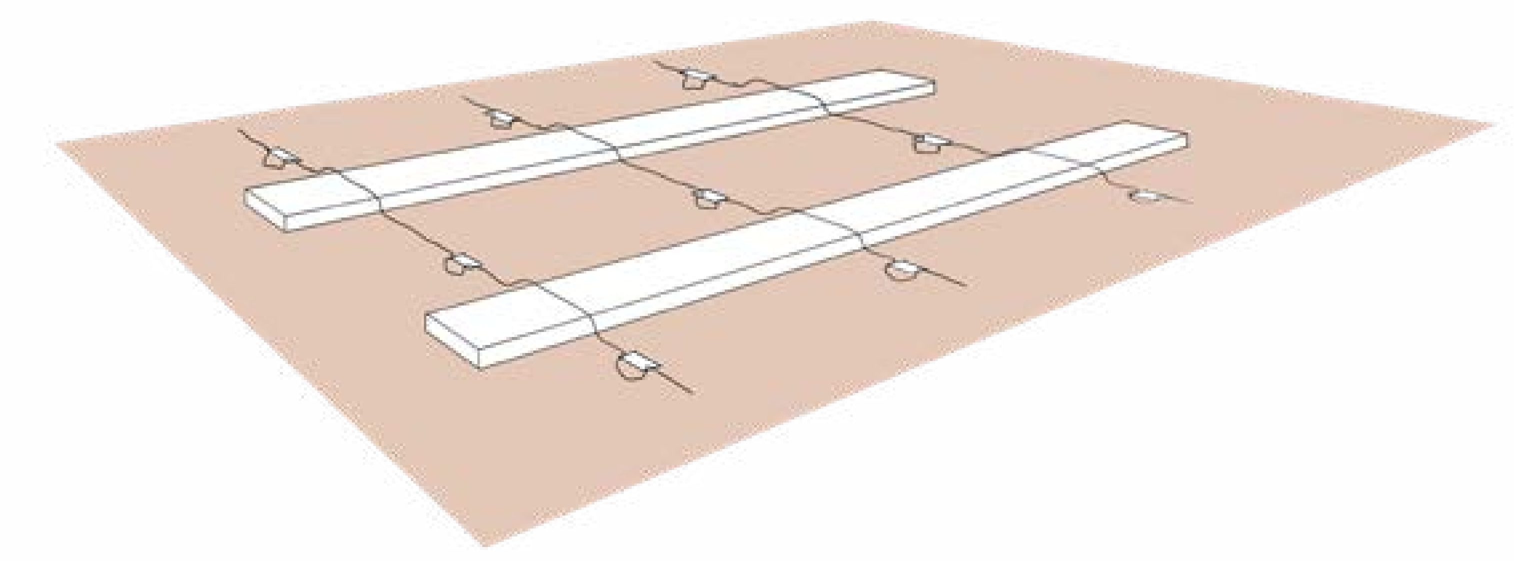


Figure 59. Wire construction to secure the L2s to the backplate.

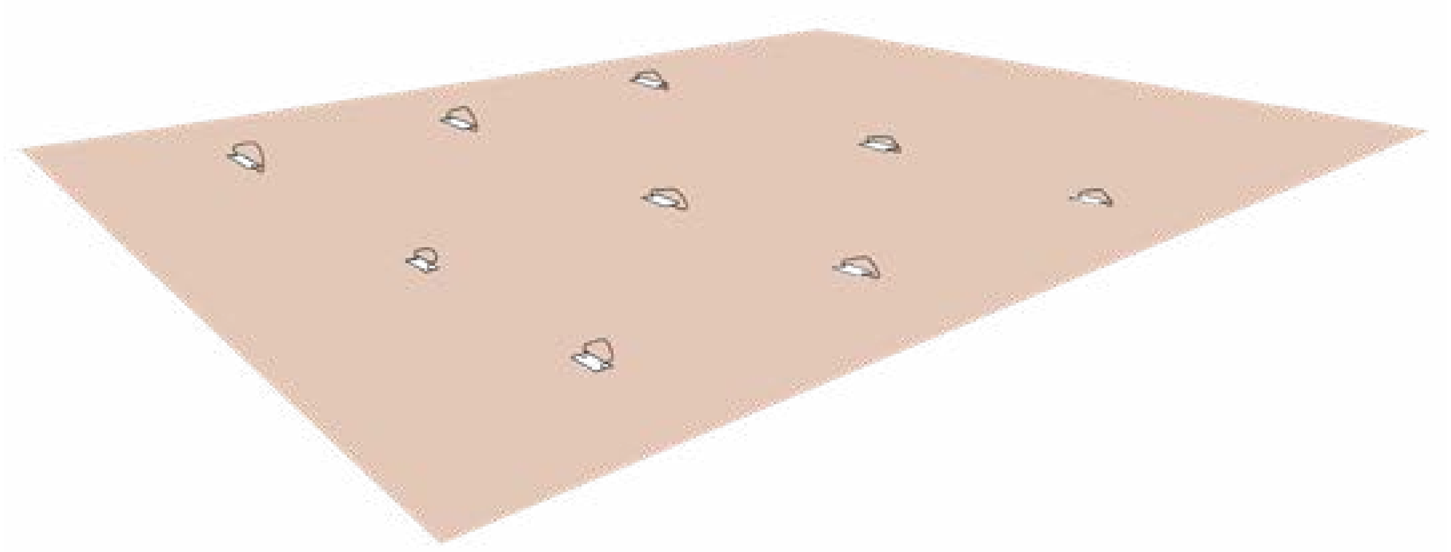


Figure 60. The appearance of the back of the product changes due to the wire construction.

4.3.2 Frame to backplate connection

In the current CoreLine luminaire, the steel backplate is attached to the aluminum frame via screws. This connection indirectly also keeps the beam shaping and diffuser in place (see Figure 6). Alternative connections are explored, which would prevent the mixed fragments of steel screws in aluminum (see Figure 61).

The proposed alternatives are:

- Plastic fasteners;
- Steel frame;
- Snap fits / clips;
- Sliding;
- Lunch box;
- Folding;
- Wire snap.

Figure 61. Mixed fragment of aluminum frame and steel screw.

Plastic fasteners

One potential solution is to replace the steel screws by plastic fasteners. Any non-liberated fasteners would then result in a mixed fragment of aluminum and plastic. Such a fragment would enter the aluminum fraction, where the plastic would serve as fuel. The loss of plastic means this solution is not completely circular, but it is an improvement compared to the current situation.

Two types of plastic fasteners have been considered: screws and rivets. As a first trial, plastic screws were inserted into the current aluminum frame. The plastic screws could not get a strong hold onto the frame and fell out as soon as the product was turned upside down (see Figure 62). The steel screws are able to form a strong connection with the frame, because they are self-tapping and have quite a wide thread (see Figure 63a). In an attempt to make the plastic screws work, the screw holes in the frame were threaded. Due to the frame's small wall thickness, there was little material to thread and half of the plastic screws still fell out once the product was flipped. Thus, if plastic screws are to be used in the product, the frame profile must be changed to include threading. Alternatively, it could be investigated if plastic self-tapping screws are strong enough to replace the current steel ones (see Figure 63c).

Another option is to use plastic rivets (see Figure 63d). These could potentially be used without changing the current frame. On the downside, they are hard to disassemble and thus not suitable for repair scenarios.

Figure 62. Half of the plastic screws fell out of the backplate when turned upside down.

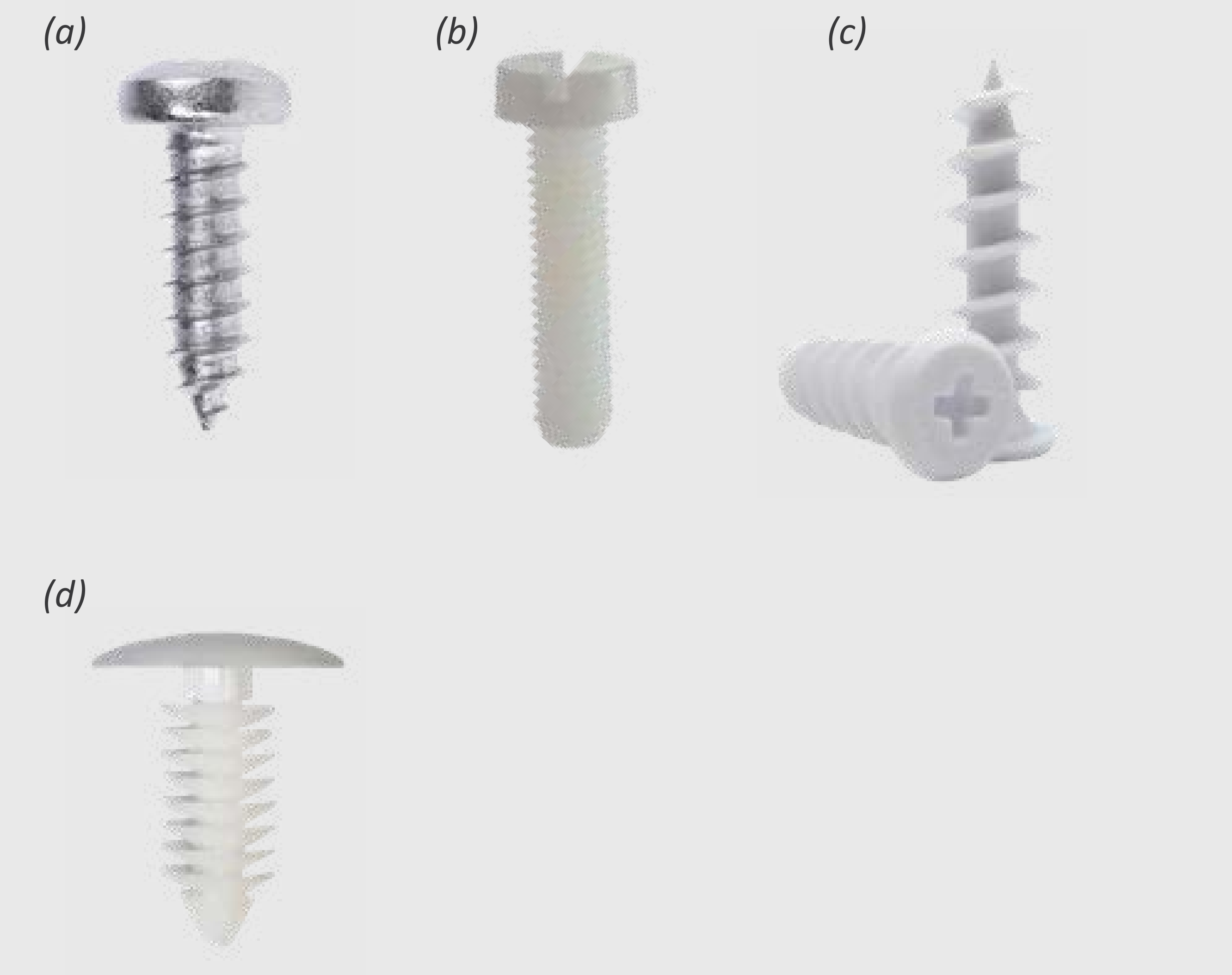


Figure 63. (a) self-tapping steel screw (b) nylon screw which was used for the prototype (c) self-tapping plastic screw (d) plastic rivet.

Steel frame

If the frame were to be made out of steel, then it would not be a problem for the screws to remain stuck during shredding. The frame would then have to be redesigned for roll forming instead of extrusion.

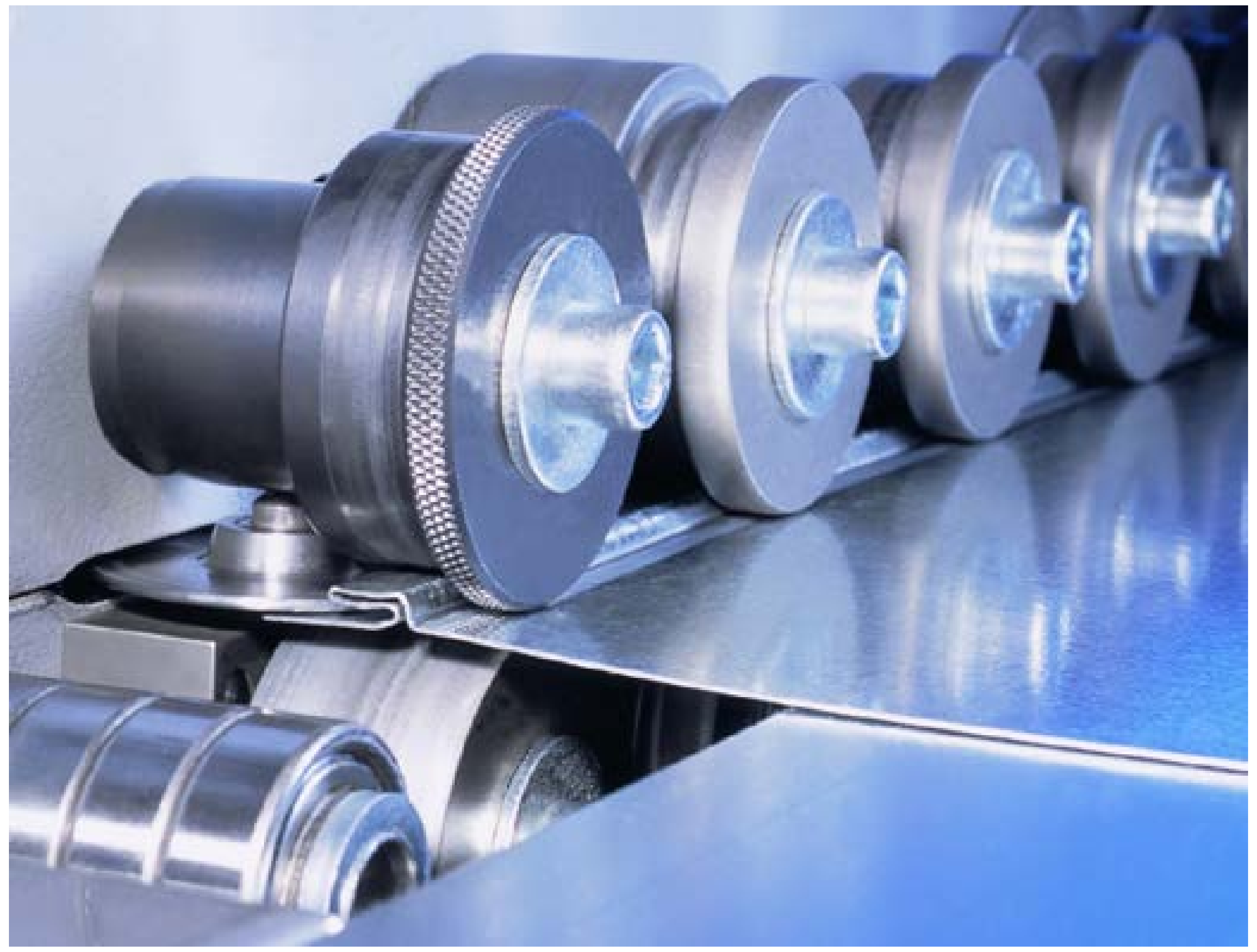


Figure 64. Roll forming.

Snap fits / clips

Another possibility is to apply snap fits or clip features to secure the backplate to the frame. Another luminaire in the Signify portfolio already contains such a connection, see Figure 66. To test the shredding behaviour of this connection, the product was entered into the shredder at the WEEE recycler. All 8 click connections that were present in the product got liberated during shredding, indicating that this is a suitable connection type.

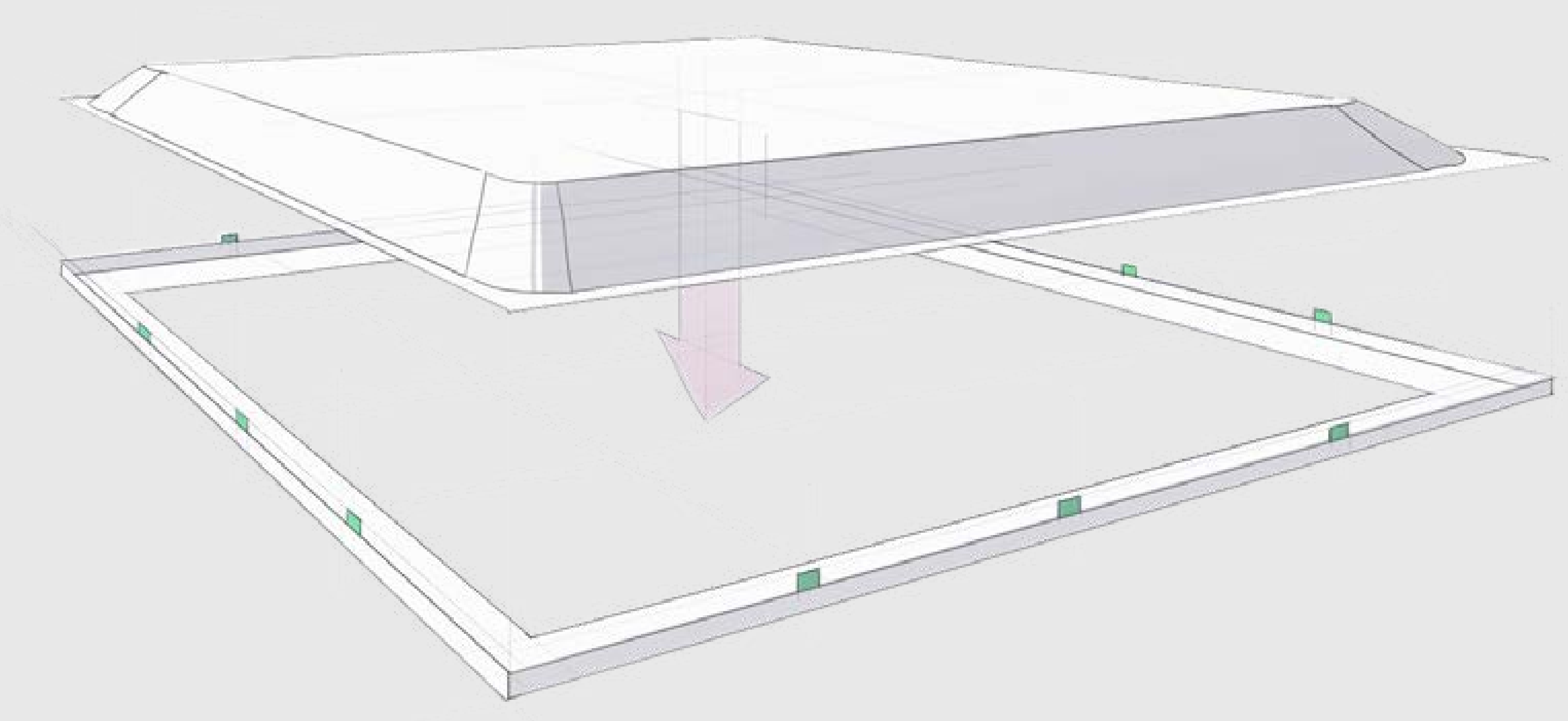


Figure 65. Clicking of the backplate to the frame.

Figure 66. Existing Signify luminaire with clipping features.

Sliding

The backplate and frame could be connected through a sliding mechanism. The frame would be made out of 4 edges, which can be attached to one another through clicking features. They would contain a gutter for the backplate to slide into (see Figure 67).
An installation product is available for the CoreLine which actually demonstrates such a sliding principle. Thus, a tried and tested embodiment for clicking the four edges together already exists.
Since the edge of the backplate which would be clamped in the frame is quite narrow and thin, it was uncertain if this construction would be secure enough. A prototype was built by a Signify employee to investigate the matter (see Figure 68). It consists of three aluminum beams with gutters to insert the backplate. The backplate was kept firmly in place, did not sag and did not get loose during strong shaking of the prototype. This confirms that a sliding mechanism - if embodied well - could work.

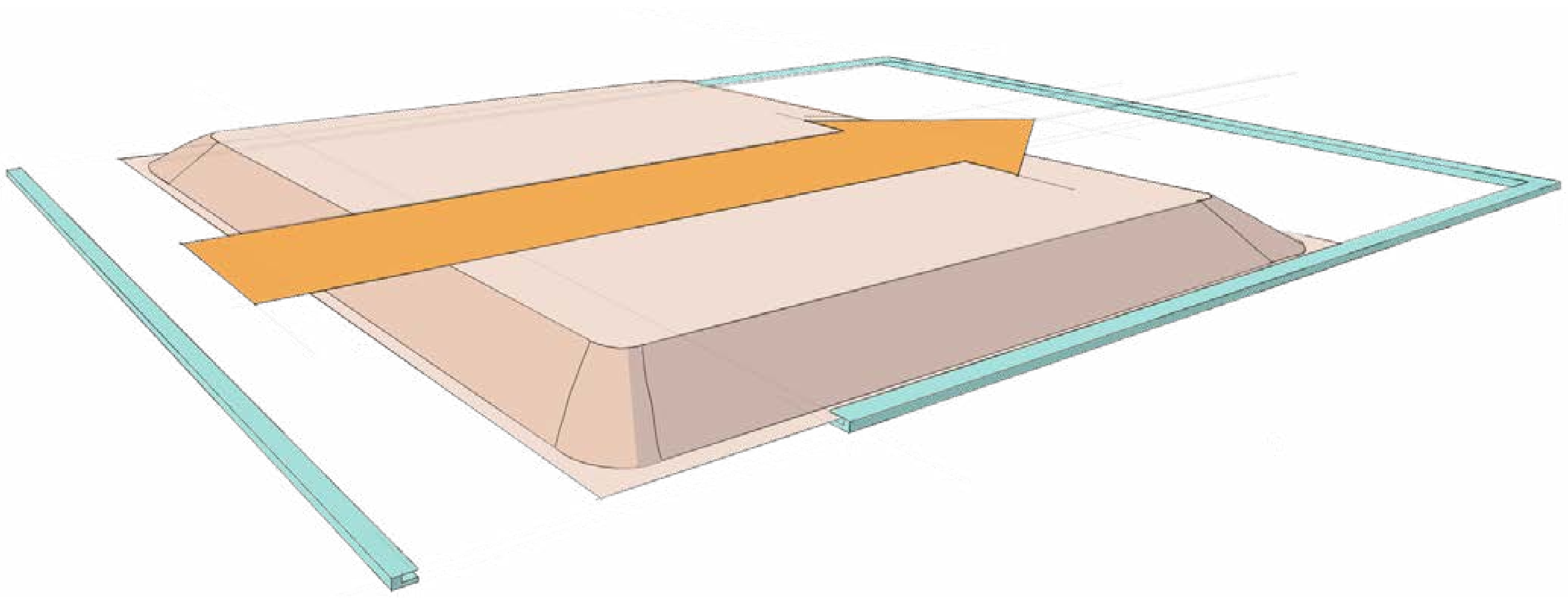


Figure 67. Sliding the backplate into the frame.

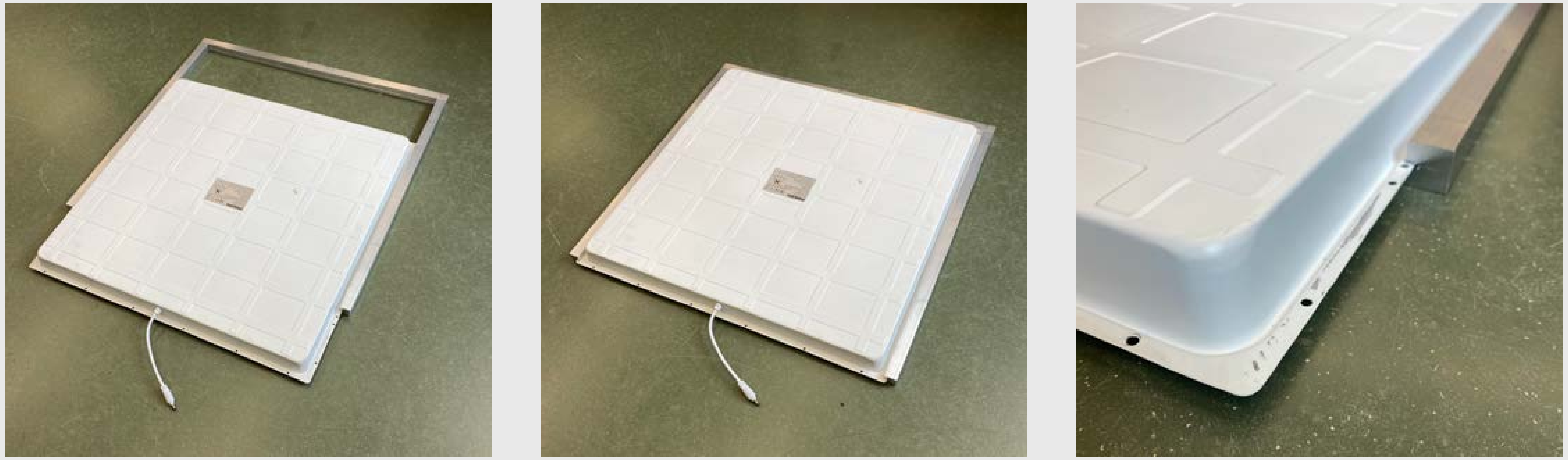


Figure 68. Sliding prototype.

Lunch box

Alternatively, an elastic wire can be used to connect the two parts, similar to how a lunch box and its lid are held together by an elastic band. However, elastic materials do not get recycled in the WEEE recycling process, so it would not be ideal from a circularity point of view. Another potential downside of this solution is the mechanical performance throughout the product lifetime; as time passes, the elastic will stretch out and lose its strength. Thus, if this direction is pursued, it should be investigated if and how this construction will remain reliable throughout the product's complete use phase.

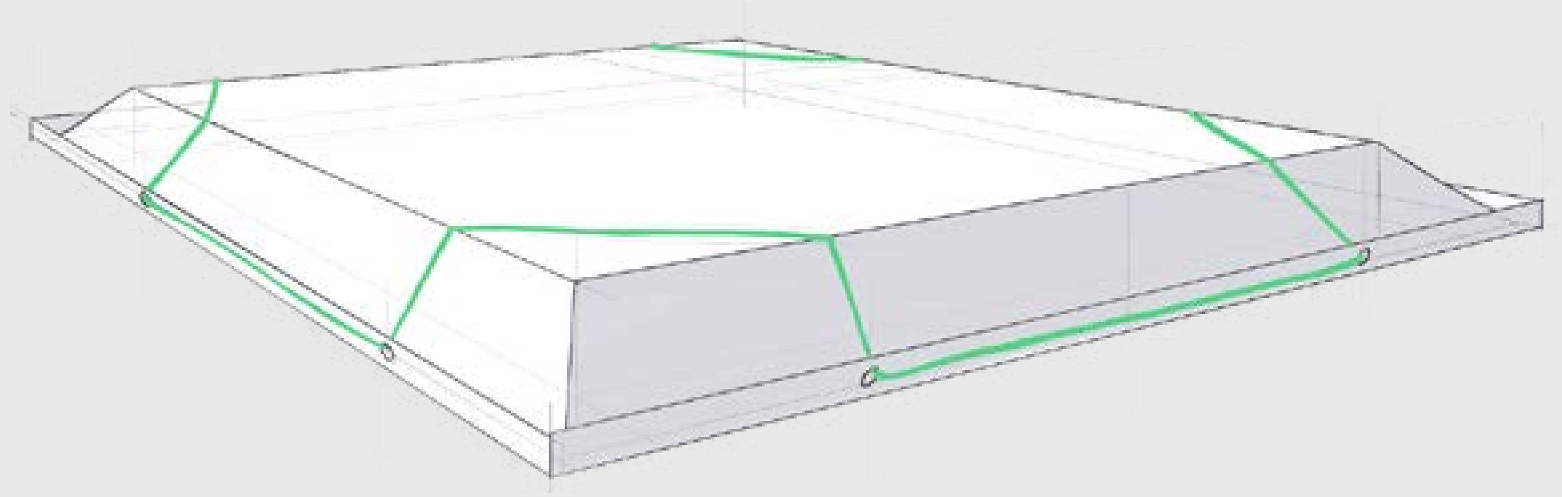


Figure 69. Frame to backplate securement via an elastic wire.

Folding

The frame could be redesigned to include flaps, which can be folded around the backplate during assembly (see Figure 70). Evidently, this solution would be unsuitable for repair scenarios.

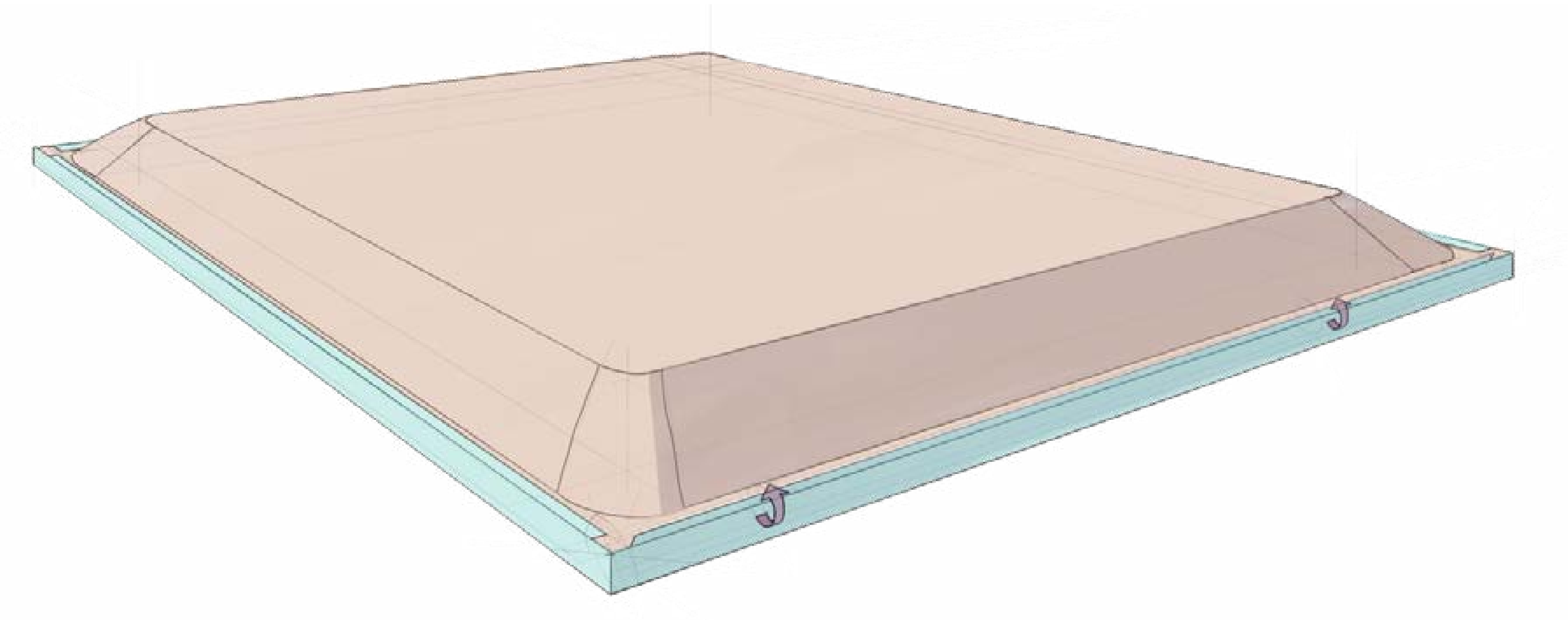


Figure 70. Frame to backplate securement via folding of the frame.

Wire snap

This solution was offered by a Signify employee and is inspired by an existing patent owned by Signify. It involves a wire going all around the product and grabbing features on both the frame and the backplate (see Figure 71). This construction prevents the backplate from moving upward, and the frame from moving downward. When the wire breaks during shredding, it will fall off and the backplate and frame will be liberated from each other. It may be challenging to make this solution suitable for repair. The wire has to be strong enough to hold the product together, but a user should be able to open and close it.

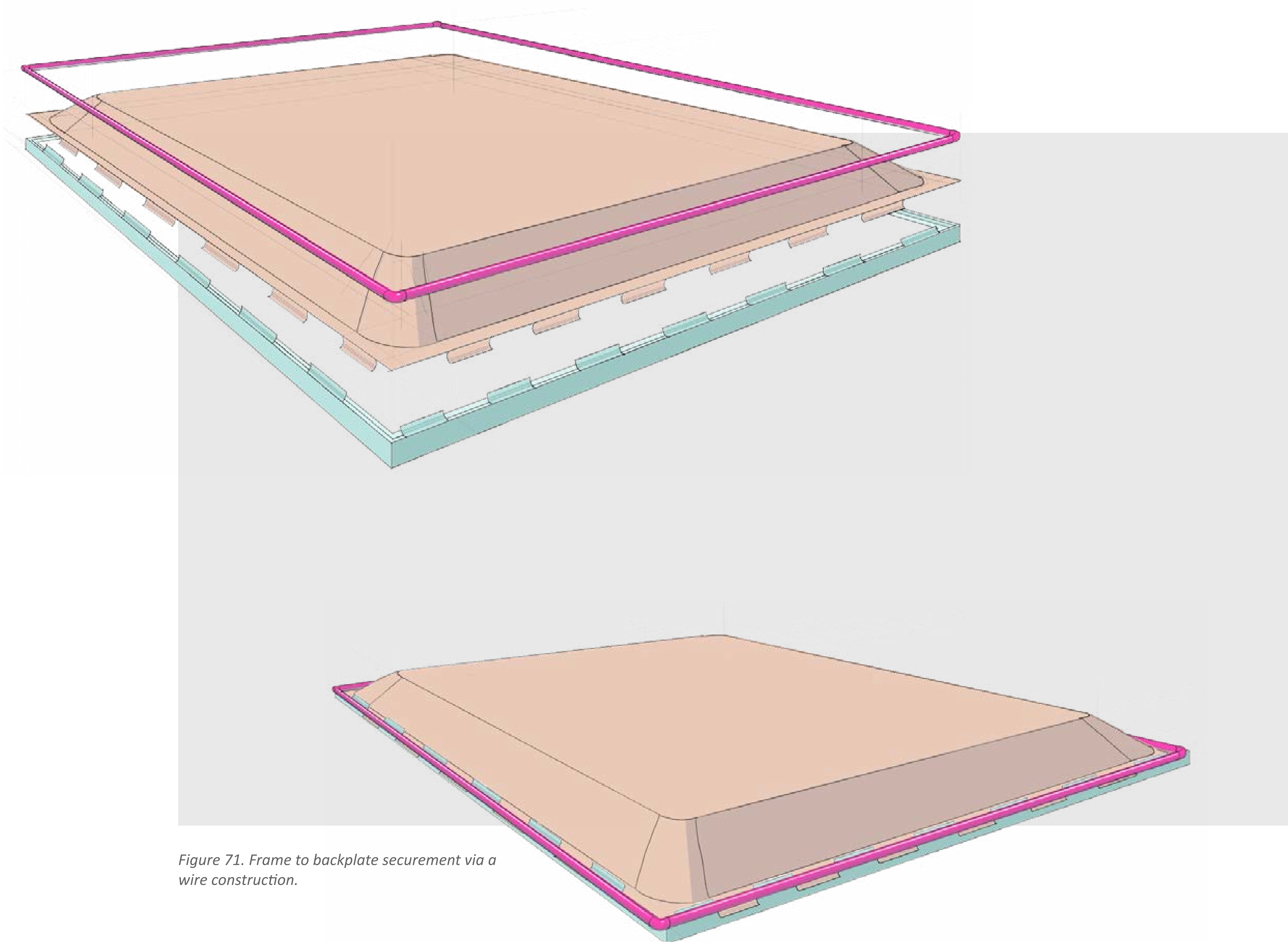


Figure 71. Frame to backplate securement via a wire construction.

4.3.3 Driver securement

At present, the luminaire's driver comes with a sticker to secure it to the panel after installation. In the redesigned product, this requirement should be met in a way that avoids mixed fragments of PC and sticker (see Figure 73).

The securement of the driver is a safety requirement; it should be possible to pull on the power supply cable with a 30 N force for the duration of 1 minute, without disturbing the cable to panel connection (see Figure 72).

As an additional challenge, the CoreLine panel is sold in combination with a range of different drivers, which have different dimensions. It is preferred that solutions for the driver securement do not require all drivers to be redesigned.

The next sections describe four potential solutions for the driver securement:

- Tie wrap;
- Cage;
- Partial box;
- Cable ring.

Figure 73. Mixed fragments of PC and rubber sticker.

Figure 72. Demonstration of the driver pull test. The cable to panel connection circled in blue may not be disturbed.

Tie wrap

An easy solution would be to secure the driver to the backplate with a tie wrap. This idea was prototyped, see Figure 74. Testing the prototype showed that it was very easy to pull out the driver from under the tie wrap. Thus, the safety requirement would not be met.

The tie wrap solution could still work, if an indent is created in the driver housing (see Figure 75). This would mean that all different driver housings need to be changed, which comes with investment costs. Furthermore, attaching the tie wrap via holes in the backplate is not ideal for repair, because it will be difficult to guide a new tie wrap through these holes after the luminaire is assembled. For this reason, eyelets should be provided on the backplate.

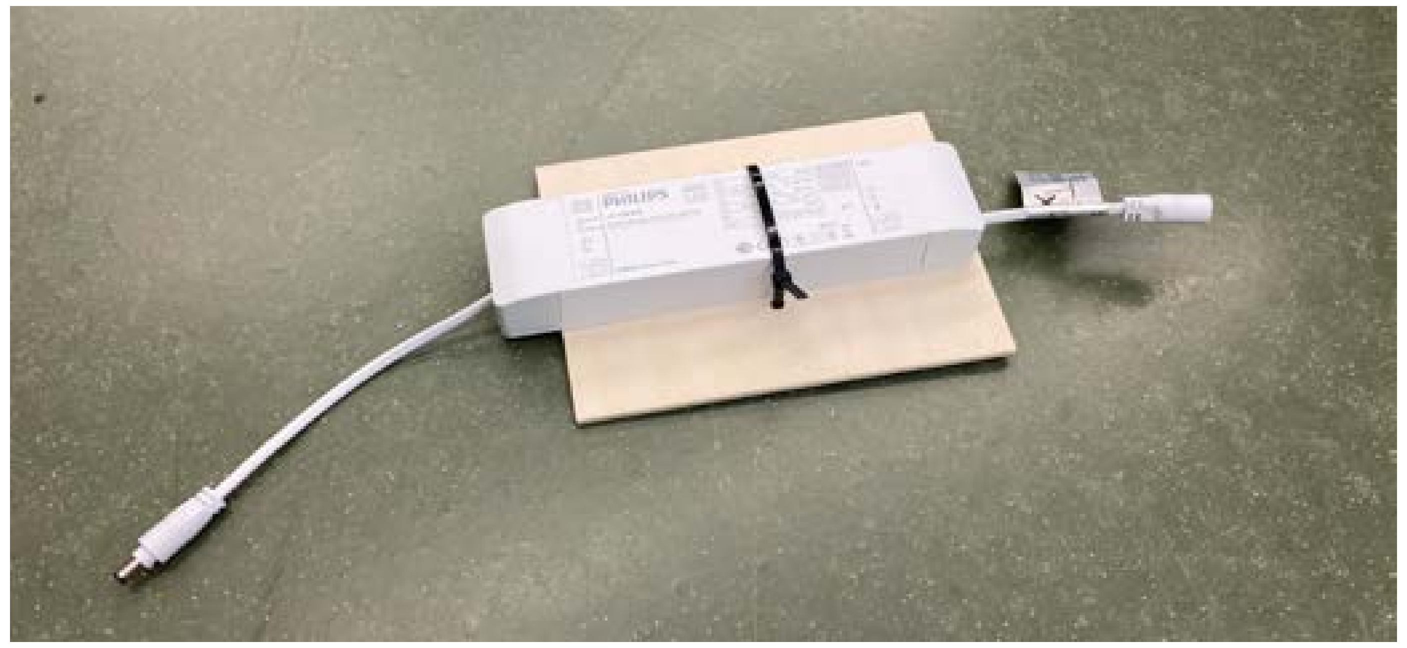


Figure 74. Prototyping the driver to backplate securement by means of a tie wrap.

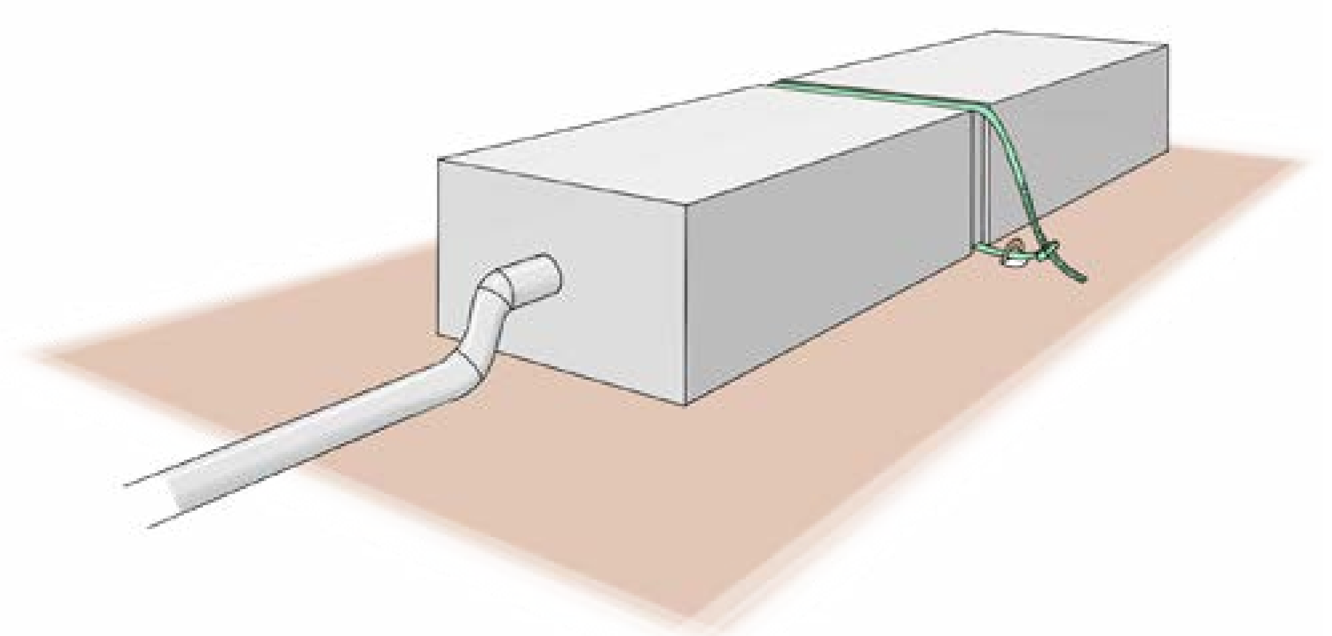


Figure 75. Driver to backplate securement by means of a tie wrap and an indent in the driver housing.

Cage

A solution that does not require any changes to the driver design, is to place a cage over the driver. A cheap option is to create a component similar to six-pack rings which are used for beverage cans (see Figure 76). If hooks are applied to the backplate according to the dimensions of the biggest driver type, and the cage has holes at different distances, then this solution can work for all driver sizes (see Figure 77).

Figure 76. Six-pack rings used for beverage cans.

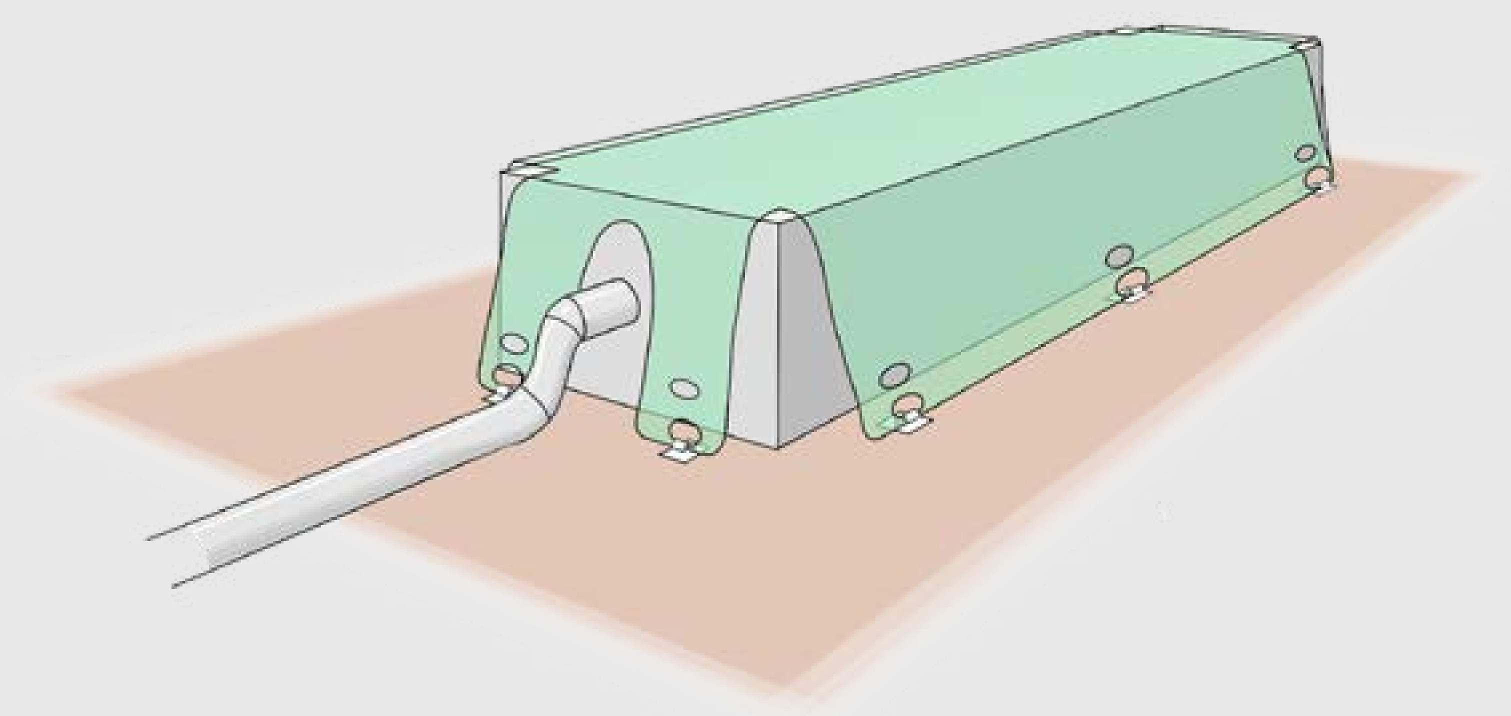


Figure 77. Cage construction to secure the driver to the backplate.

Partial box

This solution consists of two components which constrain the driver on both of its ends. See Figure 78. They should be dimensioned to be able to fit the largest driver type. Some clicking method should be designed to secure the components to the backplate.

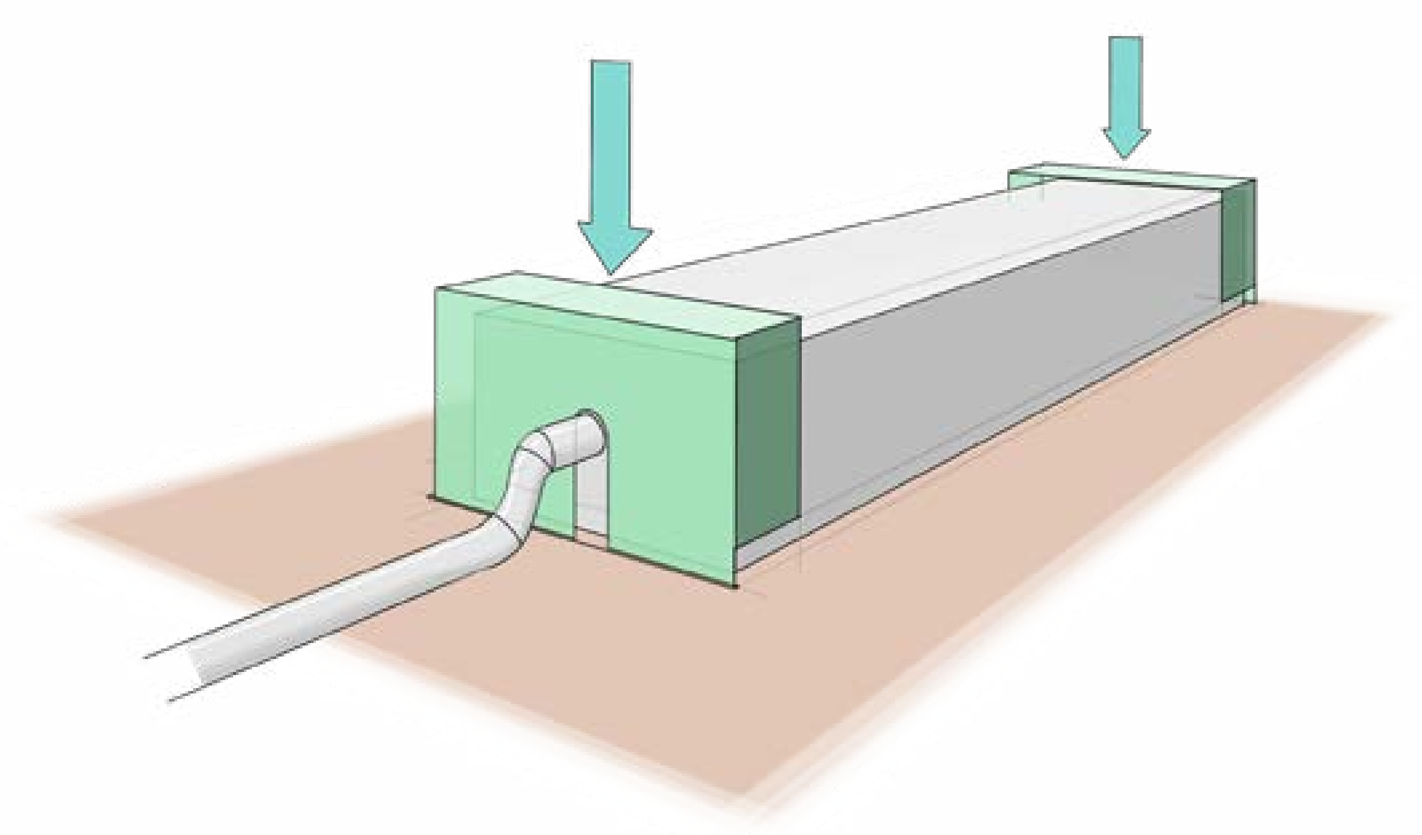


Figure 78. Partial box construction to secure the driver to the backplate.

Cable ring

This solution features a ring over the driver cable. When the cable is pulled, the driver will be blocked by the ring. As a result, no tension can occur in the cable which goes into the panel, thereby satisfying the safety requirement. The ring should be small enough that the smallest driver cannot pass through it.

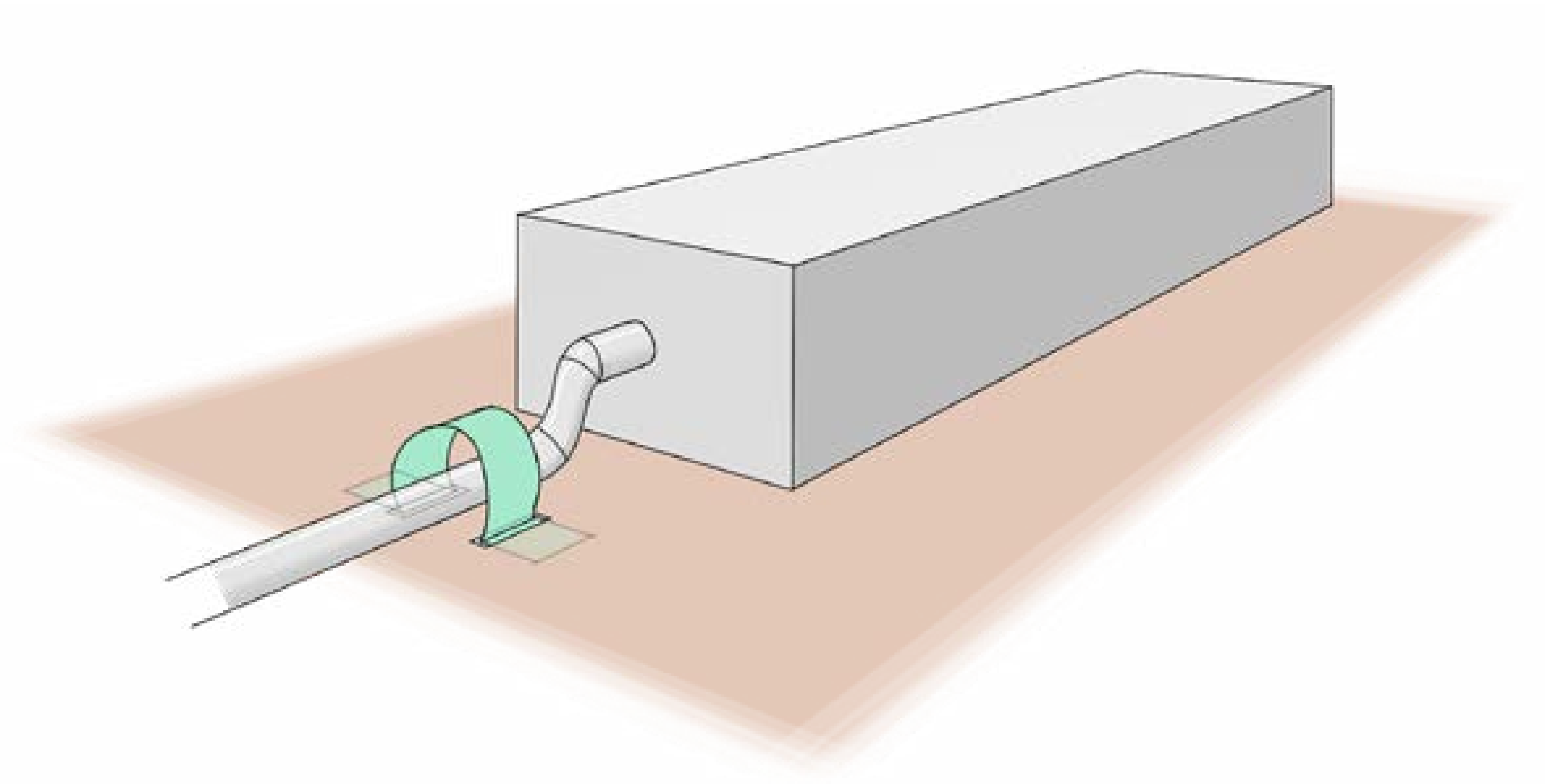


Figure 79. Cable ring to secure the driver to the backplate.

4.4 Backplate Material

During the process of exploring alternative component connections, the question arose whether there might be benefits and drawbacks to making the backplate out of plastic rather than steel. Three main considerations came into play, namely thermal performance, GWP of the raw material supply and material behaviour during shredding.

As plastics are poorer thermal conductors than steel, switching to a plastic backplate will influence the luminaire's thermal performance. Simulations were done to determine if the product would heat up too much, if the backplate were made out of PMMA (see Appendix E). The simulations showed that temperatures remain well below the required maximum, also in combination with epoxy-based L2s. Using different types of plastic would not change the outcomes significantly, according to the thermal expert who ran the simulations. Hence, from a thermal perspective, it would be alright to opt for a plastic backplate.

According to the LCA data as presented in chapter 2.1.2, the steel backplate makes up 23% of the A1 GWP of the current CoreLine luminaire. A quick estimation of switching to a plastic backplate indicates that there could be a reduction of CO2e (see Figure 80). However, the size of the reduction depends heavily on the type of plastic used. If PET is chosen, GWP could be reduced by 2 kg CO2-eq. If PS is chosen, the reduction is less impressive: roughly 0.5 kg.

Another concern was the behaviour of steel versus plastic in the shredder. The shredding experiments demonstrated that the steel backplate was quite prone to folding (see Figure 81). This triggered a question: will the L2s get trapped in folded steel even when they are not glued? If so, this would be a strong argument to move away from a steel backplate.
Prototypes were created in order to answer this question (see Figure 82). Two CoreLines were disassembled, L2s were attached to the steel backplate with tape, and the product was reassembled. The goal of this construction was to position the L2s against the backplate without securing them along their full length. One prototype contained the current aluminum L2s and the other contained epoxy strips, which are recommended to be used in the redesigned product.
The prototypes were fed into the shredder and the outputs were analysed. All folded steel fragments were unfolded to determine if they held L2 fragments. For both prototypes, there were no mixed fragments of steel and L2. This suggests that the steel backplate will not wrap around the L2s when these are not glued, and from this perspective there is no problem with keeping the backplate steel.

In conclusion, thermal performance and shredding behaviour do not give any preference between a steel or plastic backplate. Switching to a plastic backplate may reduce the luminaire's GWP, but the magnitude of the reduction depends on the type of plastic selected.

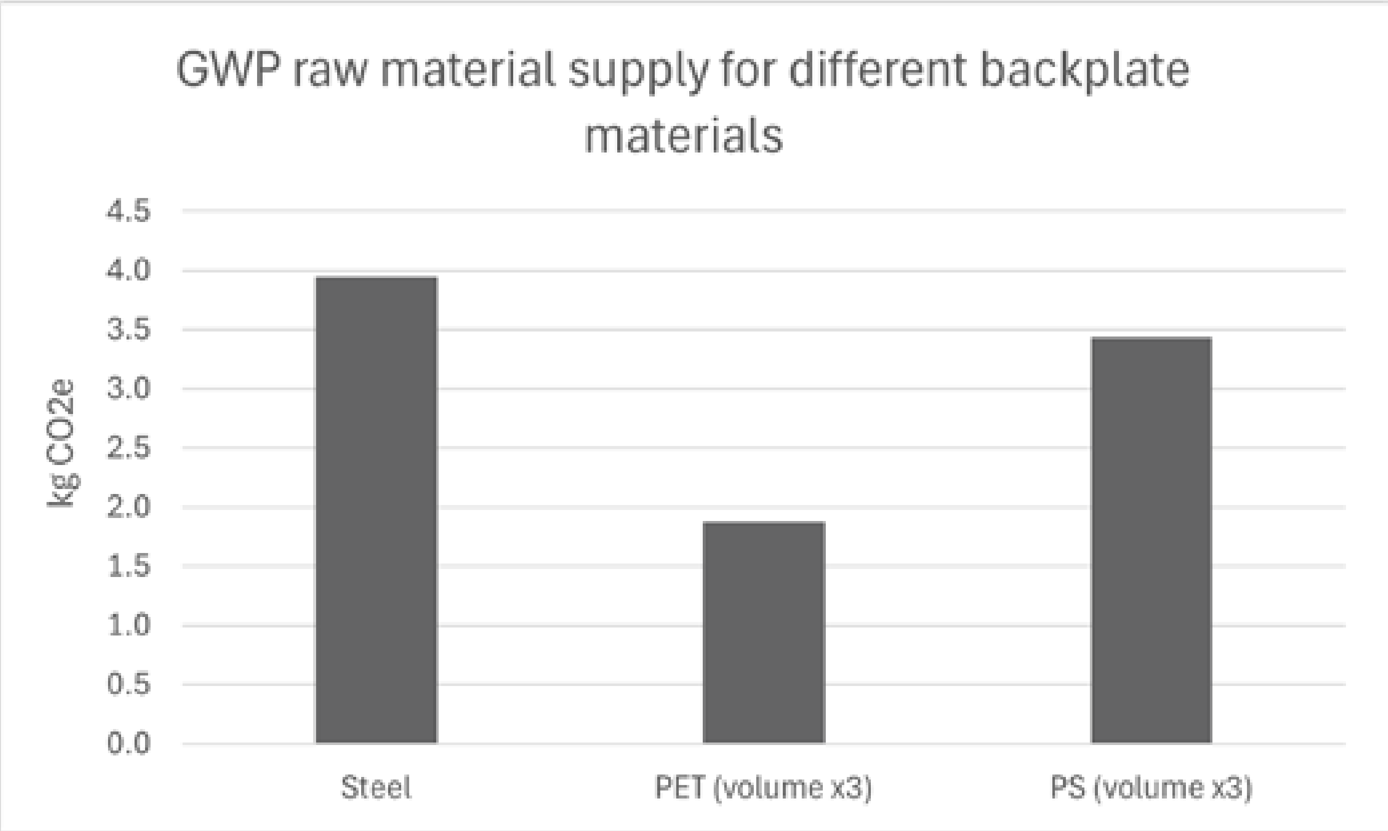


Figure 80. GWP of different backplate materials, taking into account a larger volume if the backplate is made out of plastic.

Figure 81. Steel backplate is prone to folding during shredding.

Figure 82. Prototypes to test if L2s will get wrapped up in steel backplate when they are not glued. Left: aluminum L2s. Right: epoxy L2s.

4.5 Concept Development

4.5.1 Morphological chart

All the proposed solutions are summarized in the morphological chart in Figure 83. The next step was to combine solutions into one concept.

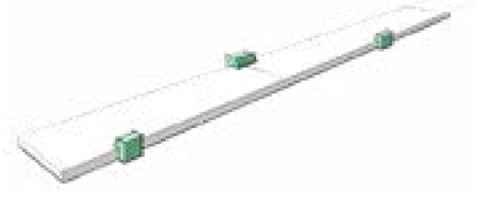
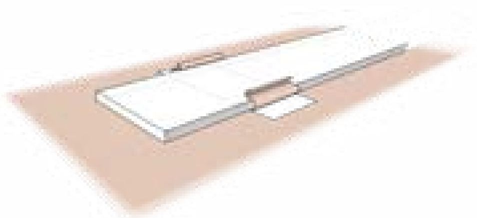
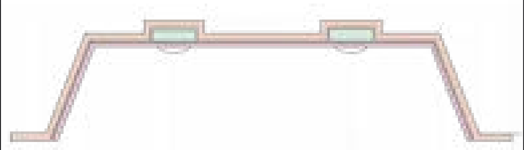
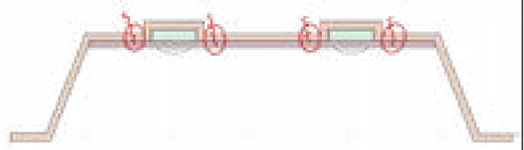
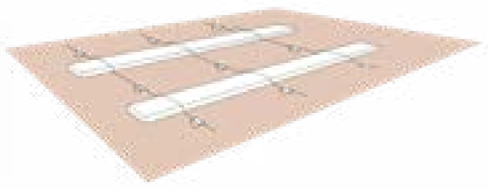
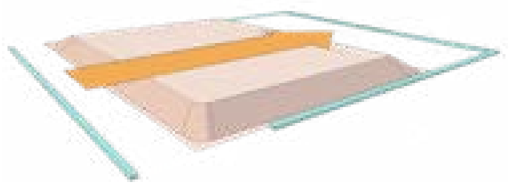
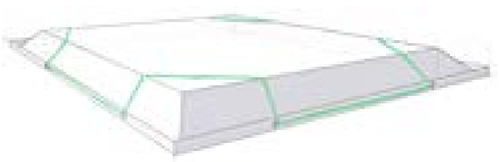
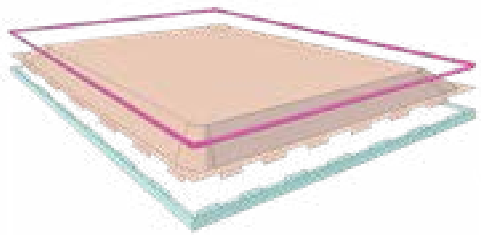
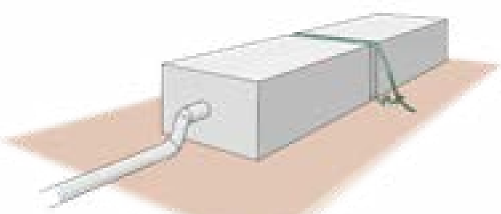
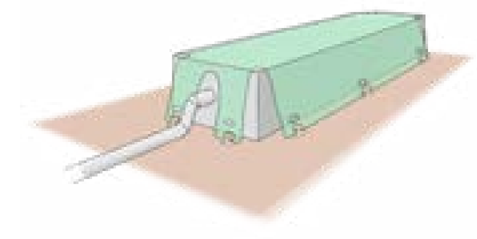
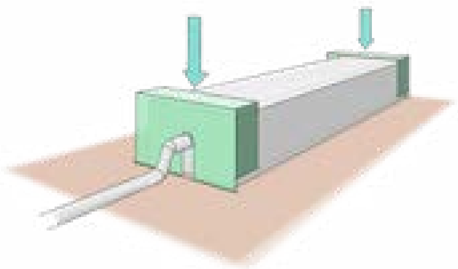
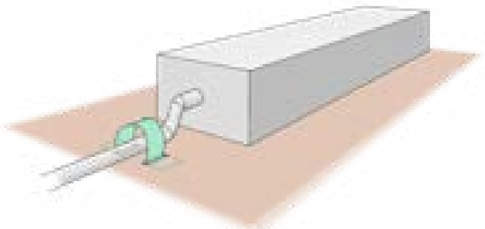
	Function	While avoiding	A	B	C	D	E	F	G
1	L2s to backplate		Plastic snap fits 	Integrated metal fasteners 	Screws + fracture lines 	Self supporting sand-wich 	Ultrasonic sandwich 	Wire traps 	
2	Frame to backplate		Plastic fasteners 	Clicking 	Slide and click 	Lunch box 	Folding 	Steel frame 	Wire snap 
3	Driver to backplate		Indent and tie wrap 	Cage 	Partial box 	Cable ring 			
4	Backplate material		Steel backplate (as-is) 	Plastic backplate 					

Figure 83. Morphological chart, listing all collected solutions.

4.5.2 Solution compatability

Typically, once a morphological chart is populated with solutions, one creates several concepts by combining compatible solutions. The concepts can then be ranked and compared. In the current design process, it was noted that most solutions are compatible with one another (see Figure 84). Consequently, choosing which solutions to combine becomes somewhat arbitrary, and there exists a risk that the most optimal combination of solutions is overlooked. For this reason, the decision was made to create a ranking on a solution level, rather than on a concept level. The highest scoring combination of compatible solutions are then combined into a concept.

The red lines shown in Figure 84 represent incompatible combinations of solutions. The incompatibility is explained as follows.

Plastic backplate & Integrated metal fasteners.
These are incompatible for obvious reasons: metal fasteners cannot be integral to a plastic component.

Plastic backplate & Screws and fracture lines.
Part of the screws likely will not liberate from the backplate during shredding. If they are attached to a plastic backplate, this will lead to mixed fragments.

Plastic backplate & Plastic fasteners.
Plastic fasteners are typically made of PA, which is not a commonly used material for thermoforming. So, the plastic of the fasteners would likely be a different type than the plastic of the backplate, which would result in mixed fragments after shredding.

Plastic backplate & Steel frame.
The point of the steel frame solution is to make components which are part of screw connections the same material as the screws (i.e. steel). The backplate is also part of this screw con-

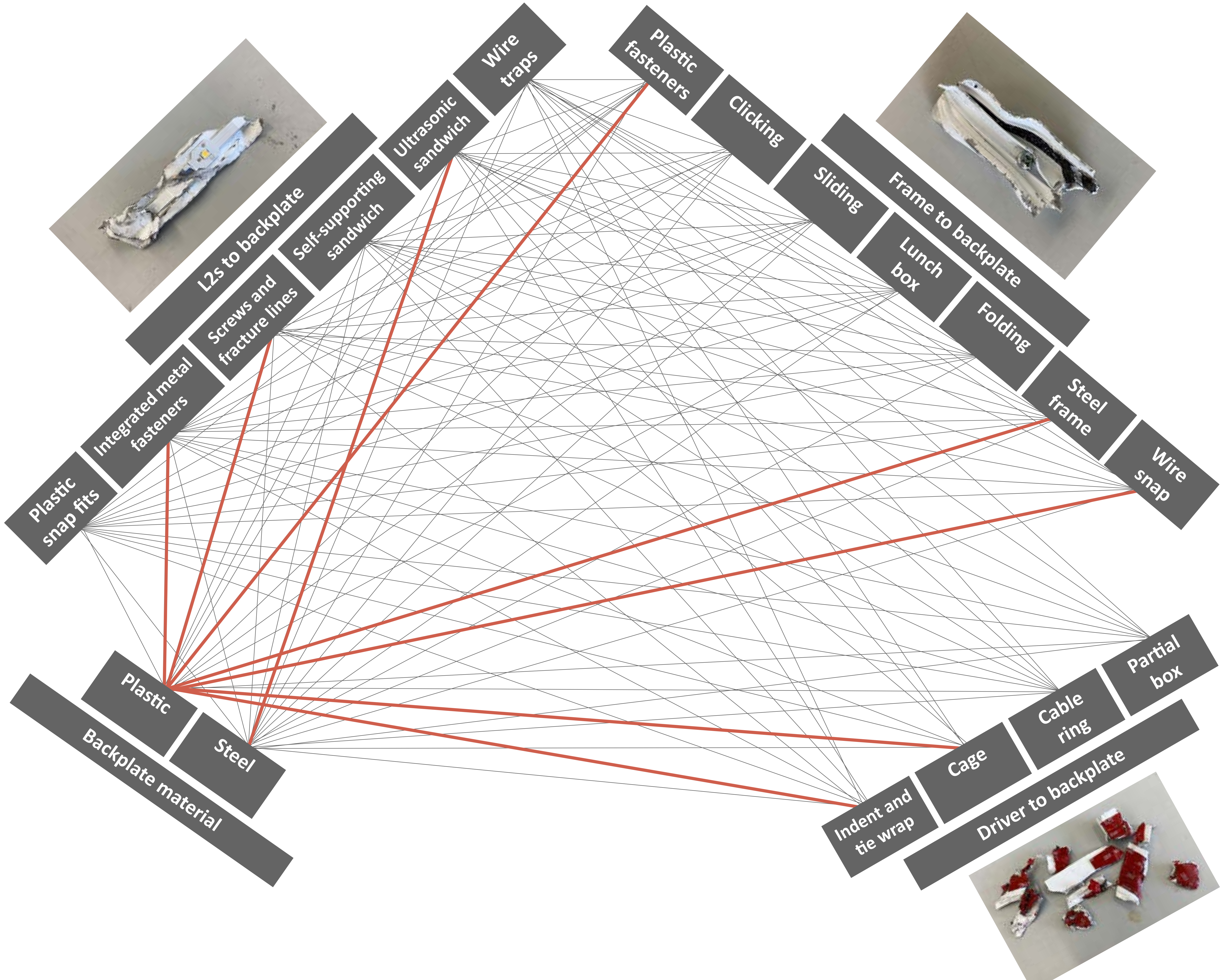


Figure 84. (In)compatability betweeen solutions. Grey lines indicate that two solutions are compatible with one another. Red lines indicate incompatibility. Explanations for incompatible combinations are provided in Appendix F.

nection, so making it out of plastic would again lead to mixed fragments, i.e. steel screws with plastic.

Plastic backplate & Wire snap.
The snapfit-like features that are required for the wire snap construction are difficult to achieve in thermoforming.

Plastic backplate & Cage.
The eyelets which are required for the Cage construction are difficult to achieve in thermoforming.

Plastic backplate & Indent and tie wrap.
The eyelets which are required for the indent and tie wrap construction are difficult to achieve in thermoforming.

Steel backplate & Ultrasonic sandwich.
For the ultrasonic sandwich, the backplate and reflector should consist of the same type of plastic, so that no mixed fragments result form shredding.

4.5.3 Solution ranking

The solutions have been ranked using the Pugh selection matrix method. The criteria on which solutions were scored and their weights are listed in Table 10. They are based on the wishes in the Programme of Requirements (see Table 9). Three of these wishes are not taken into account in the ranking, because none of the solutions affect them (namely, the wishes related to ADPE, luminous efficacy and uniformity of light). The weights have been assigned in consultation with Signify.

One Pugh matrix was created per type of mixed fragment, and an additional one for the choice of backplate material. Per criterion, a score was given between -3 and 3. A positive value indicates an improvement as compared to the current CoreLine, while a negative score represents a deterioration.
The scorings with regard to the BoM and manufacturing costs were done in collaboration with an experienced mechanical engineer at Signify. For the look & feel scores, advice was given by a Signify product manager. A Signify employee who is familiar with Signify's current portfolio helped to determine the scores for "Demonstrates a design feature that is new to the Signify portfolio". The resulting scores are visualized in Figure 85 on the next page. The scores per criterion and their rationale can be found in Appendices G and H.

Table 10. Criteria used in the Pugh

Criteria	Weight
Good liberation during shredding	5
Look & feel	5
BoM costs	5
Manufacturing costs	5
Use of materials that will actually be recycled	4
Low GWP (make phase)	4
Demonstrates a design feature that is new to the Signify portfolio	3
Repairability	2

4.5.4 Concept selection

The highest and second highest scoring combinations of compatible solutions are indicated in Figure 85, and visualized in Figures 86 and 87. The winning concept comprises a plastic backplate, L2s connected to the backplate via an ultrasonic sandwich construction, a sliding frame-to-backplate connection and a cable ring for the driver securement.

Table 11 on the next page displays the winning concept's scores for all eight criteria. Positive scores, highlighted in green, represent improvements of the concept over the current CoreLine. Negative scores, highlighted in red, indicate a deterioration.

From the table it is clear that the concept offers improvements with respect to recyclability.
The sliding frame is expected to liberate well from the backplate, exit windows and clicking corners; when the product is shredded, fragments of the backplate and exit windows are free to slide out of the frame. The clicking corners are attached via snap fits, which also liberate well during shredding.
The cable ring can be further embodied to promote liberation. If the ring is larger than the fragment size after shredding, it is likely to break and liberate from the backplate.
The ultrasonic sandwich construction to keep in place the L2s is not expected to liberate, but the components which are welded together will exist of the same plastic type, so this poses no problem for recycling.

The look and feel may be negatively affected by the sliding frame and cable ring. In the case of the sliding frame, this is due to the seams that will exist between the four sides of the frame. In the current product, the four sides are welded together and then covered in a white coating, making for a seamless result. In the sliding frame construction, the frame sides will not be welded together and so a seam will show. It can be further investigated whether buyers and users will notice and negatively perceive this

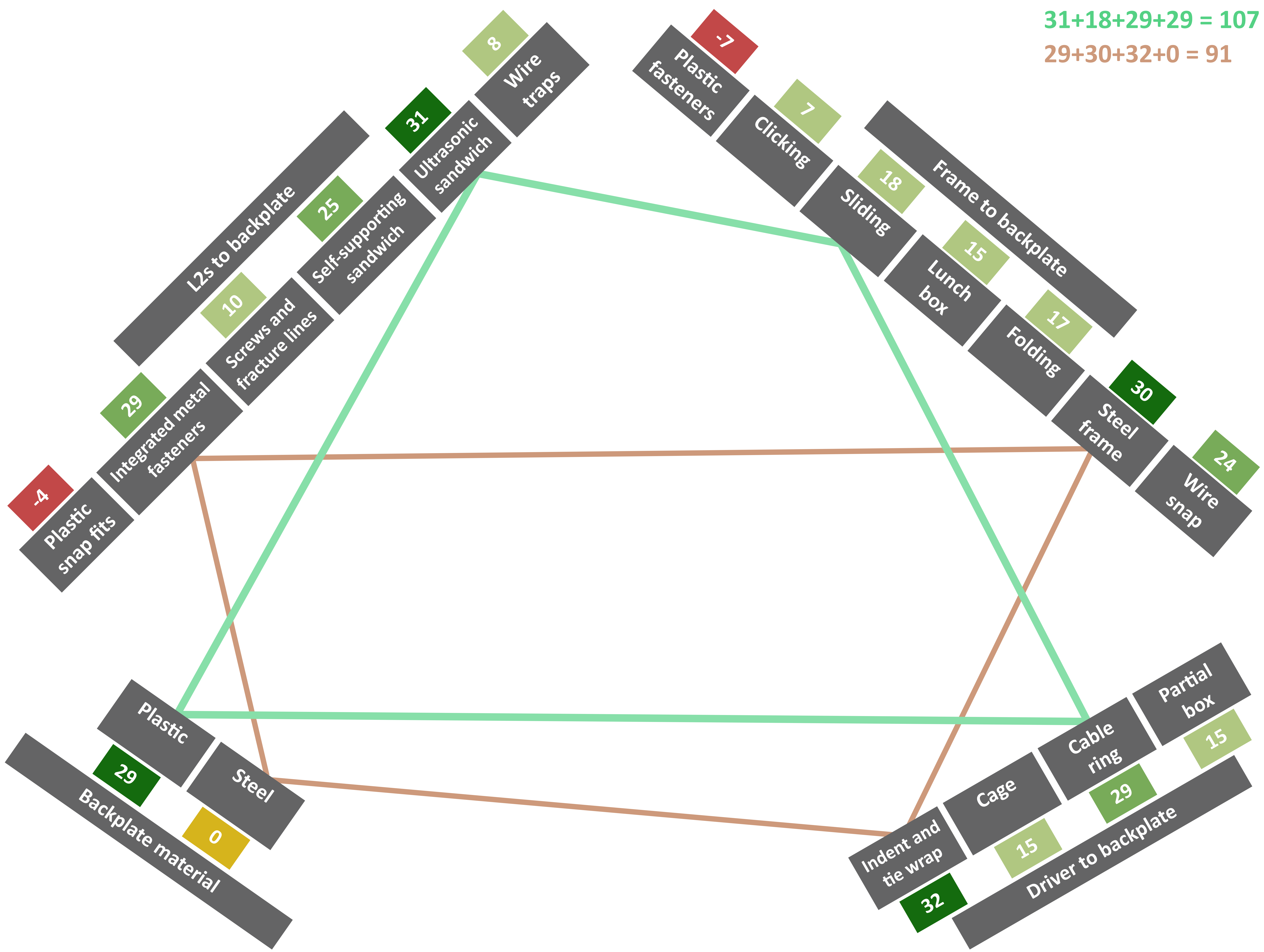


Figure 85. Concepts with the highest and second highest scores (green and brown lines, respectively). Points are indicated per solution. Green boxes represent an improvement relative to the current CoreLine; yellow boxes represent no difference; red boxes represent worse performance.

seam.
For the cable ring, small gaps have to be made in the backplate in which to insert the ring. Such gaps could give the impression that dust can enter the product, which would affect the perceived reliability of the product. The size of the gaps should therefore be minimized.

On a more positive note, the concept can likely be produced for less money than the current CoreLine. This is mainly due to the plastic backplate. The material costs of plastic are lower than those of steel, and thermoforming plastic is cheaper than stamping steel.

Furthermore, the GWP of the product may decrease. As explained in chapter 4.4, the magnitude of this reduction is heavily influenced by the type of plastic that will be used.

Positive scores are also assigned to the criterion related to newness of design features. This indicates that the proposed concept offers Signify new ways to connect components within their products, which may be beneficial not only for the CoreLine, but also in other projects.

Lastly, the repairability of the winning concept is improved for the frame to backplate and driver to backplate connections, but is worse for the L2 to backplate connection.
The sliding frame is more suitable for repair than the current screw solution, because it is a lot quicker to slide and connect the four sides of the frame together than it is to insert 24 screws. Similarly, it is quicker to detach the cable ring than it is to peel off the driver sticker. Also, the same cable ring can be used to reassemble the product, while the peeled-off sticker cannot be used again.
Repairability of the ultrasonic sandwich construction is poor. The reflector is likely to get damaged when it is removed from the backplate. Reattachment of the reflector would require access to ultrasonic welding tools, which is far from standard. In the current design, the L2s and reflector are glued to the backplate. This is also far from ideal for disassembly, but it is possible if a heat gun is used.

Table 11. Scores assigned to the winning concept per criterion. Green cells indicate an improvement of the concept as compared to the current CoreLine; red cells represent a worse outcome.

	Weight	Backplate material: Plastic	L2s to backplate: Ultrasonic sandwich	Frame to backplate: Sliding	Driver to backplate: Cable ring
Good liberation during shredding	5	0	3	2	3
Look & feel	5	0	0	-1	-1
BoM costs	5	2	0	-1	1
Manufacturing costs	5	1	1	1	-1
Use of materials that will actually be recycled	4	0	2	0	1
Low GWP (make phase)	4	2	0	0	0
Demonstrates a design feature that is new to the Signify portfolio	3	2	3	3	3
Repairability	2	0	-3	2	3

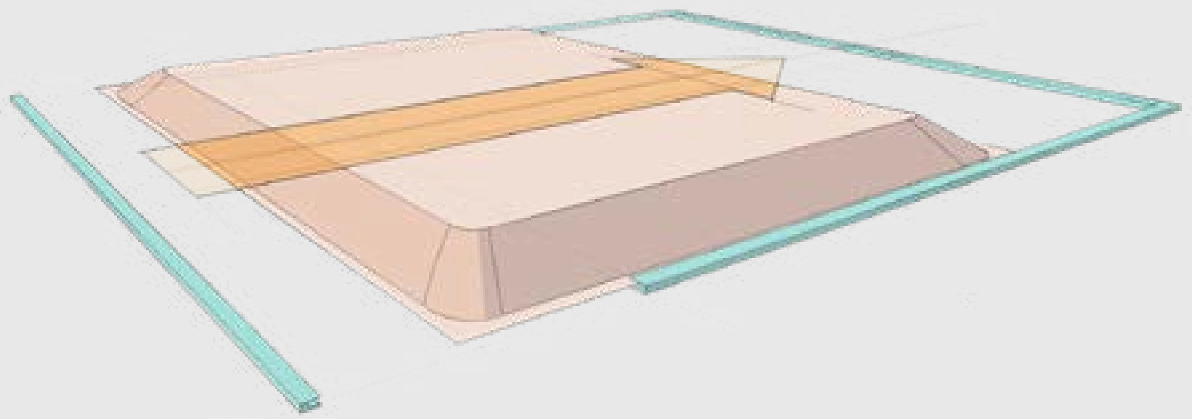
The main advantage of the winning concept in comparison to the runner-up results from the plastic backplate. The plastic backplate offers a way to reduce costs significantly, and will provide Signify with new insights and opportunities since they currently do not have a recessed luminaire with a plastic backplate.

The difference in scores with the second best concept is quite large (107 versus 91 points), representing a clear preference. In agreement with the team at Signify, the winning concept was selected for further embodiment and prototyping.

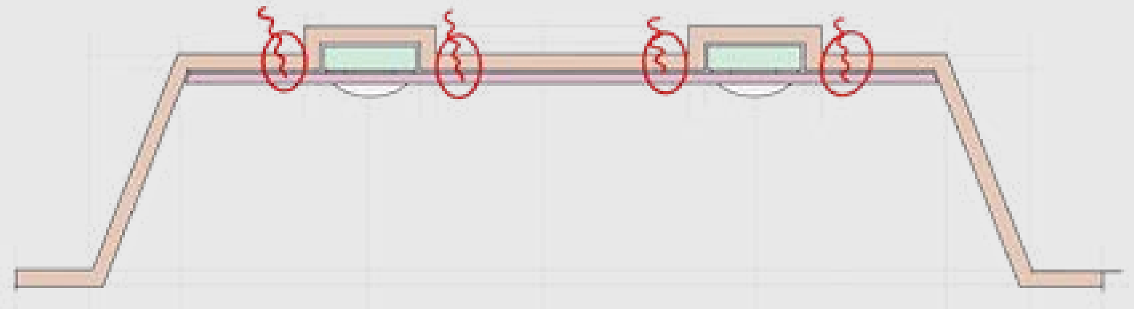
Winning concept (107 points)

Plastic backplate

Sliding frame



Ultrasonic sandwich



Cable ring

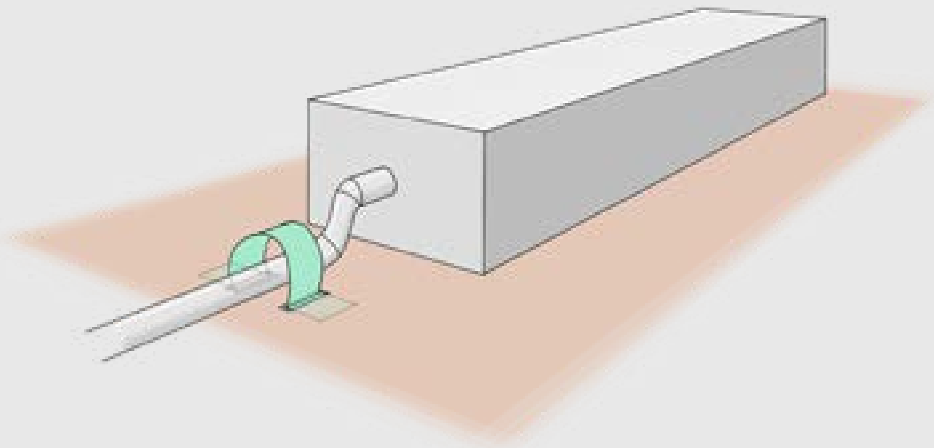


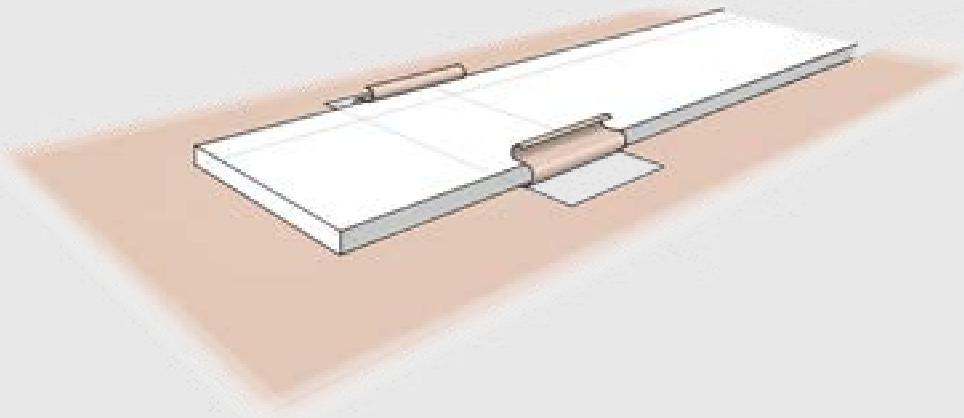
Figure 86. Winning concept.

Runner-up concept (91 points)

Steel backplate

Steel frame

Integrated metal fasteners



Indent and tie wrap

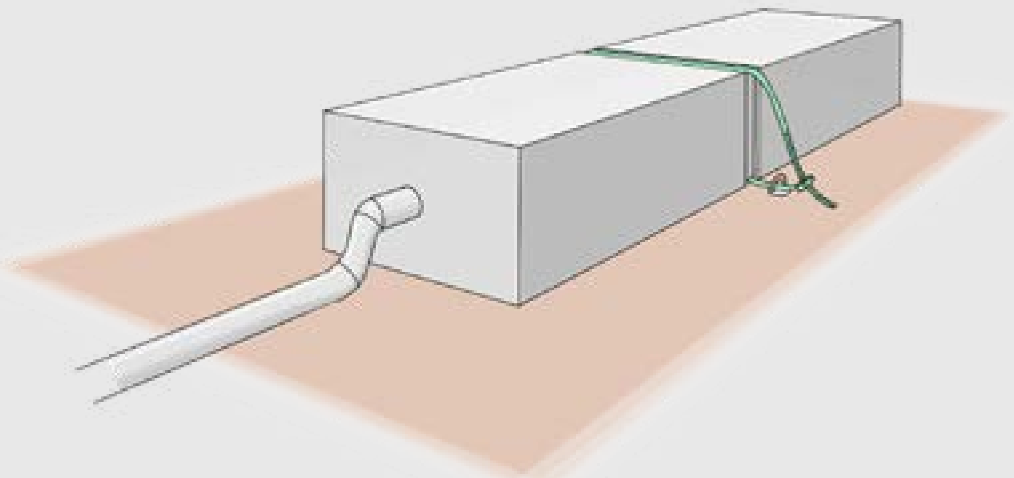


Figure 87. Runner-up concept.

4.6 Embodiment

This chapter documents the embodiment of the redesigned product. The embodiment is of an explorative nature; possibilities and challenges are identified but the design is not yet finalized. Iterative prototyping has been key to the embodiment process and is also recorded within this chapter.

Separate sections will cover the following topics:

- The plastic backplate
- The sliding frame
- The ultrasonic sandwich L2 securement
- Assembly steps
- Evaluation of complete demonstrator

Development of the driver securement was given a lower priority. In the end, no more time was left to address this aspect of the design. It is therefore left as a recommendation for future development.

4.6.1 Plastic backplate

Material choice

Given that the reflector will be ultrasonically welded to the backplate, it is important from a recyclability point of view that these two components are made of the same type of plastic. The current reflector is made of PET, but it seems like this plastic does not get recycled from WEEE streams (MGG Polymers, n.d.), (Enva, n.d.) (Galloo, n.d.). A different plastic type has to be selected, which meets the following requirements:

- The plastic will be recycled at end of life (i.e., recycling infrastructure is in place)
- The plastic is suitable for thermoforming (i.e. it is amorphous)
- The plastic is suitable as a reflector (i.e. a sufficiently high light reflectivity can be achieved).

Especially the last requirement needs more research; it should be determined what is an acceptable reflectivity value for the CoreLine recessed panel, and the maximum achievable reflectivity for different plastics needs to be researched. Additionally, considerations with respect to costs and environmental impact need to be made.

Signify employees have indicated that they expect PS to be a promising candidate to meet the requirements. Therefore, the tentative material choice for this first stage of embodiment will be PS.

Manufacturing method

The CoreLine's backplate had to be redesigned to be plastic. As mentioned, the size of the backplate does not allow for injection molding within Signify's supply chain, so it is designed for thermoforming.

Figure 88. Thermoforming at Signify.

Geometry

The geometry of the backplate remains largely the same as in the current design, to safeguard the product's optical functioning and its fit within a ceiling grid. Additionally, the backplate must have a good fit with the frame and the two exit windows, which puts constraint on certain dimensions. Figure 89 highlights these dimensions.

The outer edges of the backplate follow a curve (see Figure 89). This makes the sliding connection to the frame more reliable, because the frame now constraints the backplate not only in the horizontal but also vertical direction. The edge follows a curve rather than a sharp corner because this is more suited to the thermoforming process. More details on the shape of the curved outer edge will follow in the next section.

The curved outer edge does not cover the whole width of the backplate (see Figure 90). This has to to with assembly of the frame. When the final side of the frame is attached, some wiggle room is needed to insert the final clicking corner. More details on this are provided in section 4.6.4.

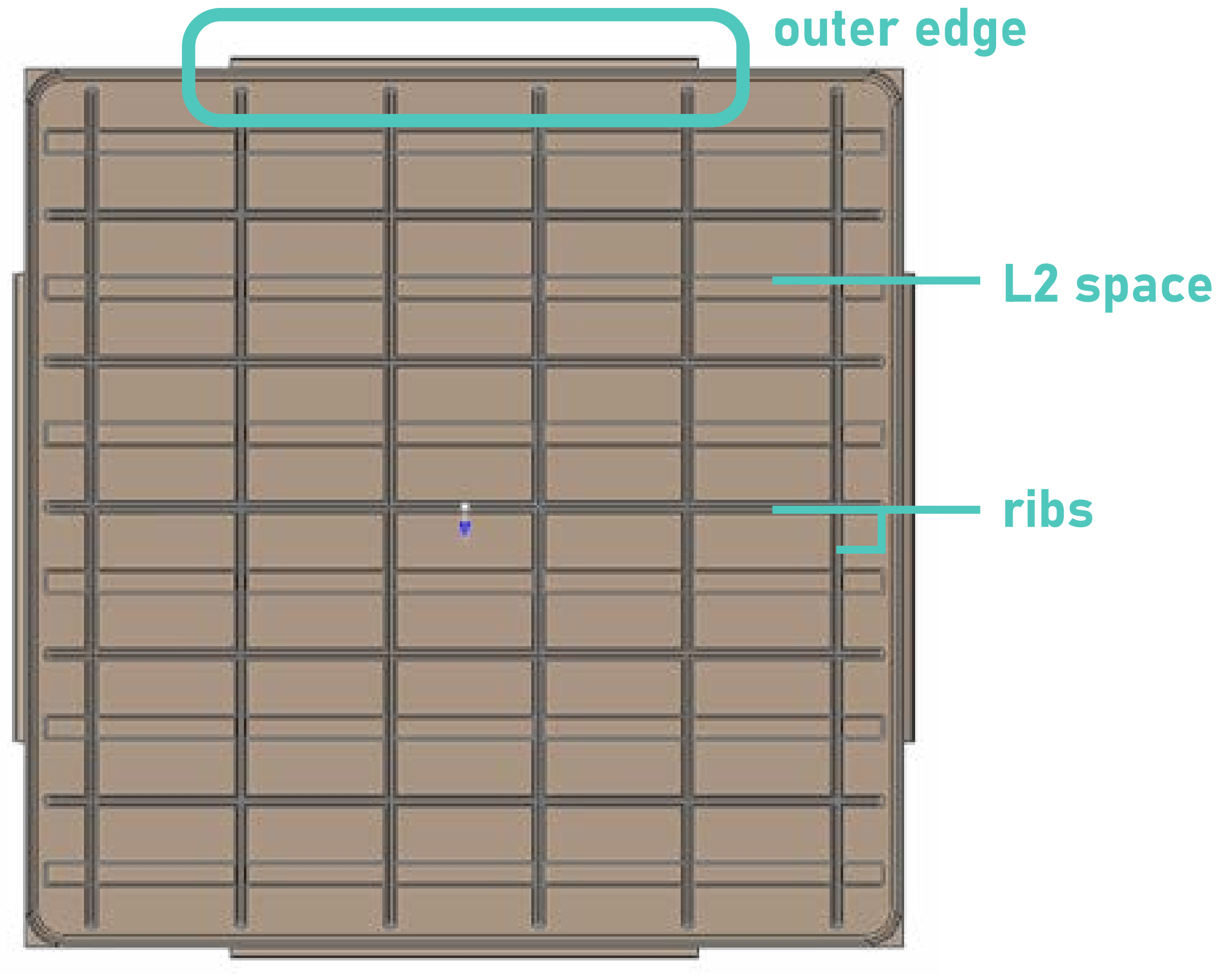


Figure 90. Top view of the redesigned backplate. The outer edges are important for connection to the frame.

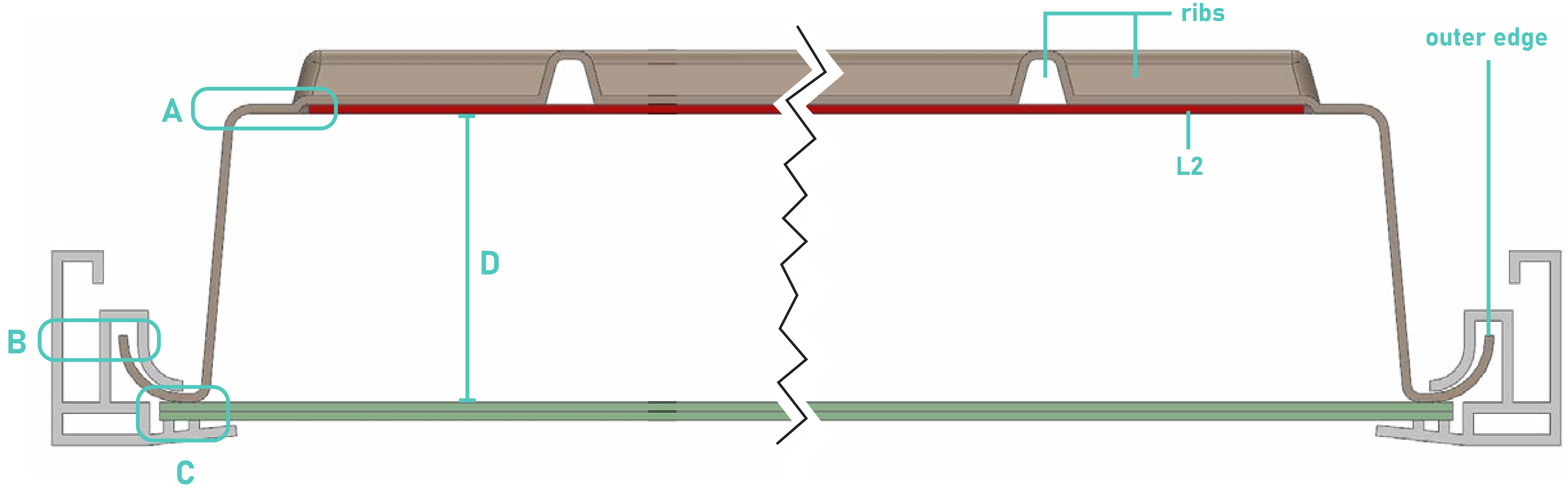


Figure 89. Cross section view of the backplate and restrictions on its dimensions. Note that only the ends of the cross section are shown, the middle is removed to allow a better view of the connection to the frame.

(A) The width of the top of the backplate must be bigger than the length of the L2s.
(B) At its widest point - i.e. at the ends of its outer edges - the backplate may not be wider than the frame, which in turn needs to fit within the grid ceiling. Also, there must be space left within the frame to insert the clicking corners (see section 4.6.2).
(C) The backplate must make contact with the exit windows, so that these are kept in place. The dimensions of the exit windows have been kept the same as in the current product.
(D) The distance between the L2s and the exit windows is kept equal to the current product, because this distance influences the optical performance. Evidently, this constraints the height of the backplate.

The last note on the backplate's geometry concerns ribbing. The current steel backplate features linear indentations to provide stiffness. In the plastic backplate, a similar configurations of ribs are applied (see Figure 90). As PS has a much lower Young's modulus than steel, the ribs need to be quite a bit taller than the indentations of the original backplate.

Load simulations were run in SolidWorks to determine the necessary rib height. In consultation with a mechanical engineer at Signify, the following requirements were determined:

> *Under a load of 4 times the gravity (= 39 Newton),*
> *• the maximum stress may not exceed 4 MPa (well below the yield strength of PS);*
> *• the maximum deflection may not exceed 10 mm.*

The backplate was modelled with a thickness of 1 mm. It was expected that 1 mm thickness is required to meet flammability requirements.
Simulations showed that the requirements could be met with a rib height of 6 mm; maximum stresses equaled 3.3 MPa and maximum deflections were 5.9 mm (see Figures 91 and 92).

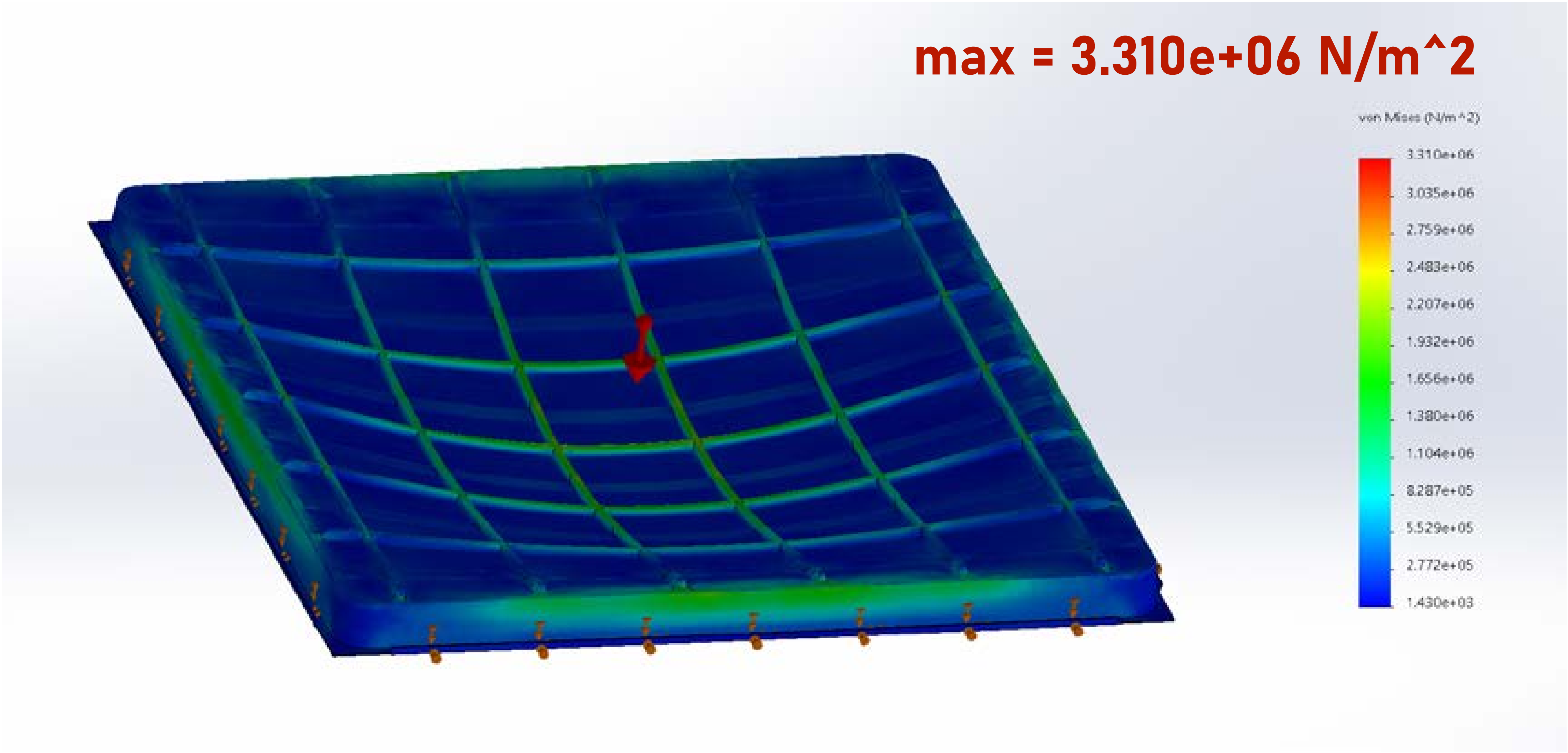


Figure 91. Stresses computed in the load simulation of the redesigned backplate.

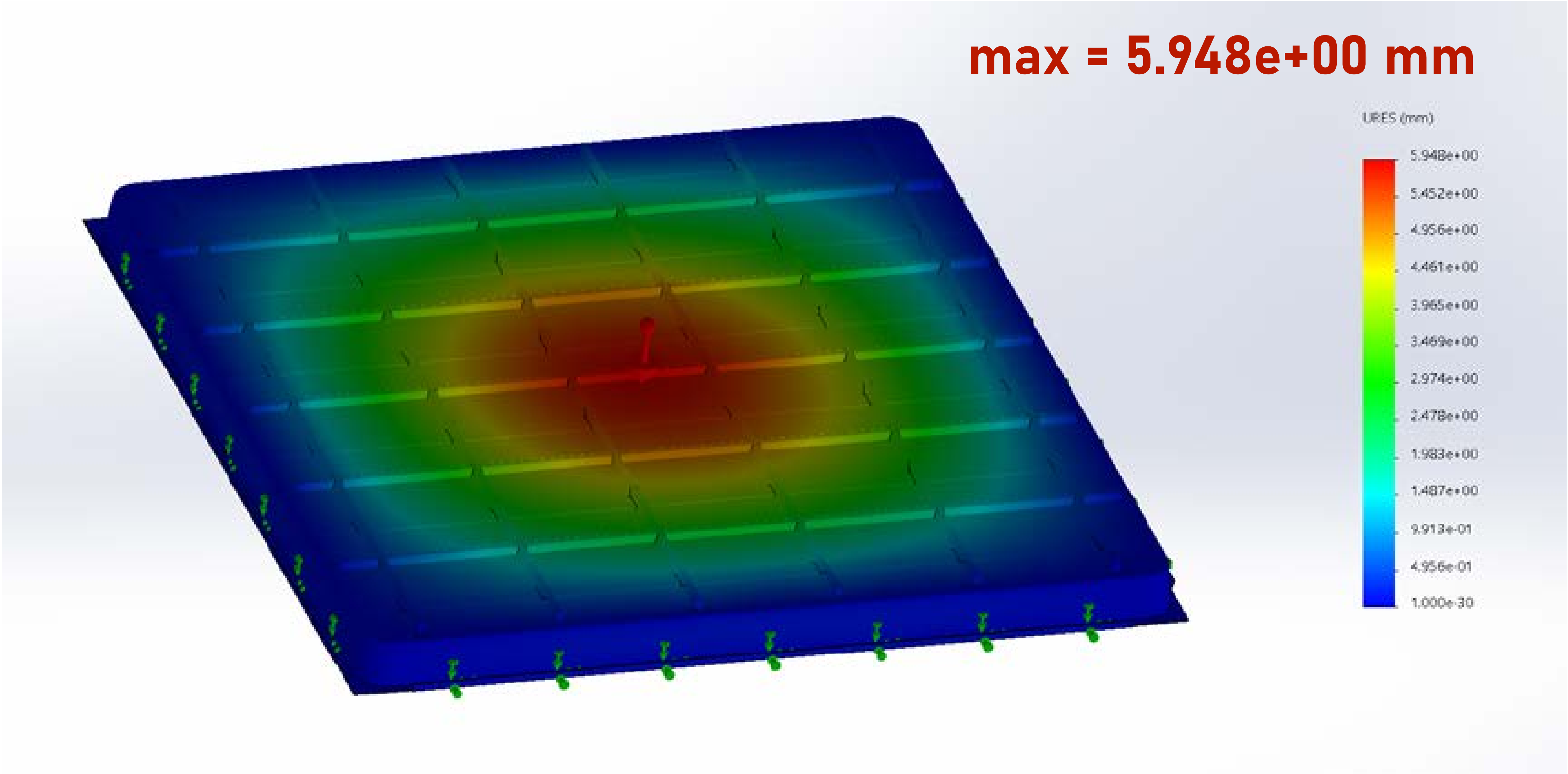


Figure 92. Deflection computed in the load simulation of the redesigned backplate.

Prototyping and demo

For the demo, the backplate is thermoformed in PS. Prototypes have been made using the thermoforming machines at the Signify and IDE workshops. The machine at IDE is big enough to allow the manufacturing of a 1:1 demo.

The next pages list the eight iterations of prototypes that were made throughout the development of the backplate, and the learnings that were acquired from each of them. Figure 93summarizes the developments throughout the prototyping.

1. Validation of suitability of PS sheet and 3D printed mold for thermoforming.
2. Quality check of edges and corners at 1:1 scale.
3. Testing the curved outer edge of the backplate.
4. Testing the curved outer edge of the backplate for increasing gutter widths.
5. Rounding off the ends of the outer edges.
6. More gradual transition of outer edge to mold base.
7. Thermoforming the complete 60x60 backplate.
8. Thermoforming the complete 60x60 backplate with improved outer edge geometry.

Figure 93. Iterations of prototypes created throughout the development of the plastic backplate.

1

Validation of suitability of PS sheet and 3D printed mold for thermoforming.

→ PS sheet and 3D printed mold seem suitable.
→ The PETG mold will deform after frequent use due to heat.
→ The inside edges and corners are still quite round; might be due to the smaller scale. Segments of 1:1 scale should be tested.

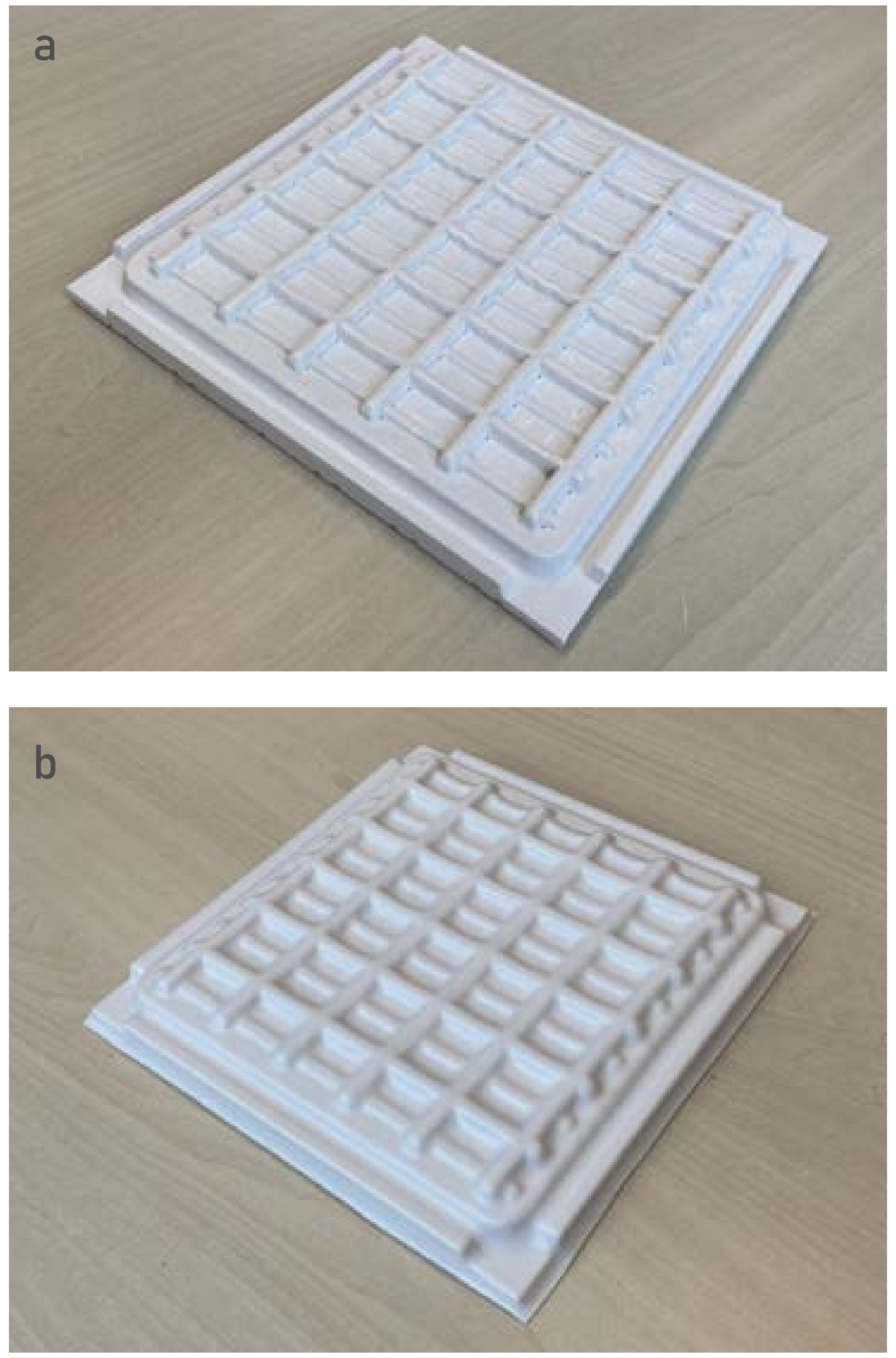


Figure 94. (a) 3D printed mold of 1:3 backplate.
(b) result from thermoforming.

2

Quality check of edges and corners at 1:1 scale.

→ The 1mm radii work well with the 1mm thick PS; no deformities along the edges.
→ On this 1:1 scale, the inside edges and corners become sharp enough.
→ The ribs can be made a lot lower.

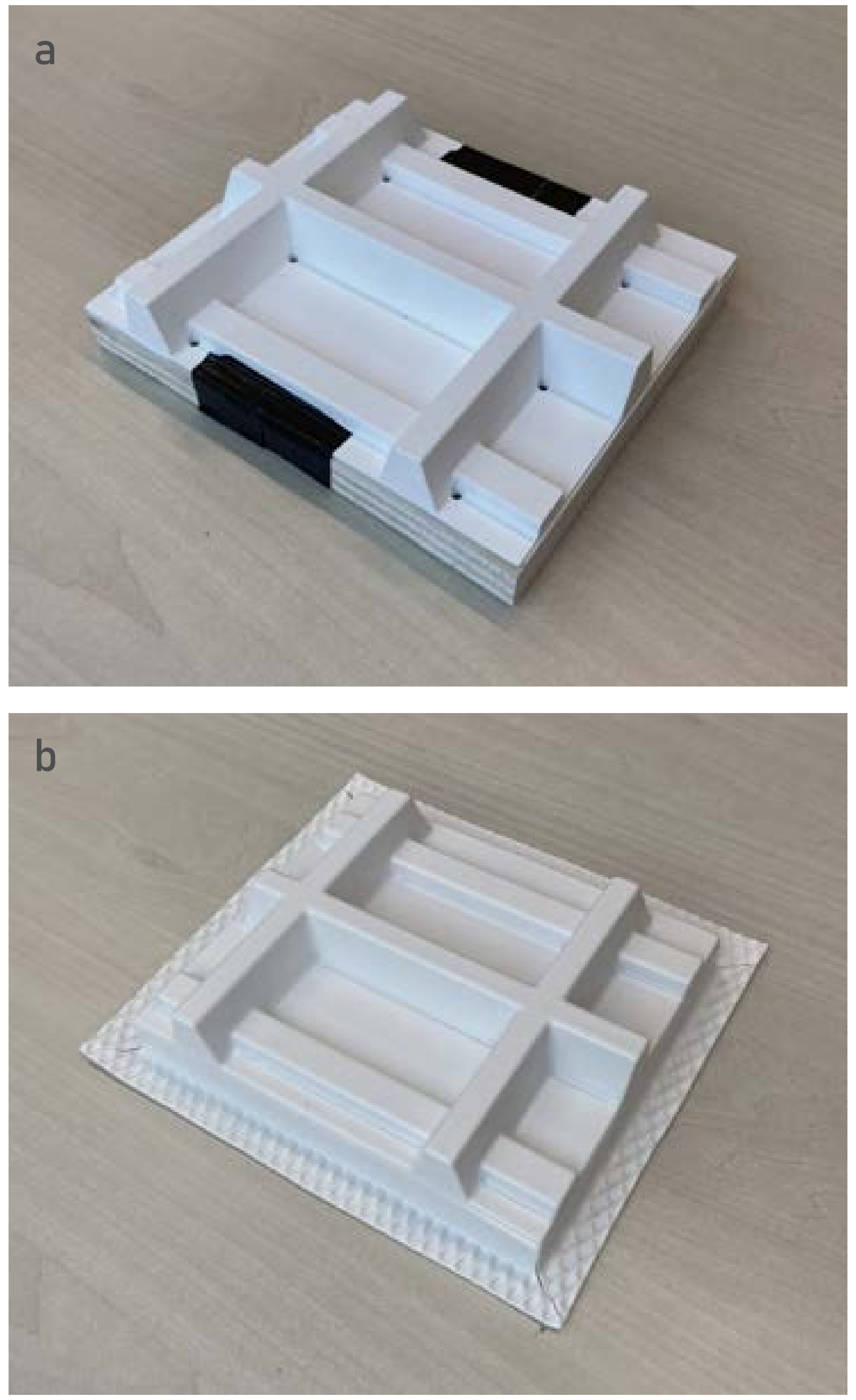


Figure 95. (a) 3D printed mold of 1:1 backplate section.
(b) result from thermoforming.

Testing the curved outer edge of the backplate.
A mold was made representing a corner of the backplate. The outer edges were also included in the mold (see Figure 96 (a)).

→ The outer edge of the backplate proves most challenging; the sheet either does not go deep enough into the gutter or it gets very thin and "rockets" are formed. Lowering the outer edge did not help.
→ The air vents should be smaller to create a stronger vacuum (advice from IDE workshop staff).

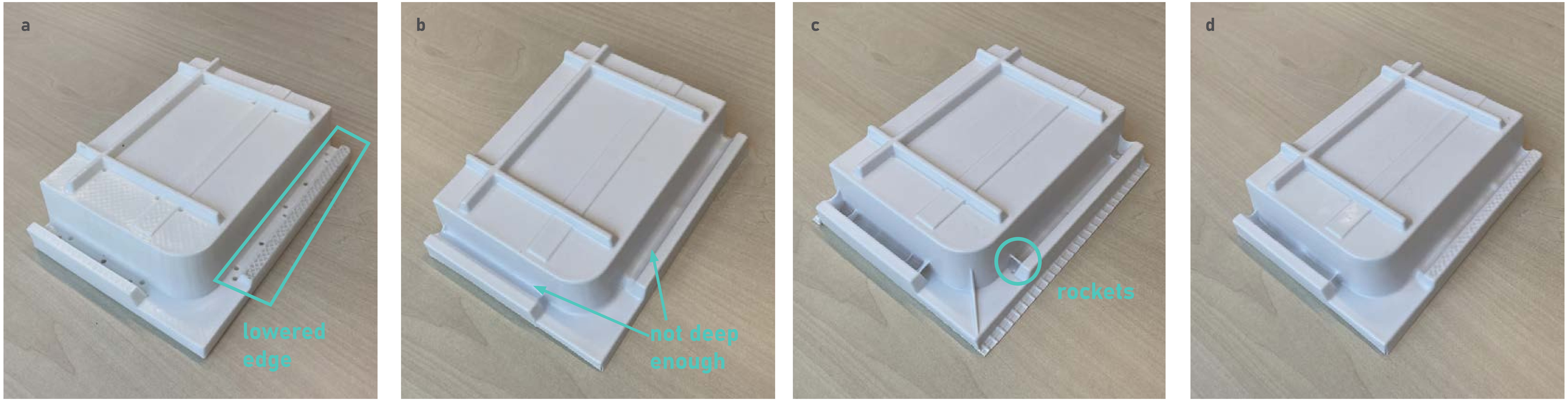


Figure 96. (a) 3D printed mold of 1:1 backplate corner. (b) result from thermoforming; sheet does not go all the way into the gutters along the edges. (c) result from thermoforming; increased heating of the PS sheet led to thinning of the materials and rockets. (d) result from thermoforming after one of the edges was shortened; the PS sheet still did not go completely into the gutter and formed rockets.

Testing the curved outer edge of the backplate for increasing gutter widths.
To tackle the challenge of the outer edge, a mold was printed with gutters of increasing width (see Figure 97).

→ Increasing the gutter width allows the plastic sheet to reach the bottom of the gutter. Good results were achieved with a gutter width of 14 mm (see Figure 99 (d)).
→ It is preferred that the gutter width stays as close to the original 7 mm as possible, so that the area on which the L2s are positioned remains as close as possible to its original size. This helps with the L2 spacing and optical performance of the product.
→ The plastic sheet gets closer to the mold in the middle of the gutter than at the ends (see Figure 99 (b) and (c). Rounding off the edges of the outer edge may allow the sheet to sink further toward the mold.

Figure 97. 3D printed mold for testing edges with different gutter widths.


Figure 98. Result from thermoforming.

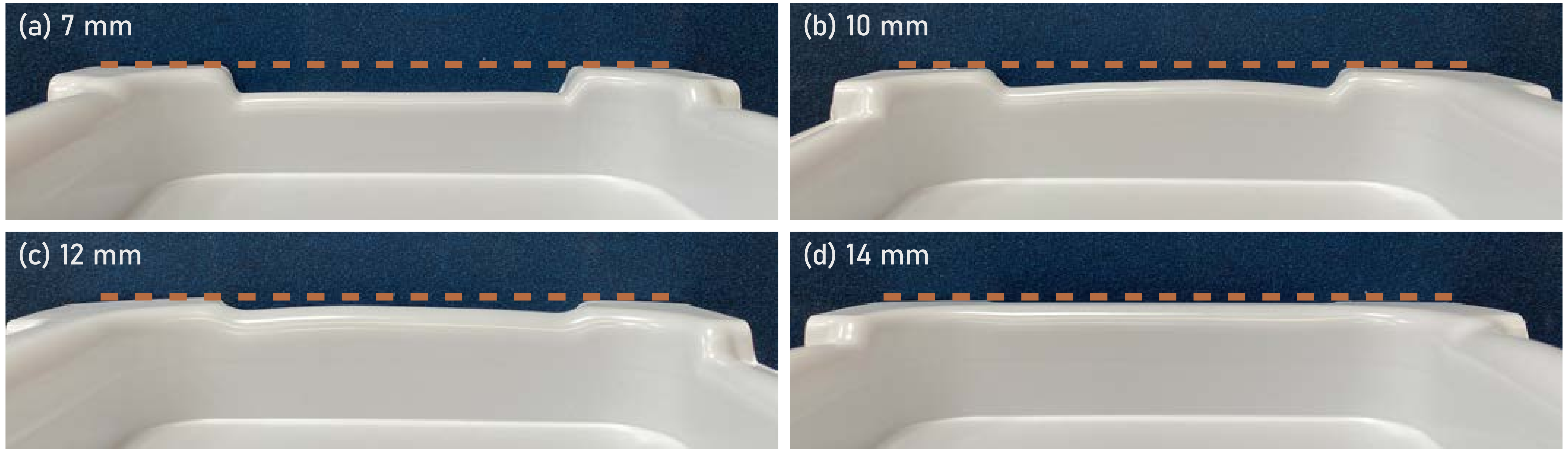


Figure 99. Bottom side of the thermoforming result. All four sides - with different gutter widths - are shown, along with an indication of how far the plastic sheet should have reached, if it had been sucked all the way to the mold surface. Only the side with a 14 mm gutter has reached the mold.

Rounding off the ends of the mold's outer edges.
A variation of the previous mold was created, but with a larger radius on the ends of the outer edges (see Figure 100). Again, four different gutter widths were used.

→ The radius on the ends of the outer edges helps. Now, the thermoforming is successful already at a 10 mm wide gutter; the 7 mm gutter is almost successful (see Figure 101).
→ At the 7 mm gutter, rockets are formed right at the ends of the outer edge. This could mean the transition between the edge and the base of the mold is still too steep.
→ If the ends of the outer edge go down even more gradually, it might be possible to get good results with a 7 mm wide gutter.
→ The duration of heating has a large impact on the thermoforming result (see Figure 101 and 102). If the sheet is not heated long enough, the material does not get sucked completely onto the mold. Thus, an unsuccessful thermoforming trial does not necessarily mean that the mold needs to be changed, but can also mean a longer heating duration is necessary.

Figure 100. 3D printed mold for testing edges with different gutter widths. The ends of the edges have been given a larger rounding (indicated by brown circle).

Figure 101 (left). Thermoforming was successful for the 10, 12 and 14 mm wide gutters. The material did reach the bottom of the 7 mm wide gutter, but also formed rockets at both ends of the edge.

Figure 102 (right). When the plastic sheet is not heated long enough, the material does not get pulled completely into the mold geometry. This copy was heated for a duration of 15 seconds, while the one in Figure 101 was heated for 20 seconds prior to forming.

More gradual transition of outer edge to mold base. In this iteration, the transition between the outer edges and the base of the mold was made more gradual (see Figure 103). The gutter width was set at 7 mm, and the L2 chambers and ribs were added as well, to verify whether thermoforming would be successful with all elements of the backplate being present.

→ The outer edge can now be successfully thermoformed (see Figure 104 and 105). The rockets appearing at the end are likely due to the sudden end of the gutter, which will not be present in the complete backplate mold.
→ The same geometry will be applied for the outer edges of the mold for the complete backplate.

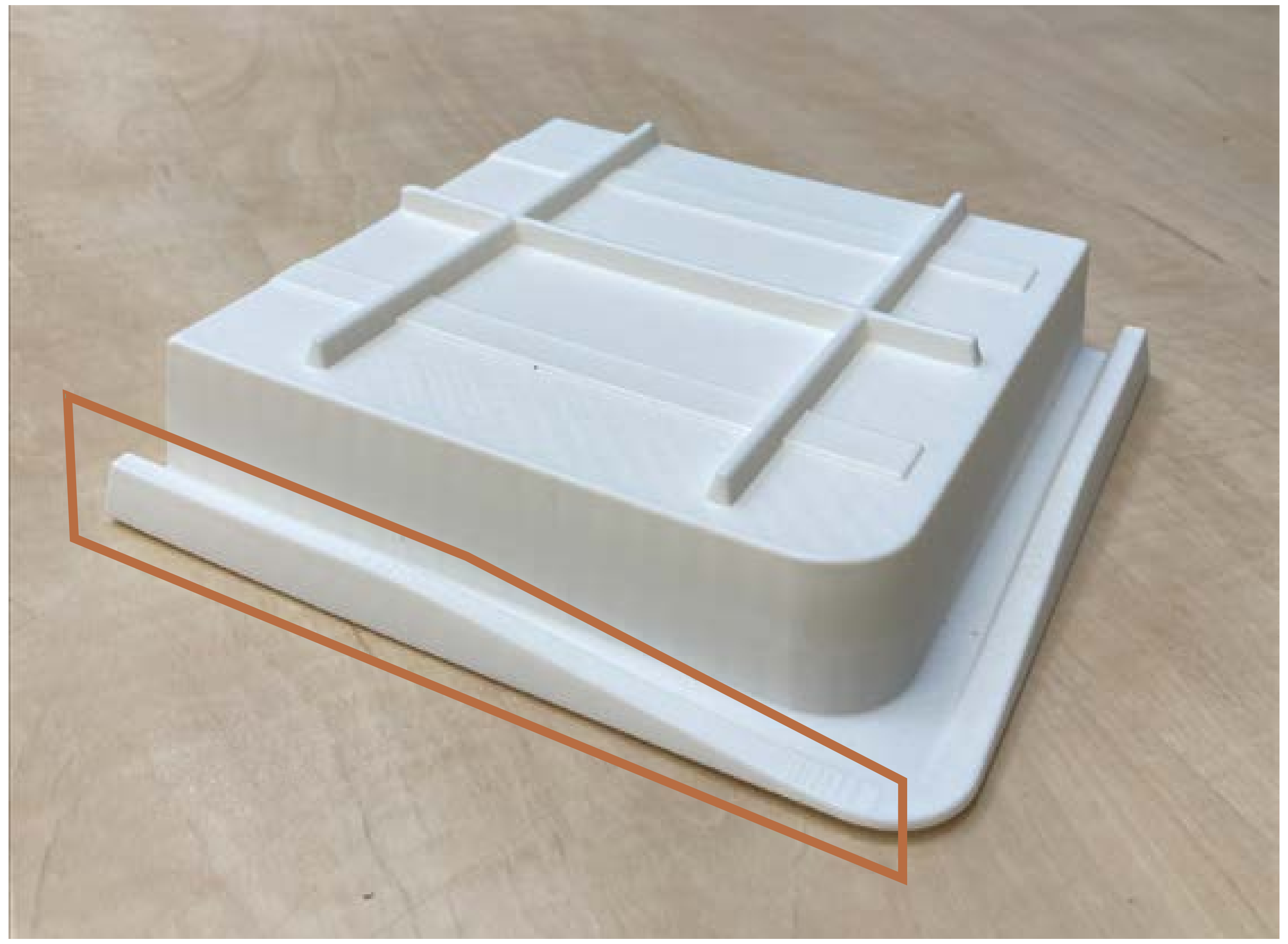


Figure 103. Mold of the corner of the backplate with a very gradual transition from the outer edge and the base of the mold (outlined in brown).

Figure 104. Result from thermoforming.

Figure 105. Result from thermoforming. The outer edge has reached all the way into the bottom of the mold gutter, resulting in a straight bottom (indicated by the brown dashed line).

Thermoforming the complete 60x60 backplate.
To prototype the complete backplate, a mold was created out of sixteen 3D printed parts (see Figure 106). Three copies of the backplate were made using this mold. For the most part, results were satisfactory. The spaces for the L2s and the ribs came out well (see Figure 107).

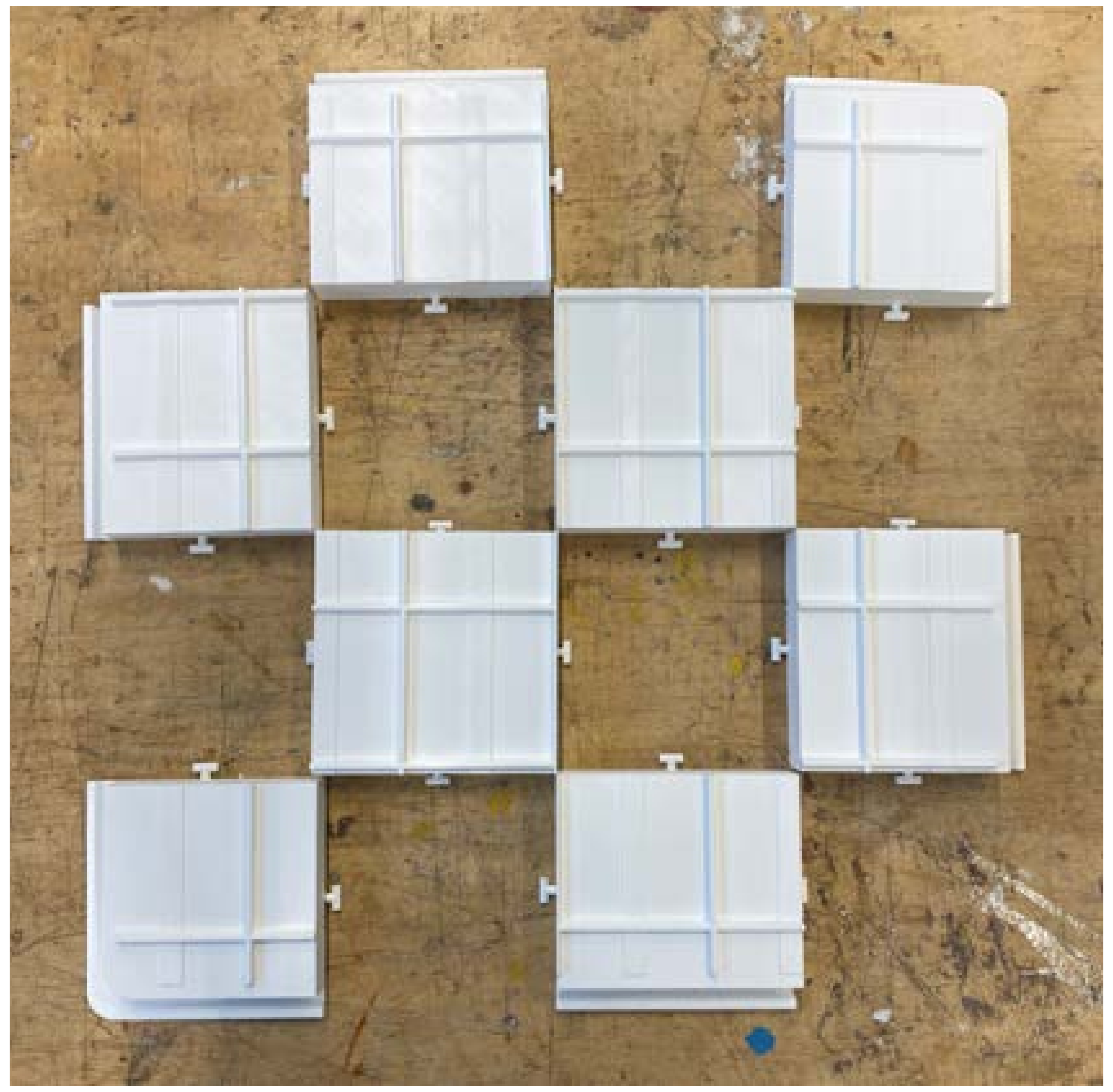


Figure 106. Eight out of sixteen mold parts. The mold parts are joined together via T-shaped features.

Figure 107. Thermoformed backplate in 1:1 scale.

The outer edges of the backplate did not turn out perfect. For all three copies, there was:

- one outer edge that was pulled all the way into the mold (see Figure 109 (a));
- one outer edge that was clearly not pulled all the way into the mold (see Figure 109 (b));
- two outer edges that were somewhere in the middle (see Figure 109 (c) and (d).

Employees of the IDE workshop suspect that their thermoform machine does not function properly on one side. This could explain the inconsistent edge results.

Also, the deeper the PS gets pulled into the outer edge, the thinner the material gets (see Figure 108). As a result, it is very easy to bend, which makes the connection to the frame less secure. A wider mold gutter and bigger radii might help to prevent such thinning of the material.

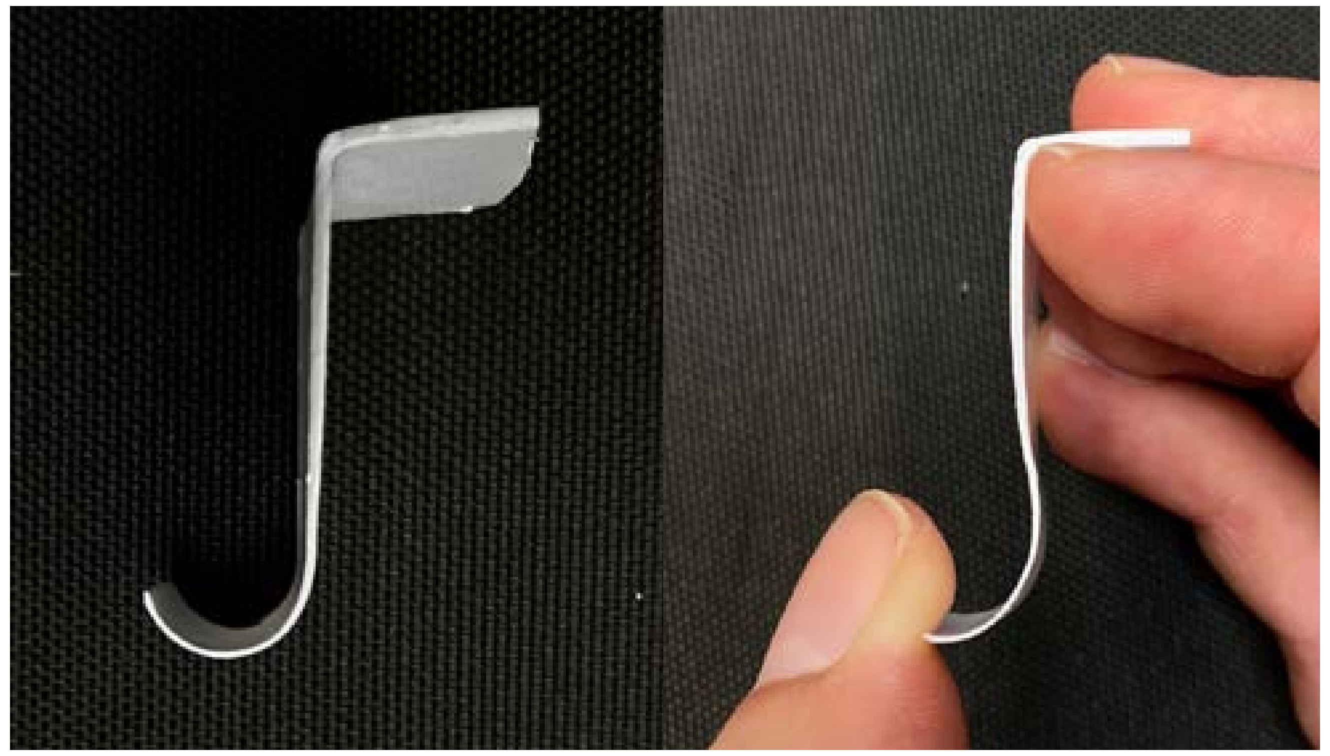


Figure 108. The PS sheet gets thinner toward the bottom of the mold gutter. It therefore bends quite easily.

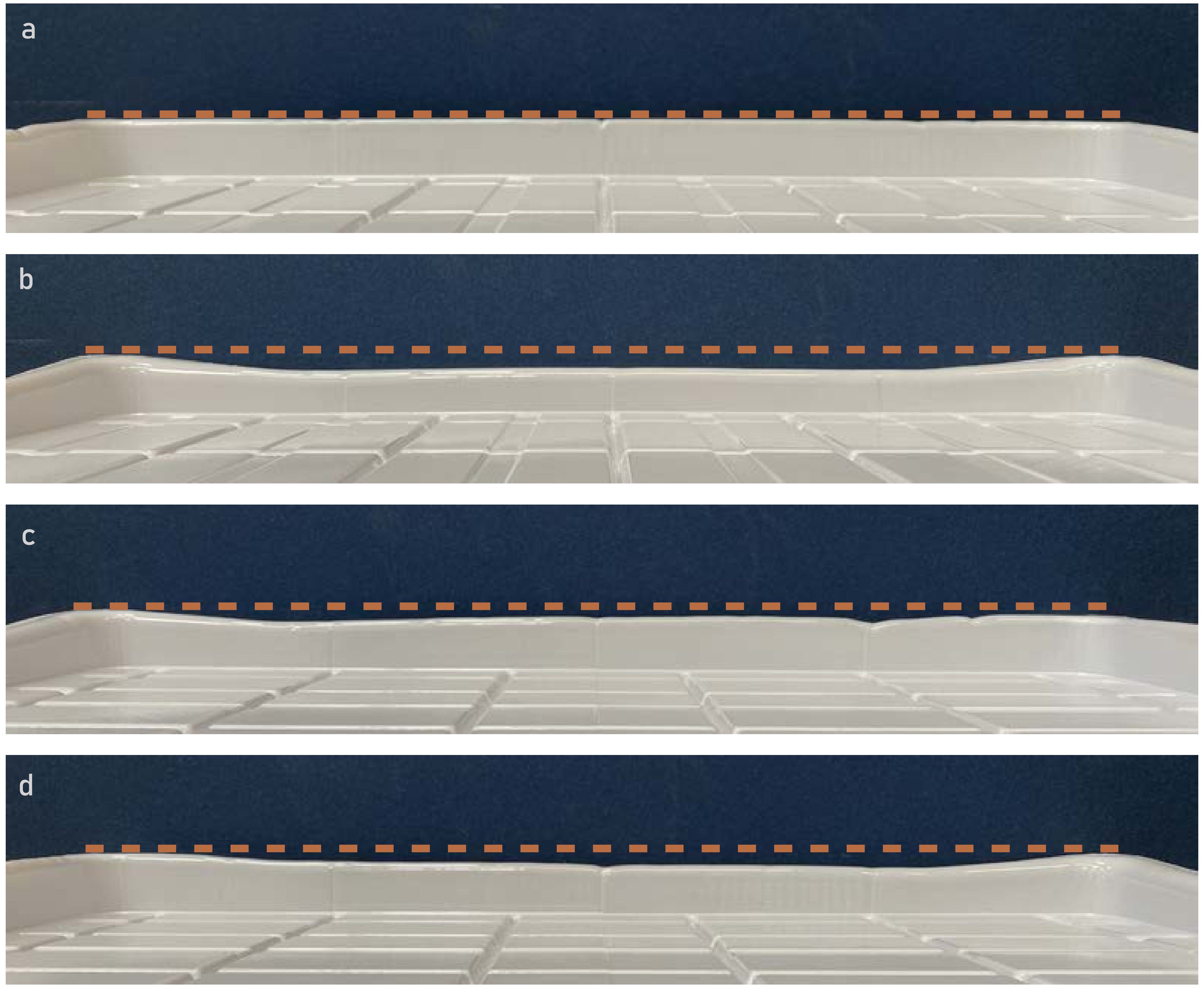


Figure 109. The four outer edges of the thermoformed backplate. Photos were taken while the backplate lied upside down on a table. The brown dashed lines indicate how far the edge should reach when successfully thermoformed.
(a) One outer edge is successfully pulled all the way into the mold gutter.
(b) One outer edge is far away from being pulled all the way into the mold gutter.
(c), (d) Two edges are somewhere in between (a) and (b).

Thermoforming the complete 60x60 backplate with improved outer edge geometry.
Changes were made to the mold in order to improve the outer edges. Figure 110 shows the shape of the outer edge in the previous and the current iteration.

The problem in the previous iteration seems to be that not enough of the PS sheet can be pulled into the outer edge gutter. This results in extreme thinning of the sheet and it not reaching the bottom of the mold. If more of the sheet close to the gutter can be pulled into it, this could solve the issue. To enable this, the following changes were made to the mold (see Figure 110):

- The chamfer angle was increased;
- Radii were enlarged.

Due to these changes, the thermoforming results have improved. Now, three out of four outer edges go down all the way into the mold gutter (see Figure 112). It remains impossible to produce four good outer edges on the thermoforming machine at IDE.

Another imperfection that remains is the thinness of the curved outer edge (see Figure 111). The sheet gets similarly thin as in the previous iteration, making for a flimsy, easily bendable result.

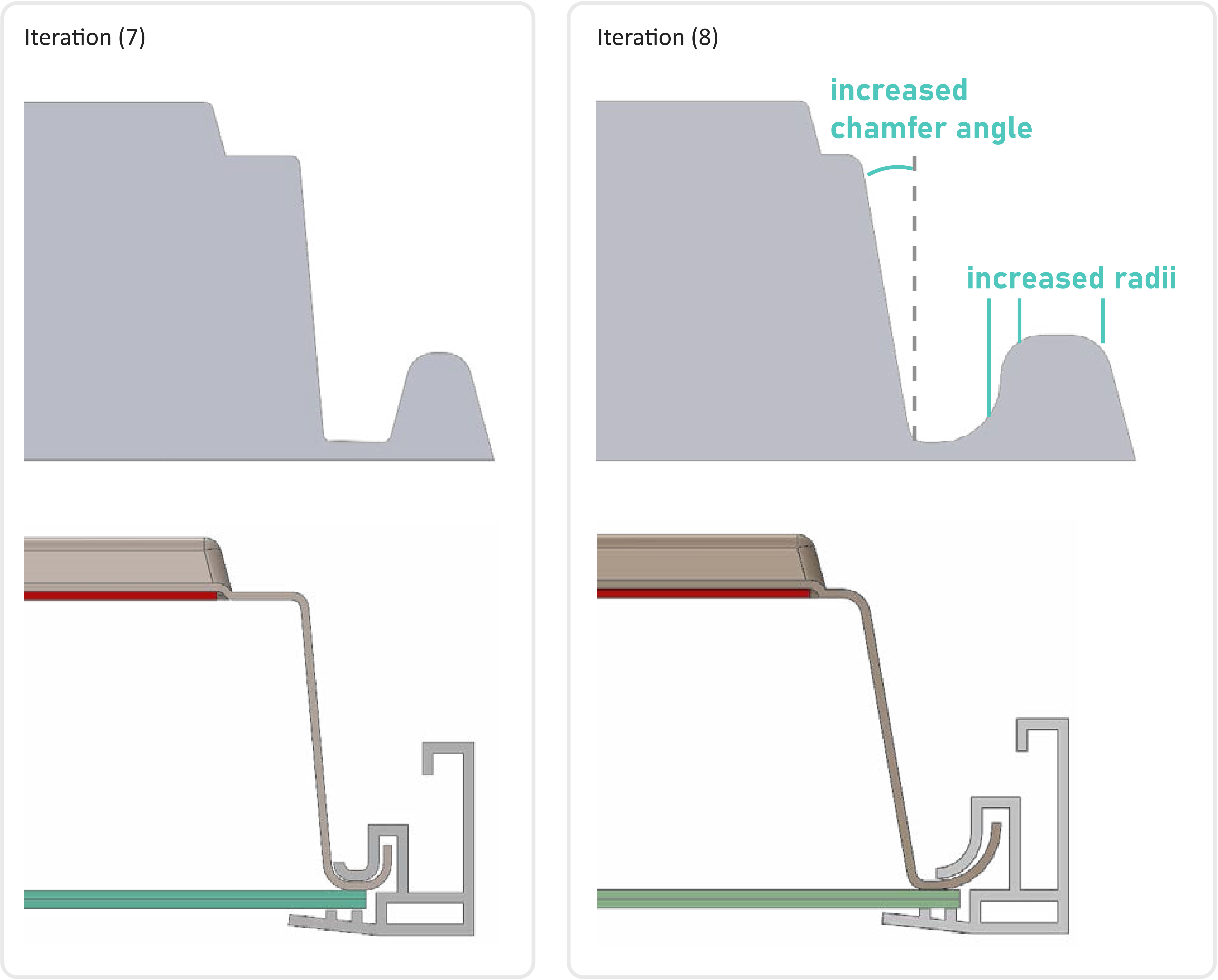


Figure 110. Cross sections of the backplate molds and assembled products, corresponding to iterations 7 and 8.

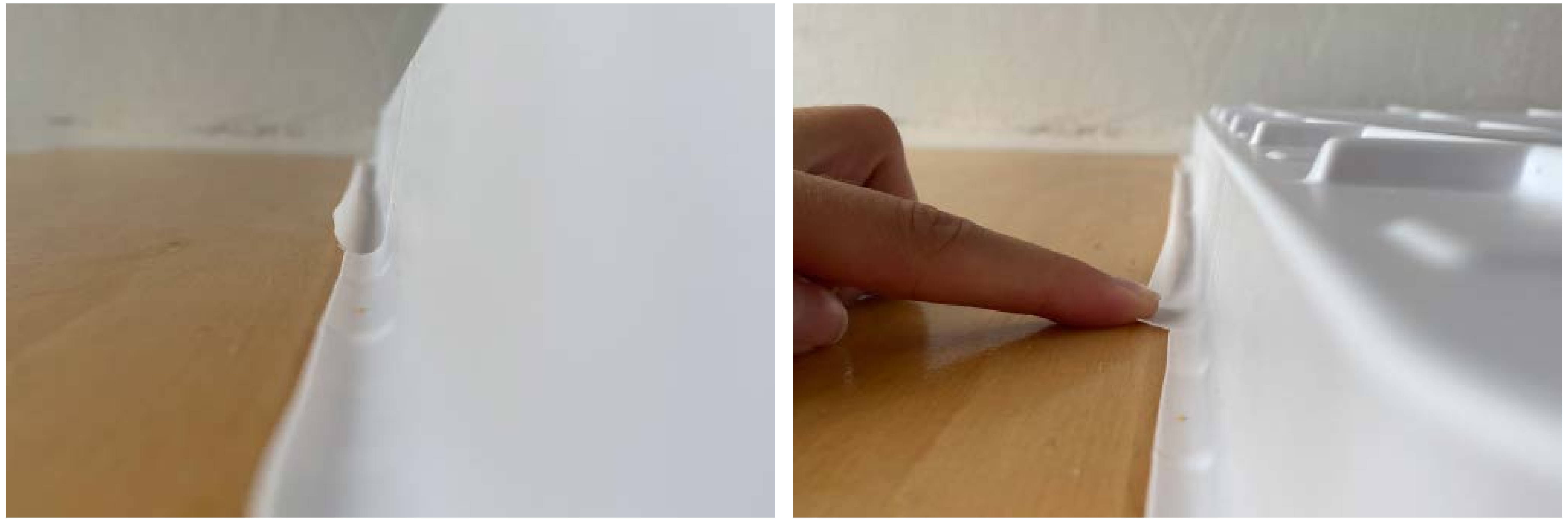


Figure 111. The curved outer edge becomes very thin, making it very easy to bend.

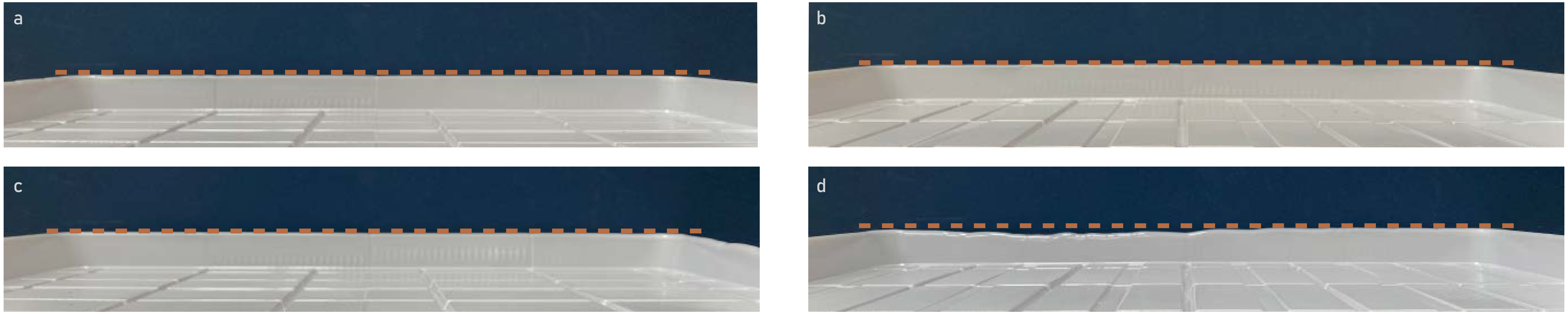


Figure 112. The four outer edges of the thermoformed backplate. Photos were taken while the backplate lied upside down on a table. The brown dashed lines indicate how far the edge should reach when successfully thermoformed.
(a), (b), (c) Three outer edges are successfully pulled all the way into the mold gutter.
(d) One outer edge is not pulled all the way into the mold gutter.

4.6.2 Sliding frame

The frame exists out of four identical sides and clicking corners to connect them together (see Figure 113). After assembly, the clicking corners will be hidden within the frame parts.

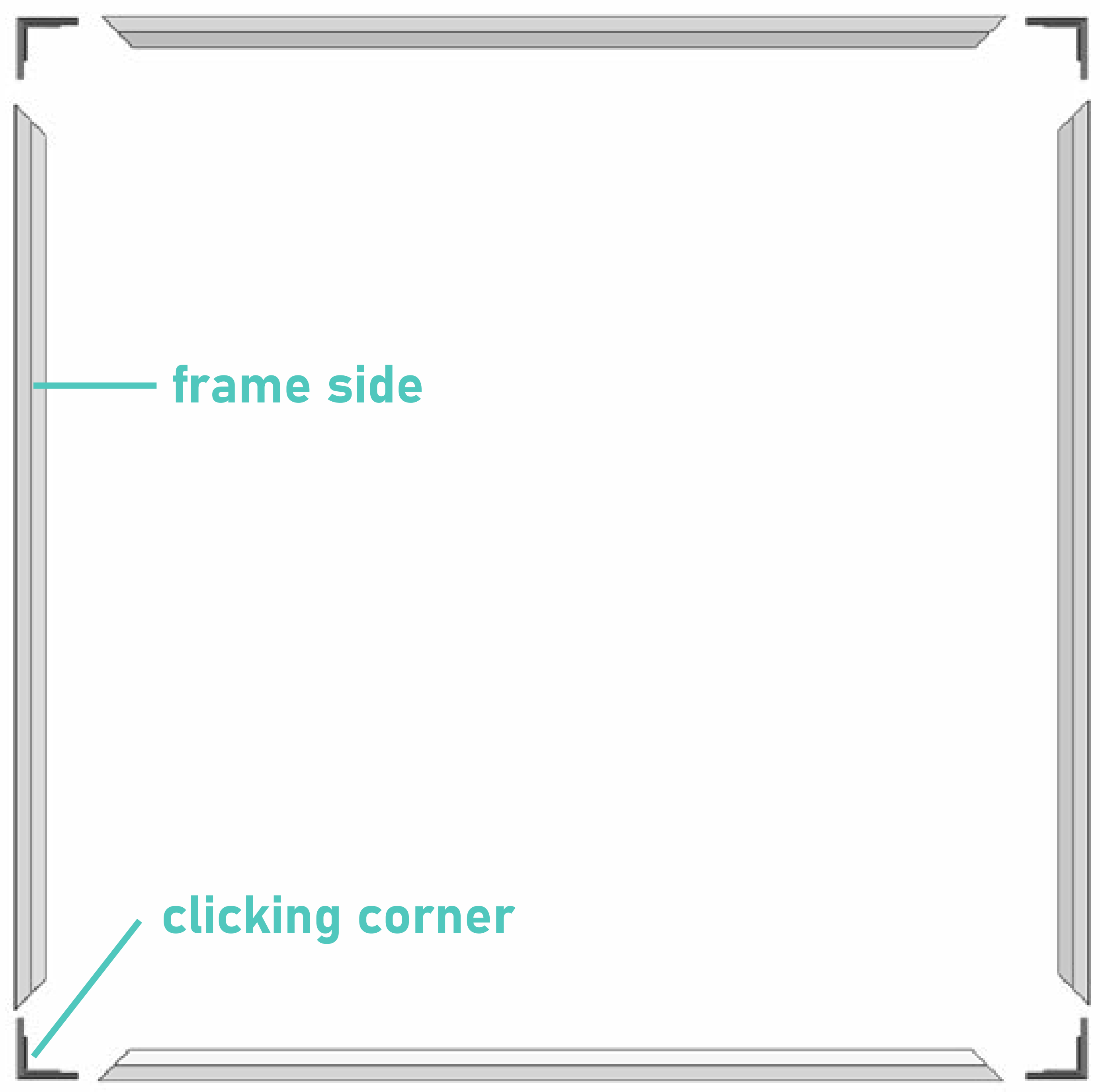


Figure 113. The redesigned frame, consisting of four frame sides and four clicking corners.

Material choice

The choice was made to create the frame - the sides as well as the clicking corners - from PS, just like the backplate. Two main considerations contributed to this decision:

- Costs; plastic is cheaper than aluminum.
- When the luminaire is switched on, it gets warmer. All components then undergo thermal expansion. If components which are connected to each other expand to different degrees, there is a risk that the product will make creaking noises whenever it is switched on. This is very undesirable, as it is distracting to the user of the luminaire. The sliding construction which will secure the backplate to the frame likely could be developed in such a way that the creaking can be avoided, but it is easier to make the frame and backplate from the same material.

Additionally, switching from aluminum to PS reduces the GWP of the product's make phase quite significantly (see Figure 114). It must be noted that switching from aluminum to steel - as proposed in the runner-up concept - would also lower the GWP to a similar extent.

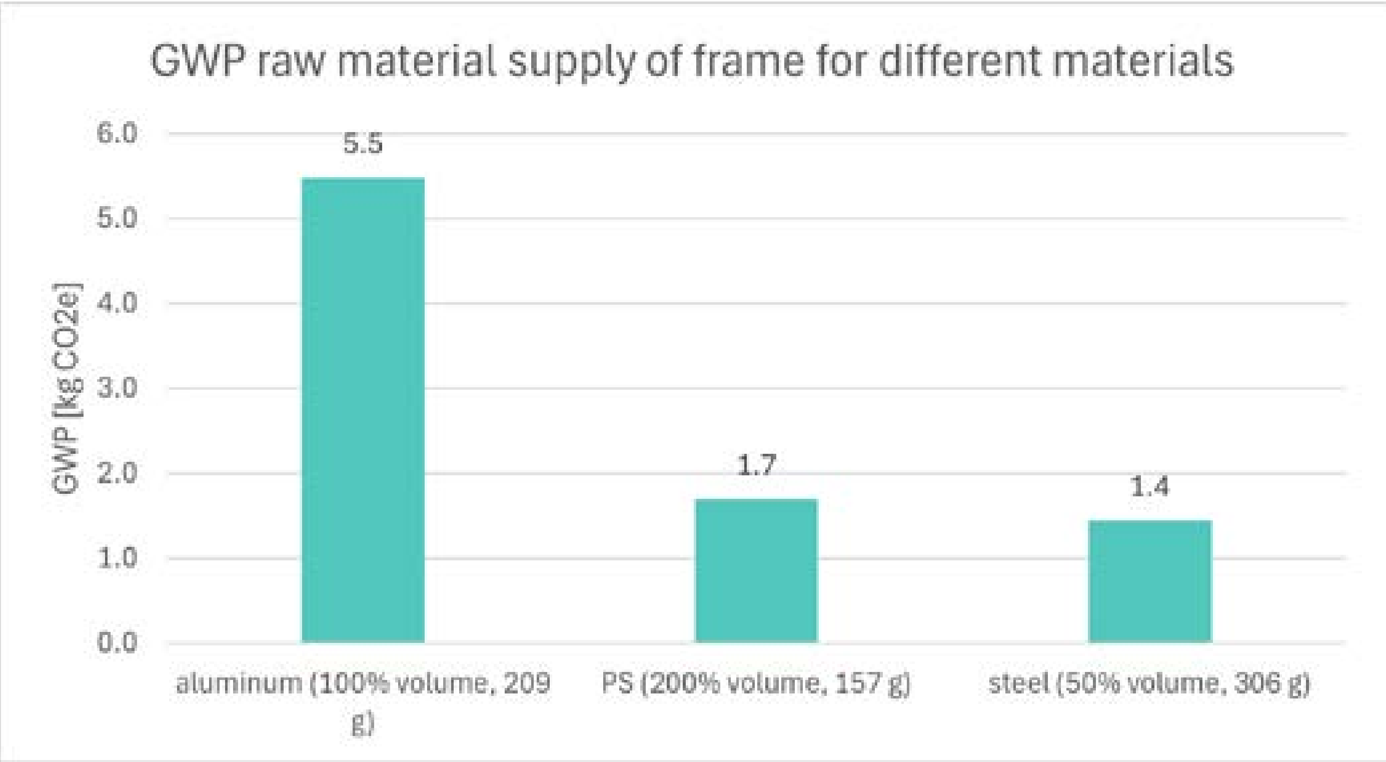


Figure 114. GWP associated with the raw material supply of the frame, computed for different materials.

Manufacturing method

The frame is designed to be manufactured via plastic extrusion. Additionally, the frame will come with small clicking components which will allow the four sides of the frame to connect to each other. These clicking components are designed for injection molding.

Geometry

The geometry of the frame must serve to:

- accomodate the exit windows;
- provide a surface for the backplate edges to hook under;
- accomodate the clicking corners.

These functions are all included in the profile as shown in Figures 115 and 116. Taking into account the manufacturing process, the wall thickness of the frame profile is set at 1.2 mm. The extruded frame needs to be post-processed. The ends need to be cut at 45 degrees so that the four sides of the frame do not overlap. Then, cut-outs need to be made to match with the click finger of the clicking corners (see Figure 116).

The geometry of the clicking corners and their interface with the frame was inspired by the existing CoreLine installation accesory (see Figure 117). However, the clicking corners for the frame include only one set of click fingers instead of two, so that they can be shorter and the frame does not need to be made a lot taller (see Figure 116).

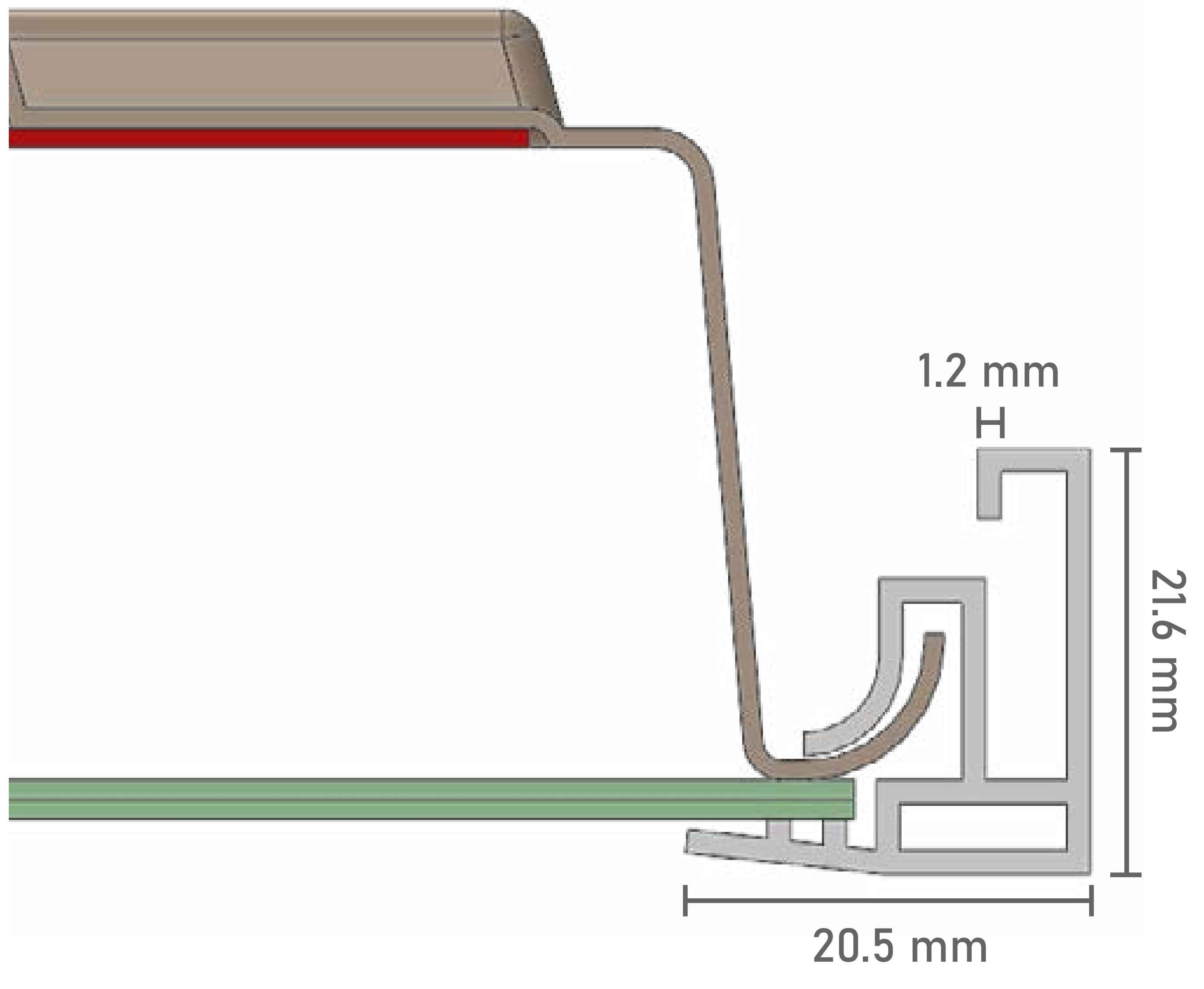


Figure 115. Cross section of the redesigned frame, assembled with the backplate (brown) and exit windows (green).

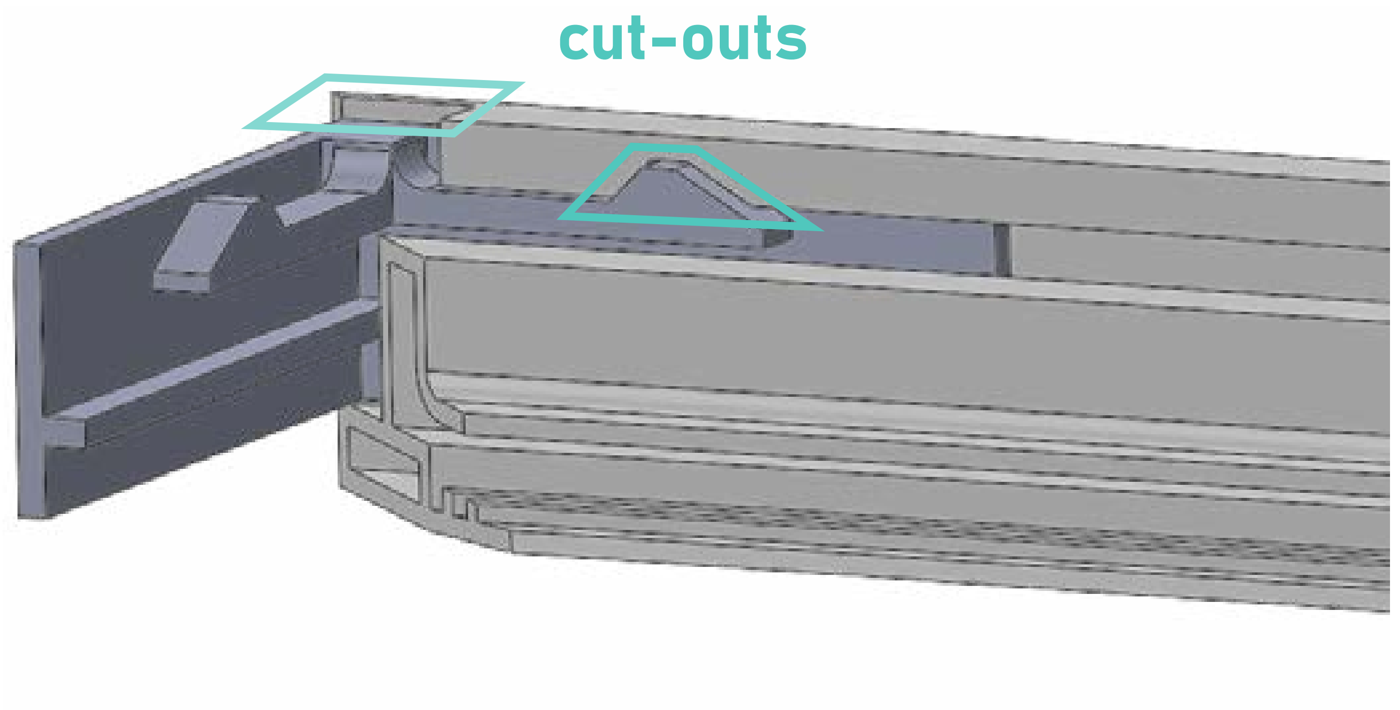


Figure 116. After extrusion, cut-outs have to be made in the frame sides to make them match the clicking corners.

Figure 117. The existing CoreLine accesory, demonstrating a slide and click construction.

Prototyping and demo

Since plastic extrusion and injection molding facilities were not available, prototypes of the frame 3D printed. The iterations of the frame and clicking corners are documented in the next pages and summarized in Figure 118..

1. Testing vertical printing orientation without supports.
2. Connecting the frame side to the clicking corner.
3. Imroved fit between frame side and clicking corner.
4. Complete frame.

Figure 118. Iterations of prototypes created throughout the development of the frame.

1

Testing vertical printing orientation without supports.
A quick initial version of the frame was printed to check if there were issues printing a relatively tall object with thin walls. The frame segment was printed vertically without supports and this gave good results.

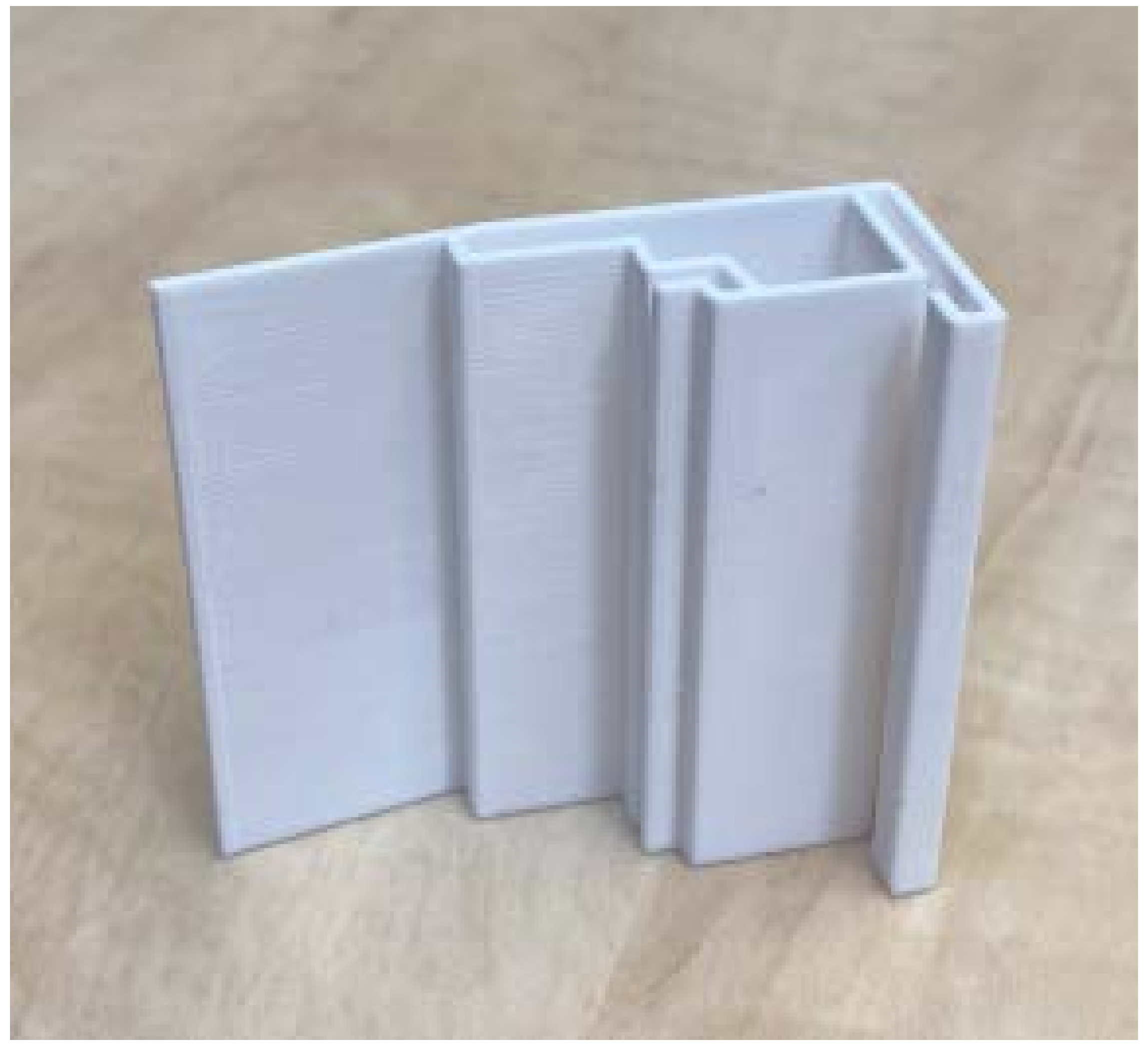


Figure 119. Vertical printing of frame segment without printing supports.

2

Connecting the frame side to the clicking corner.
A frame segment and a clicking corner were printed to test their connection.

→ There needs to be more space to enable insertion of the click finger.
→ The frame can be slightly heightened and the click finger can be made smaller.

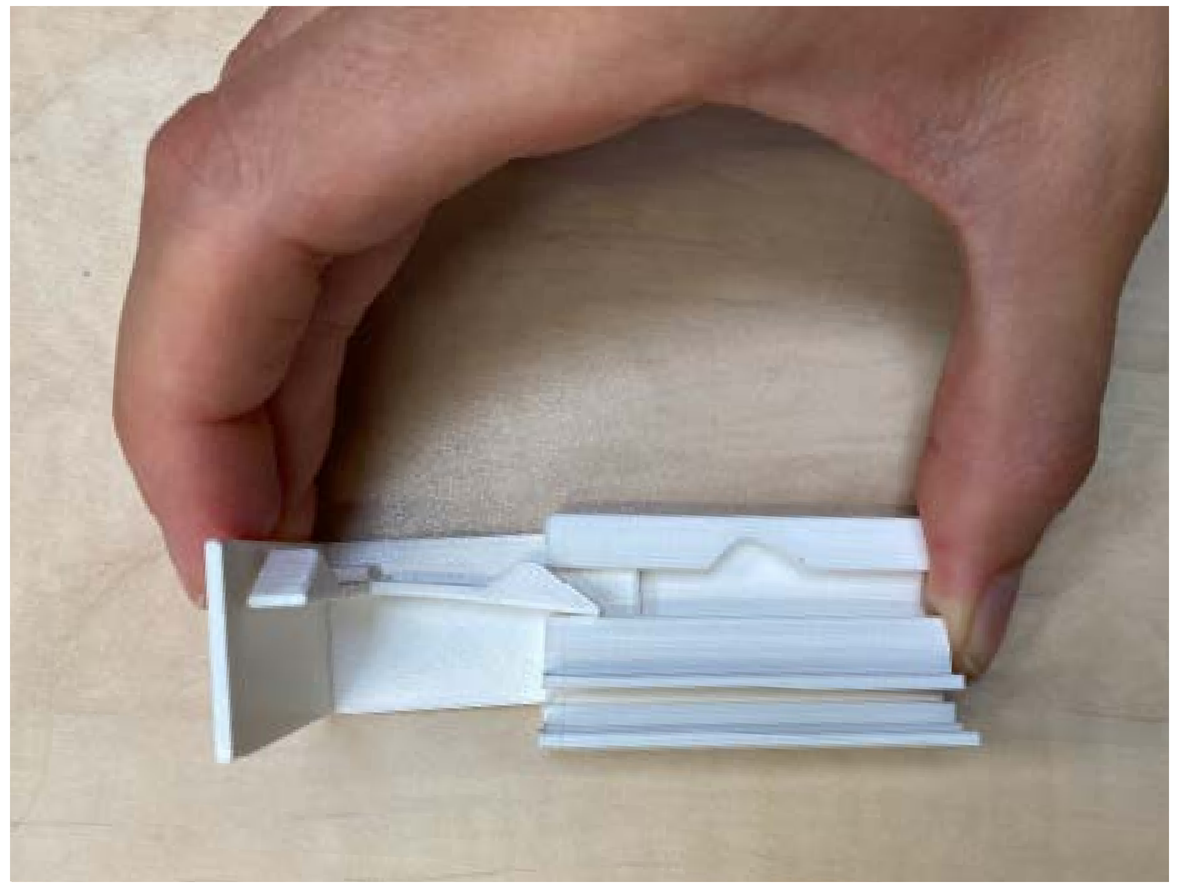


Figure 120. First iteration of frame and click corner combination. The frame did not provide enough space for insertion of the click corner.

3

Imroved fit between frame side and clicking corner.
→ The clicking corner fits well into the frame ends (see Figure 121). The parts can be removed from each other with a reasonable amount of force.
→ The two frame parts fit together nicely, the seam is only 0.5 mm wide (see Figure 122).

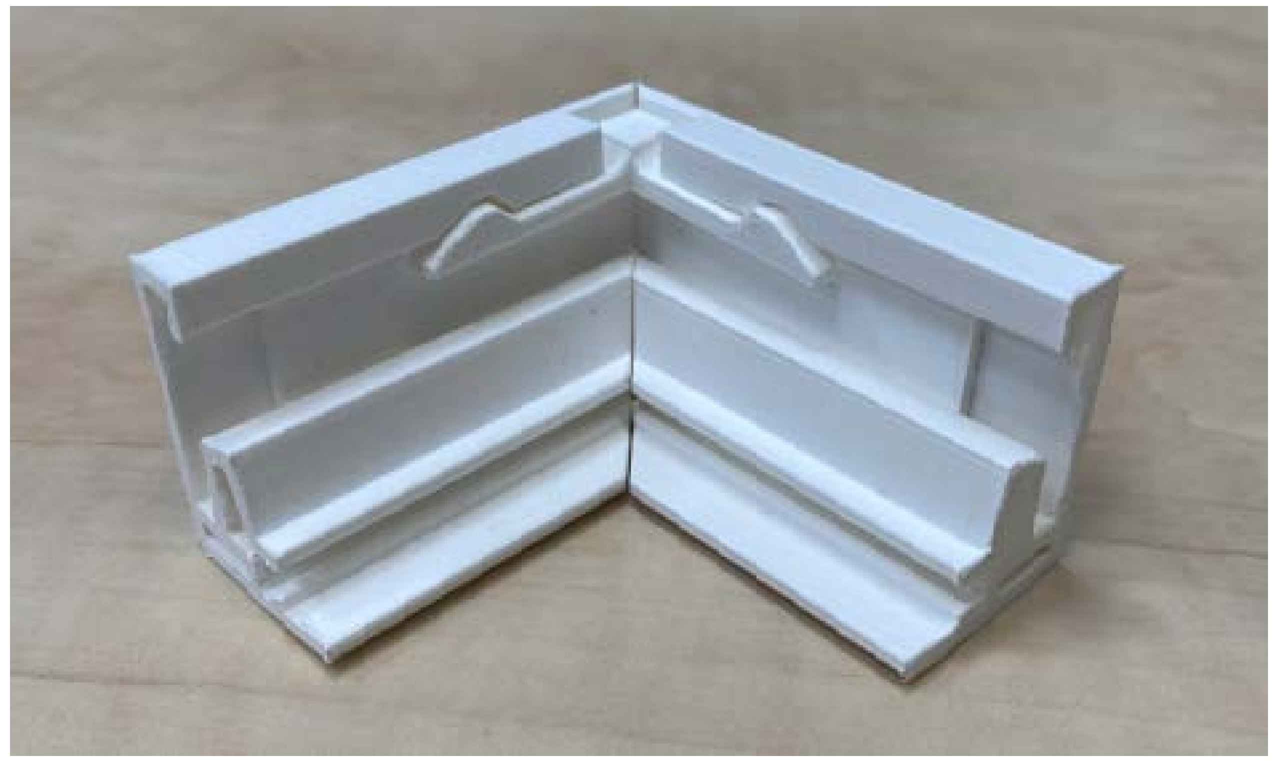


Figure 121. Good fit of clicking corner and frame segments.

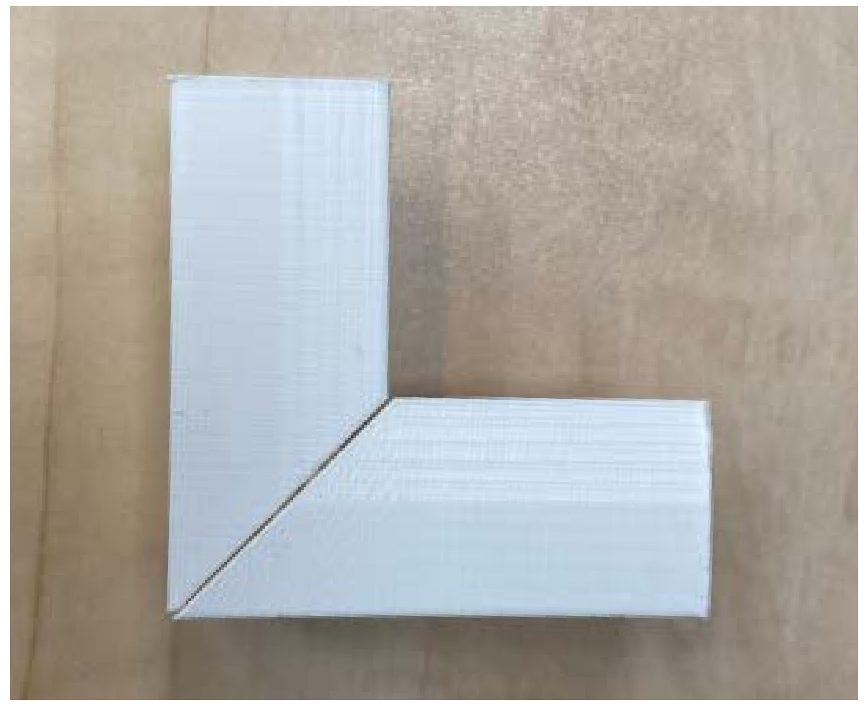


Figure 122. The seam between the frame ends is only 0.5 mm wide.

4

Complete frame.
For the final frame, the same clicking geometry as in the previous iteration was applied. The shape of the profile is adapted to match the curve of the backplate's outer edges (see Figure 115).

Each side of the frame is built up of three parts, because the available 3D printers did not have sufficient build volume to make one complete side of 595 mm.

→ The fit between the assembled frame and the exit windows is good (see Figure 133).


Figure 133. Good fit between the frame and exit windows.

4.6.3 L2 ultrasonic sandwich

In the proposed redesign, the L2s is sandwiched in between the backplate and the reflector. The reflector is attached to the backplate by means of ultrasonic welding.

Material choice

For recyclability reasons, the backplate and the reflector should consist out of the same material. If the backplate is made out of PS, the reflector should consist of PS as well.

Geometry

The ultrasonic welding should be done on both sides of each L2, so that they are securely kept in place (see Figure 134). The exact embodiment of this welding - e.g. how wide will the weld seam be - has not yet been explored.

Prototyping and demo

The ultrasonic welding of the reflector to the backplate has not been tested. For the sake of the demonstrator, the welding connection is replaced by glue.

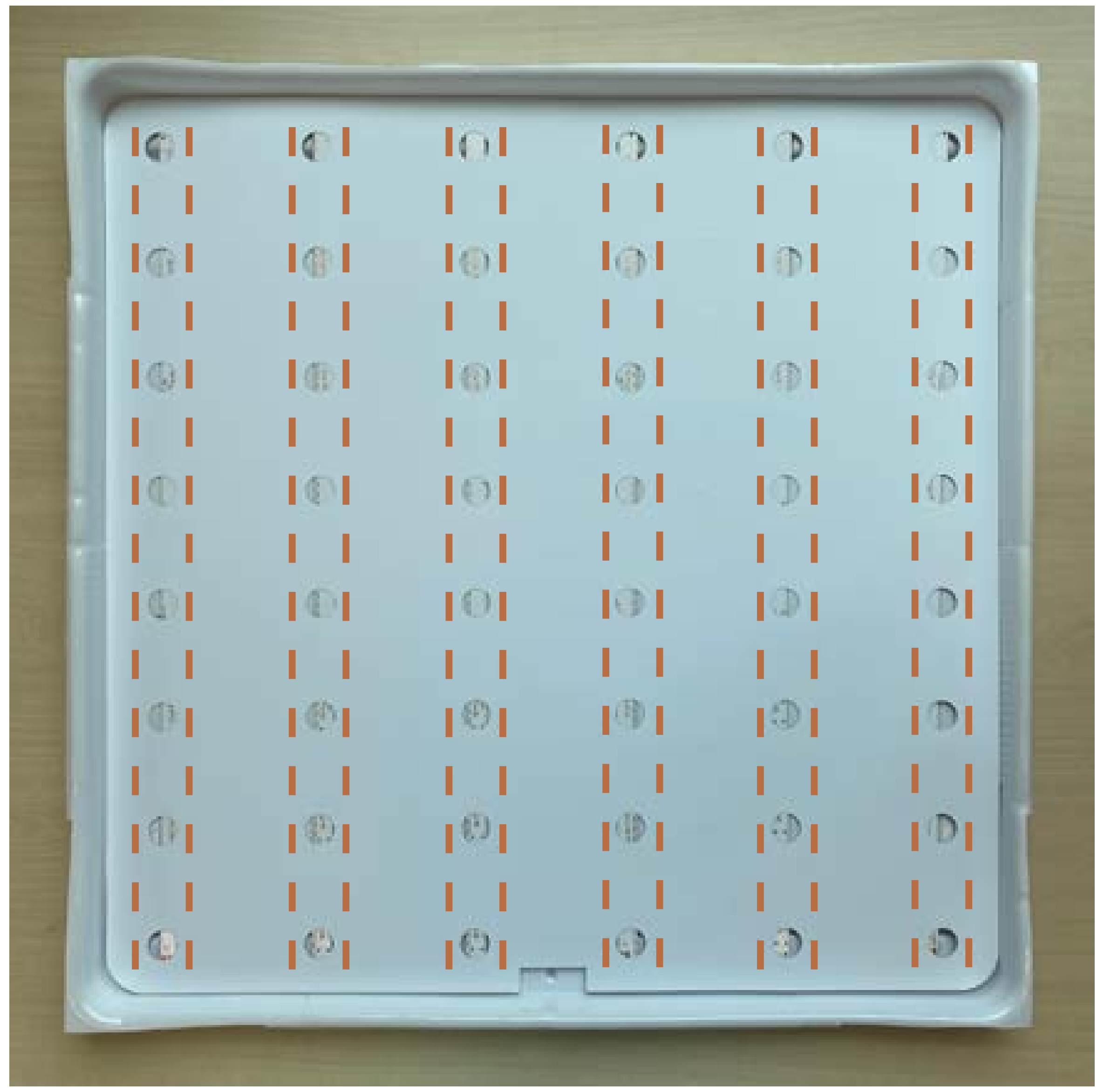


Figure 134. The reflector should be ultrasonically welded to the backplate along both sides of each L2 (indicated by brown dashed lines).

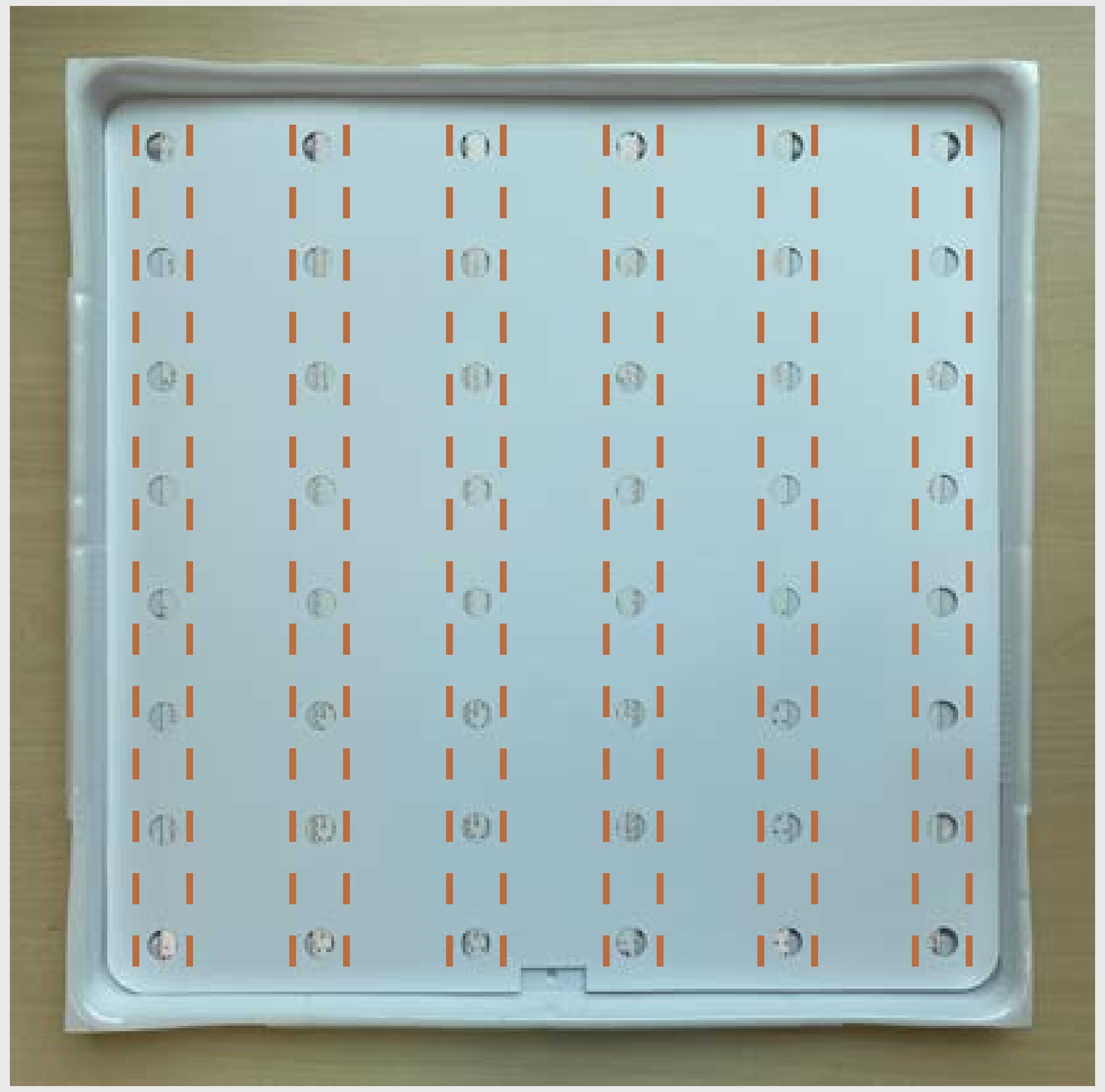
4.6.4 Assembly

Assembly of the luminaire is explained in Figures 135-138 across the next four pages.

Step 1
Place the backplate on the table, upside down.

Step 2
Place the L2s in their designated spaces.

Step 3
Place the reflector and ultrasonically weld it to the backplate (along the dashed brown lines).



Step 4
Place the exit windows on the table.

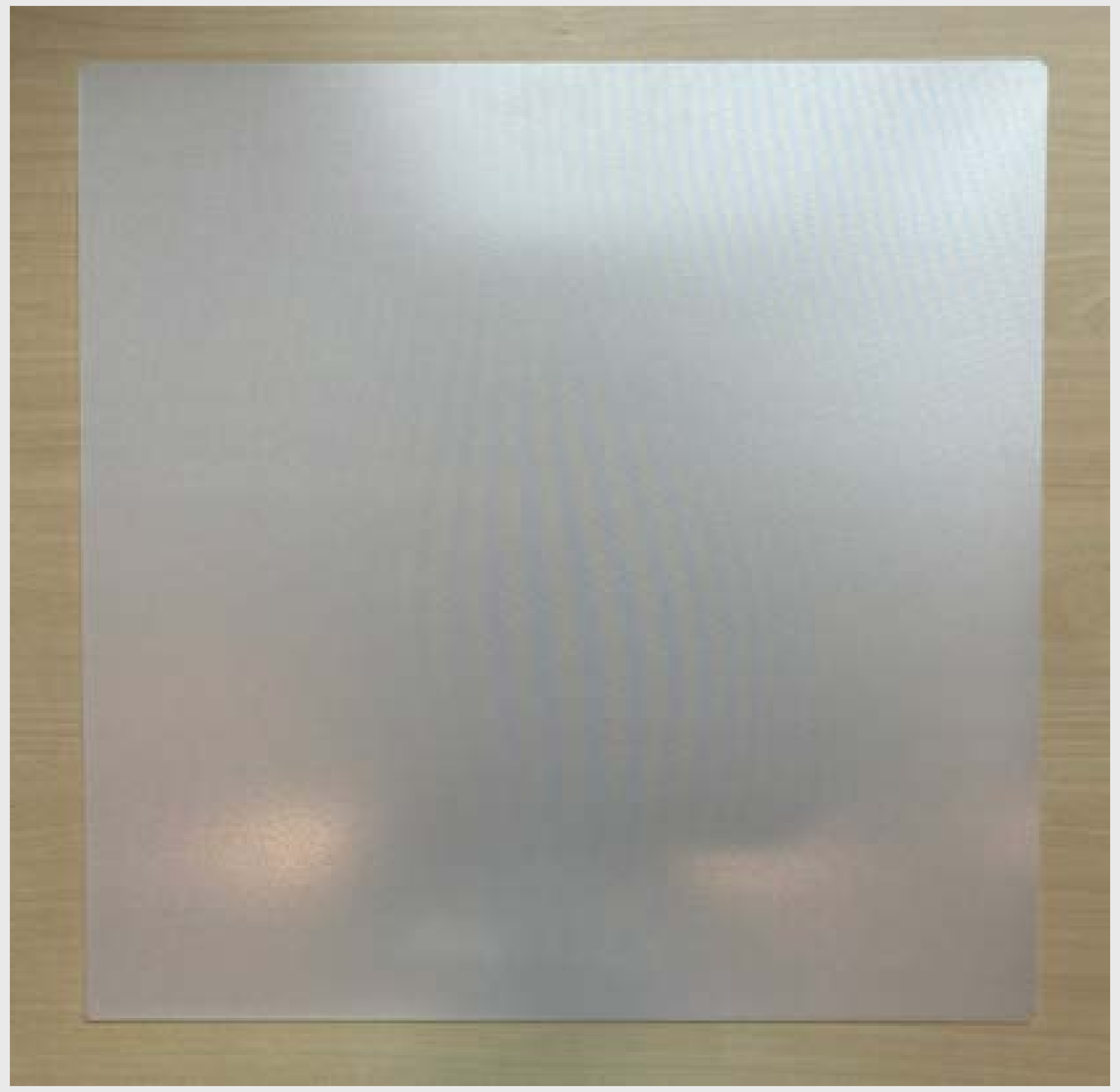


Figure 135. Steps 1-4 of assembly of the product.

Step 5
Place the backplate over the exit windows.

Step 6
Slide one side of the frame sides onto the backplate and exit windows.

Figure 136. Steps 5 and 6 of assembly of the product.

Step 7
Attach clicking corners to both ends of the frame

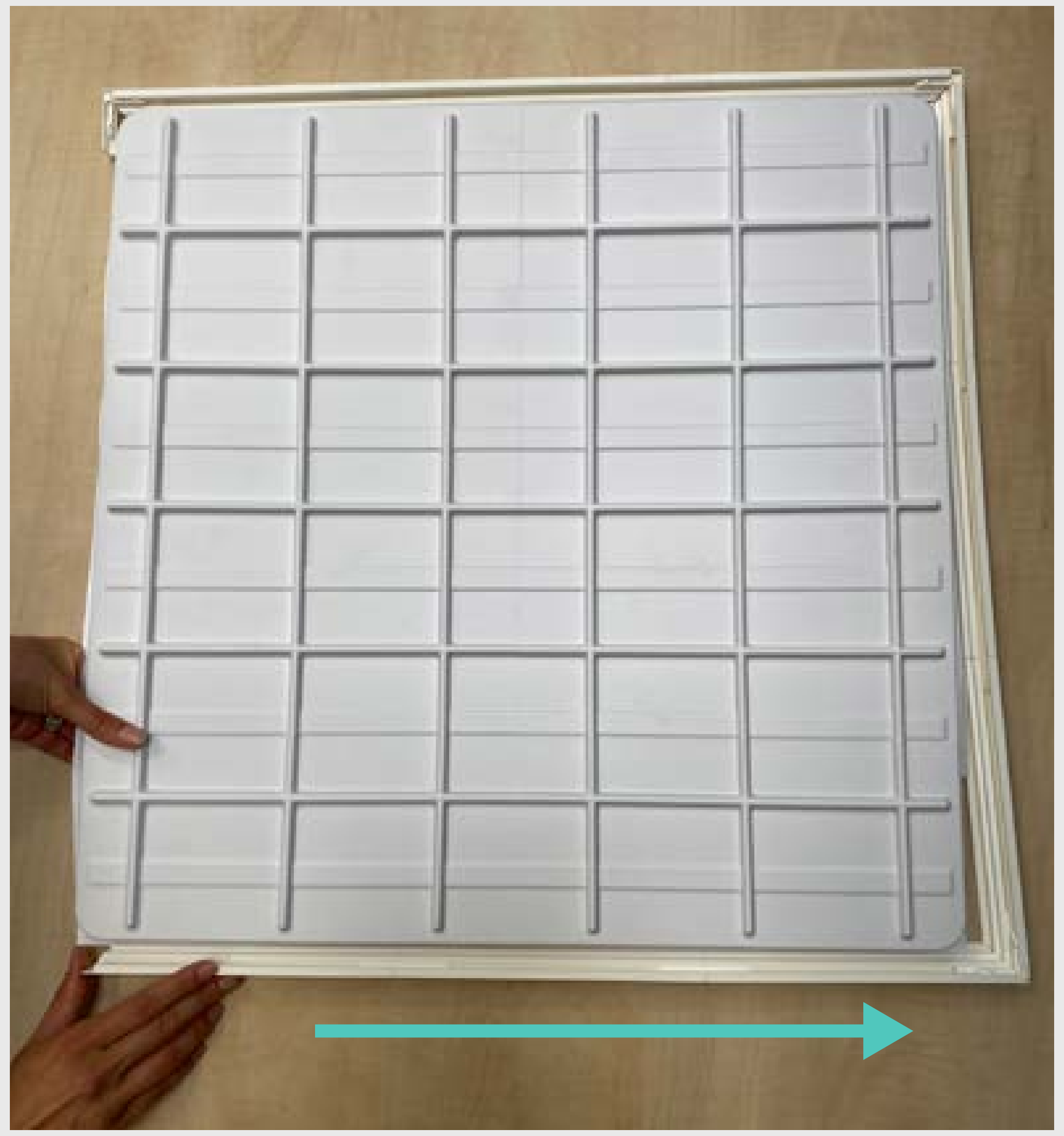
Step 8
Slide the second side of the frame onto the backplate and exit windows, and click it onto the clicking corner.

Step 9
Attach the third side of the frame in the same manner as in step 8.

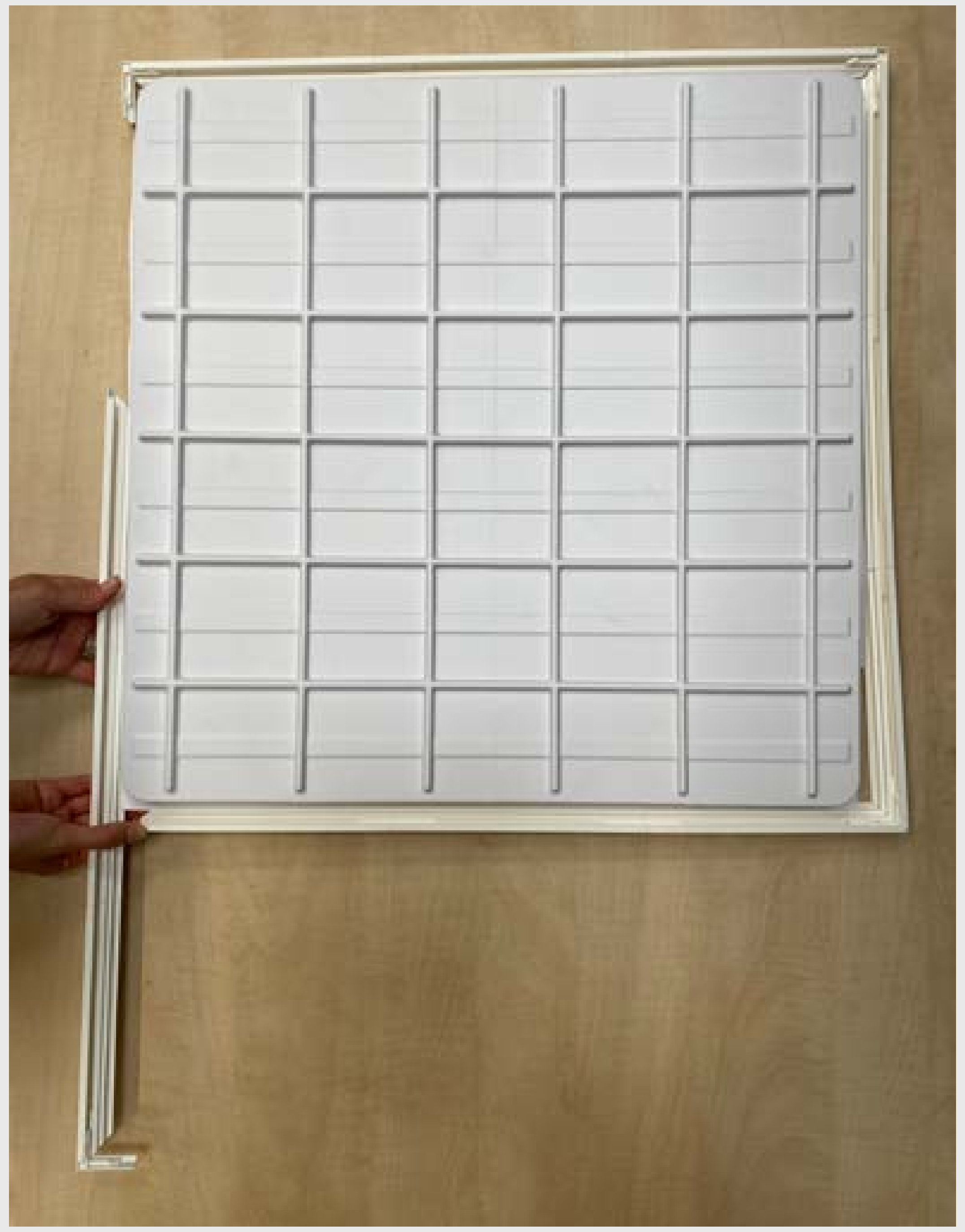
Figure 137. Steps 7-9 of assembly of the product.

Step 10

To attach the final side of the frame, first push back one of the previously attached sides.



Slide on the final frame side.



Connect the final clicking corner.

Assembly is finished.

Figure 138. Step 10 of assembly of the product.

4.6.5 Complete demonstrator

The separate components together form the complete demonstrator (see Figure 139). It provides a first proof of concept that the CoreLine can be recreated in plastic, with thermoforming of the backplate as a promising alternative to metal stamping. It also demonstrates the challenges to be solved, mainly related to assembly and mechanical performance.

Assembly

Although the frame, backplate and exit windows fit together, the flimsiness of the backplate's outer edges make assembly tricky. Especially when the final frame side is attached (see Figure 138), the previously attached sides are quite prone to release from the backplate. Thus, further development of the backplate should focus on achieving thicker outer edges.

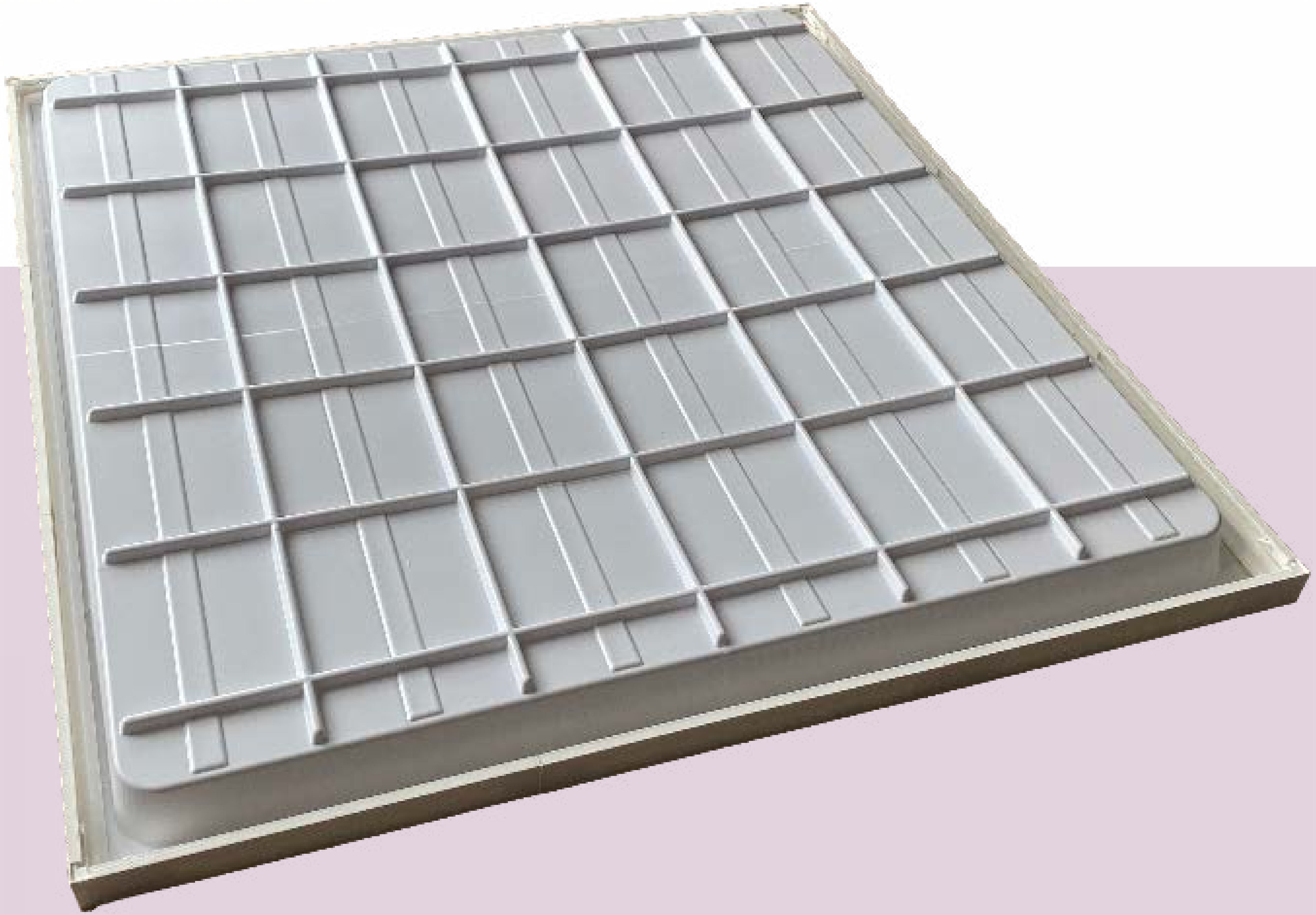


Figure 139. The complete demonstrator.

Mechanical performance

The demonstrator shows a larger deflection than was predicted based on simulations, namely 10 mm instead of 6 mm (see Figure 139). The difference may occur due to the fact that in the simulation, the backplate was modelled with a constant wall thickness of 1 mm. In reality, the PS sheet gets stretched out during thermoforming, resulting in wall thicknesses below 1 mm. Changes in the design are needed to achieve acceptable deflection values.

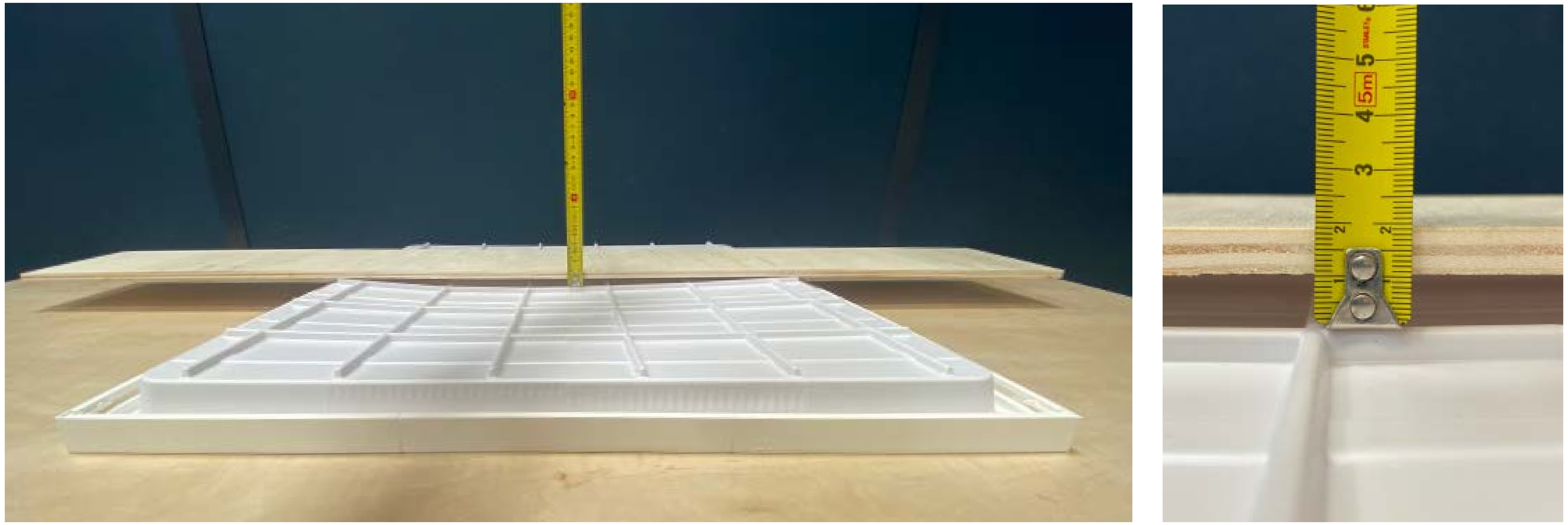


Figure 139. Maximum deflection of the backplate is 10 mm.

5. Discussion

This chapter starts out with an evaluation of the redesigned product. Then, some remarks follow relating to the application of design guidelines, the interplay between the recycling industry and design for recycling, and the tension between recyclability and repairability.

5.1 Evaluation of Redesign

5.1.1 Material choice

One of the challenges in this project has been the application of design guidelines concerning material choice. As described in chapter 5.1, unclarity existed about the recycling of different types of plastics, and the impact of additives. After the concept featuring a plastic backplate and frame was selected for further development, new information related to additives came to light.

Namely, in the status quo of plastics recycling, plastic fragments with a density above 1.08 kg/m3 are not recycled, because they might be brominated [refer to Galloo interview appendix]. Pure polystyrene (PS) - which is the assigned material for the backplate and frame - has a density of 1.05 kg/m3 and thus it would get recycled. However, since the CoreLine recessed luminaire replaces a tile of a building's grid ceiling, it is considered a structural part of the building and therefore needs to meet certain flammability requirements. It is likely that pure PS of 1 mm thickness would not meet these reruirements, and flame retardant additives would have to be added. This would increase its density to above the 1.08 treshold. Fragments of the backplate and the frame would therefore not be recycled, which would be a big loss as they together comprise a large part of the total product weight.

This means that further steps are necessary before the presented concept can be marketed as a recyclable luminaire. Several directions may provide solutions.
Firstly, Signify could consider to switch to the runner-up concept, which features a steel backplate and frame. Steel does not need additives in order to meet the flammability requirements. As of now, this direction is less interesting to Signify, because the move to a plastic luminaire provides them with opportunities in the face of potential metal scarcity and developments in localised manufacturing.

Secondly, changes in the luminaire's electronics might eliminate the need for flame retardants in the PS. The exact flammability requirements imposed on a luminaire depend on the electrical power it uses. This in turn depends on the efficiency of the LEDs; a higher efficiency means that less power is needed. If it is possible to sufficiently reduce the power usage of the CoreLine, then the flammability requirement it needs to meet becomes less strict. Then, the PS components might pass the tests without any flame retardant additives. Wall thickness of the components could be slightly increased to help reach sufficient flame resistance.

Thirdly, the luminaire and its installation could be adapted, so that it is attached below a grid ceiling tile, instead of replacing it. The luminaire would then no longer be subject to the flammability requirements and the flame retardant additives can be omitted from the plastic. The challenge of this direction is to still make the luminaire look integrated within the grid ceiling.

Furthermore, Signify could circumvent the recyclability issue by maintaining ownership of the product and organising its recycling. If a recycler is aware of the exact additives present in a plastic waste stream, they can take measures to recycle it properly. However, it is questionable whether there is a business case for this scenario.

Lastly, flame retardant additives in plastic might pose less of a problem if changes in the recycling industry take place. For instance, chemical recycling - as opposed to mechanical recycling - allows for removal of additives from plastics. It must be noted that the energy demand of chemical recycling is much higher than that of mechanical recycling, so the desirability of this scenario is debatable.
Another potential solution lies in the sorting methods used by plastics recyclers. Using density-based separation, PS containing flame retardant additives cannot be recognized as PS and so will not be recycled. However, plastics can also be identified using infrared separation, which is not affected by density. PS with flame retardant additives would still be recognized as being PS, and could then be recycled.
Although these scenarios may solve the issue in the future, we cannot be certain that they will actually happen. So, if Signify wants to market the redesigned CoreLine as a recyclable luminaire prior to such industry changes taking place, they should consider exploring one of the previously described directions.

5.1.2 Further development

In further development of the CoreLine office luminaire, the following points are important.

As mentioned, the choice for PS for the backplate, reflector and frame is only tentative. More research is necessary to determine if this is actually the best option. A main point of research should be the light reflectivity that can be accomplished in PS. In addition, PS should be compared in more detail to other plastics in terms of costs and environmental impacts.

Secondly, the backplate design should be optimized to reduce the thinning of PS in the curved outer edges. If the backplate is very thin in this area, the connection to the frame is less secure. Increasing the gutter width of the outer edges may offer improvements, but there are likely other options to be explored as well.

Sagging of the backplate turned out to be more than anticipated. Approaches to reduce this sagging include:

- Using a slightly thicker PS sheet for thermoforming the backplate.
- Increasing the number of ribs in the backplate.
- Increasing the height of the ribs in the backplate.

Furthermore, the amount of material used in the frame could probably be reduced. In the proposed redesign, the frame profile includes geometry both for the connection to the backplate and for accomodation of the clicking corners (see Figure 140). These functions could be combined into the same geometry, if more material is removed during post-processing, see Figure 141. This reduces the frame height from 21 to 14 mm.

Another option to consider, is to connect the frame and backplate by means of ultrasonic welding. If they are both made from the same type of plastic, such as PS, then welding them together poses no problem for recycling. This might be a cheaper solution than the proposed construction, for which additional components need to be injection molded (i.e. the four clicking corners). Also, this direction removes the challenge of creating a thicker outer edge, since such a curved surface for connection to the backplate would no longer be necessary.
It should be noted that welding the backplate and frame together would make it impossible to repair the product, while the proposed slide and click solution is much more suitable for repair.

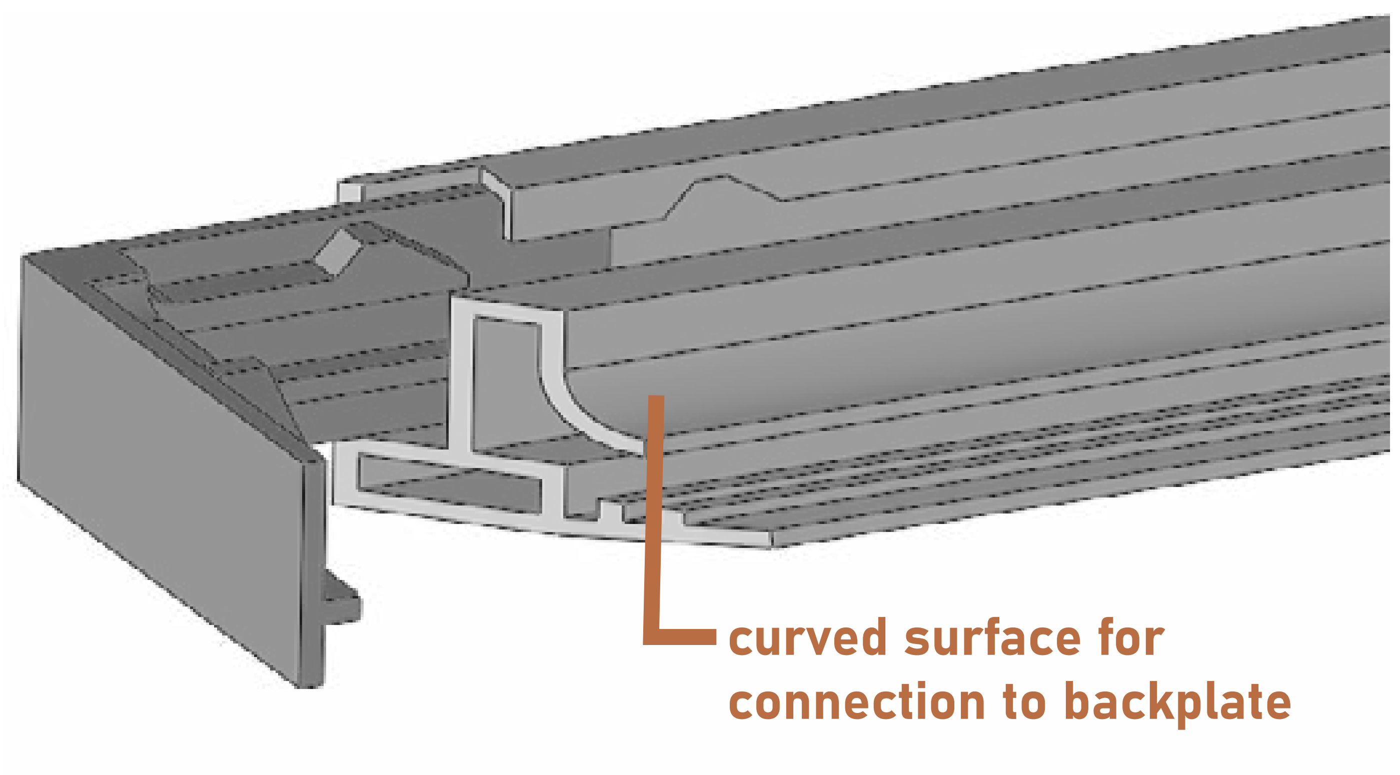


Figure 140. Proposed redesign of the frame as presented in chapter 4.6.2. The frame is 21 mm tall.

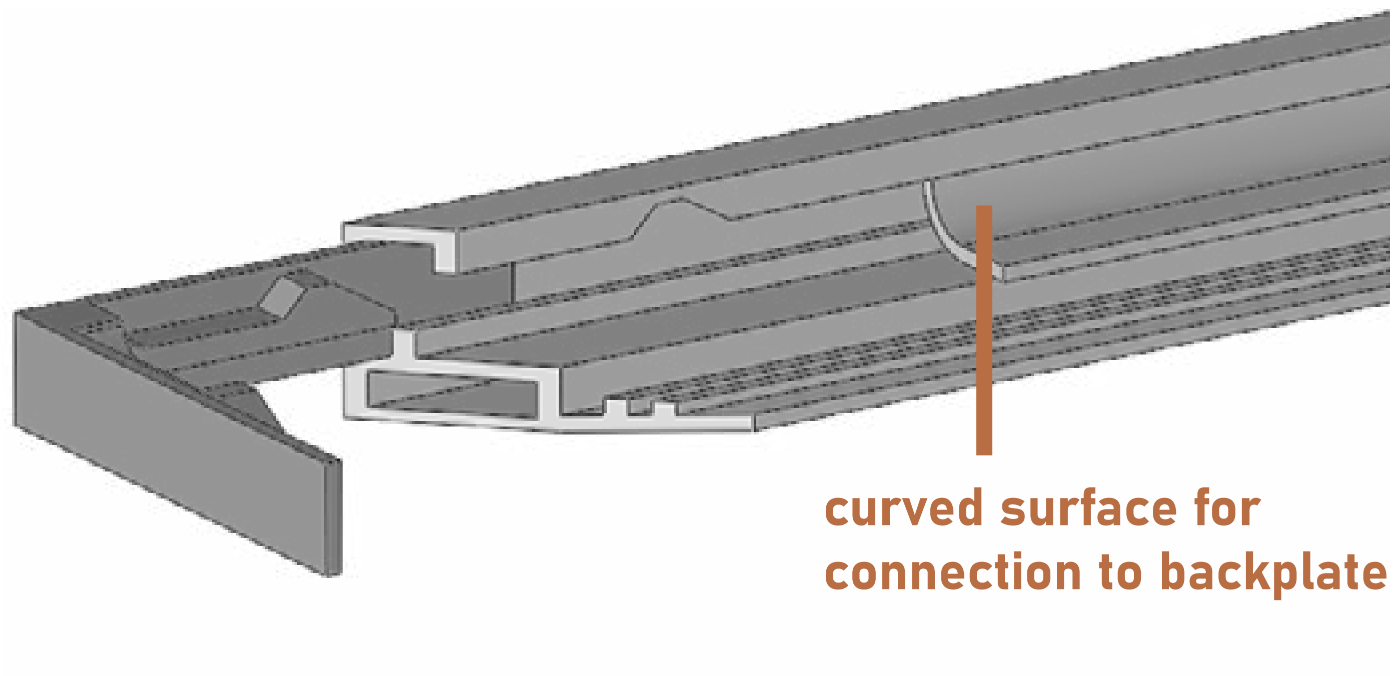


Figure 141. Alternative design of the frame, being 14 mm tall.

For securing the L2s to the backplate, there is also an additional alternative that was not mentioned in the morphological chart of chapter 4.5.1. Namely, the L2s could simply be taped to the backplate. A prototype for this direction has already been tested in a shredder and the L2s liberated well from the tape connection (see chapter 4.4). It could be explored if there is a tape which can attach the L2s securely to the backplate throughout the complete use phase, but will also release when entered into a shredder.

Finally, there are two aspects of the proposed redesign that have not been explored during the embodiment stage, and will need further development. Firstly, there is the matter of the driver securement via a ring around its cable. Secondly, a detailed design of the ultrasonic welding of the reflector to the backplate needs to be made.

5.2 Applying Design Guidelines

Throughout this project, I have worked with the design for recycling guidelines as proposed by Berward et al. (2021). In trying to apply these guidelines, I have made the following observations.

Although the guidelines provided a very good start in identifying recyclability issues, acquiring more detailed knowledge of the recycling process has helped me to make better design choices. For instance, the existing guidelines warn against "fixing ferrous metals to non-ferrous metals in either parts or fasteners." Following this guideline, it was easy to recognize that the CoreLine's connection of steel screws in the aluminum frame is problematic. However, it did not lead to the realization that the L2s aluminum -core L2s are also a combination of ferrous and non-ferrous metals. This realization only came after acquiring a better understanding of the material flows within the recycling process. For this reason, I would argue that design for recycling guidelines should be accompanied by an overview of the recycling process.

As mentioned, guidelines regarding the use of different plastic types and additives have caused confusion. It can be difficult and time-consuming to determine which types of plastic get recycled. It gets more complex because there are differences between waste categories. For instance, while PET does get recycled from plastic bottles, it does not seem to be recycled from WEEE streams. I believe it would be very helpful for designers to have access to an overview of which plastics do and which do not get recycled from which WEEE stream. The challenge here is that recycling may be different across countries and continents, and is subject to change as the recycling industry develops over time.

With regards to additives in plastics, it may be helpful if guidelines provide some more information per additive type. For instance, flame retardant additives apparently increase a plastic's density, which can affect recycling. If there are other types of additives which impact a plastic's recyclability, it is important for designers to know.

5.3 Recycling Industry and Design for Recycling

In the current project, the CoreLine luminaire has been optimized for the currently standard method of liberation: shredding. However, shredding comes with pitfalls of incomplete liberation and loss of critical raw materials. In the future, the recycling industry might move away from shredding and implement other liberation technologies. It is therefore important for companies and designers to stay up to date with major developments in the recycling industry, and adapt their design practices accordingly.

5.4 Recyclability vs. Repairability

This project has been focused on design for recyclability. Along the way, repairability has been added as a nice-to-have. The final concept is mostly suitable for repair, except for the L2 to backplate connection, which is ultrasonically welded. It is currently not expected that the CoreLine will enter a repair scenario, but if this changes in the future, then the L2 to backplate connection should be reevaluated.

6. Guidelines

The second deliverable of this graduation project is a set of guidelines to support the design of recyclable luminaires. To communicate the guidelines to the research team at Signify, a poster format was chosen (see Figure 142). This is a commonly used approach within the team to share knowledge, and makes the information quickly accessible to the whole team.

The poster is divided into three parts. The first part is the overview of the concentration step in the WEEE recycling process, as introduced in chapter 2.2.1 (see Figure 143). An understanding of the recycling process is expected to help understand and successfully apply the guidelines. Photos of the materials are included to make the process less theoretical and more tangible.
The design guidelines are divided into two main categories: component connection and material selection.

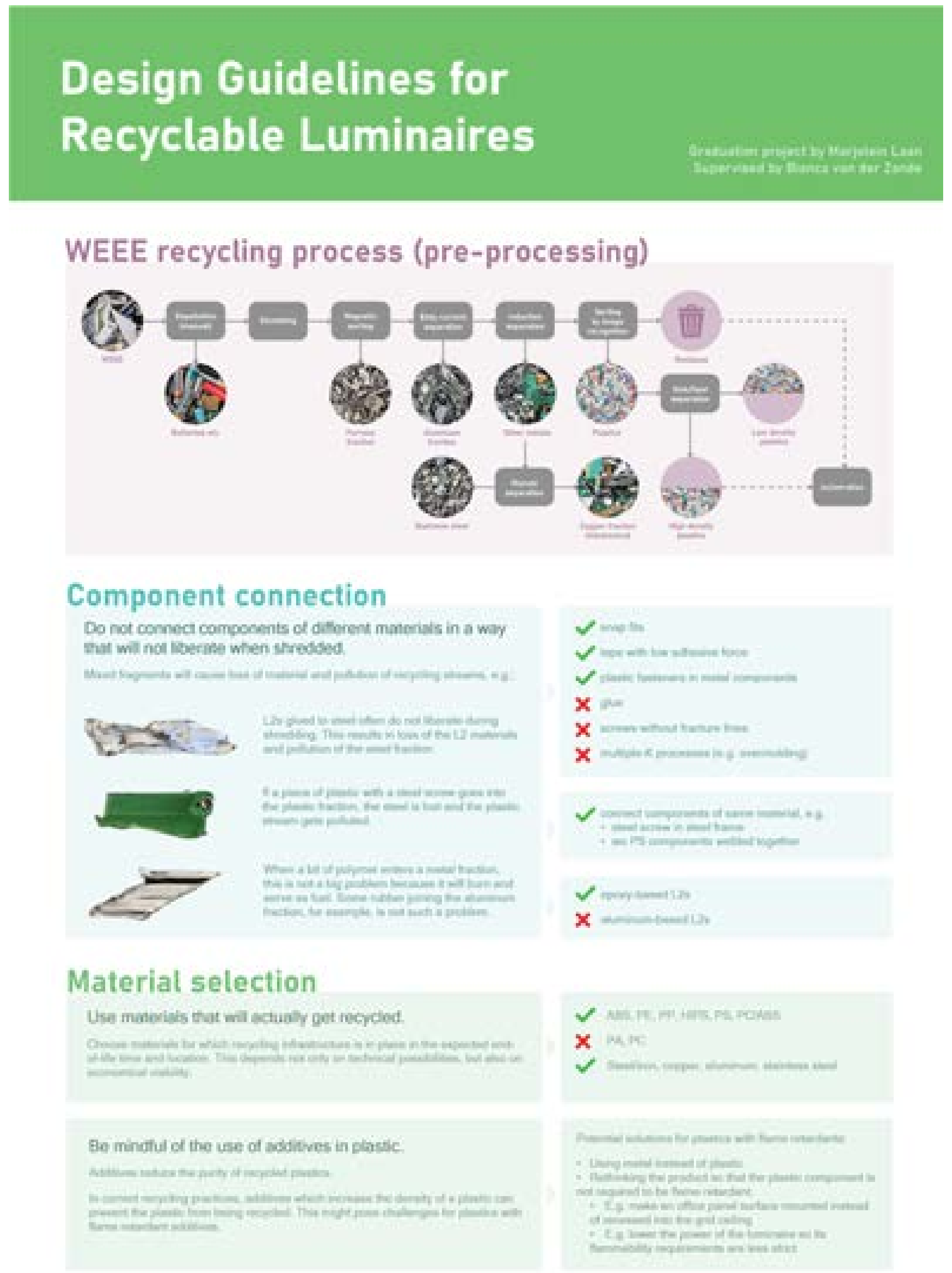


Figure 142. The guidelines for designing recyclable luminaires in poster format.

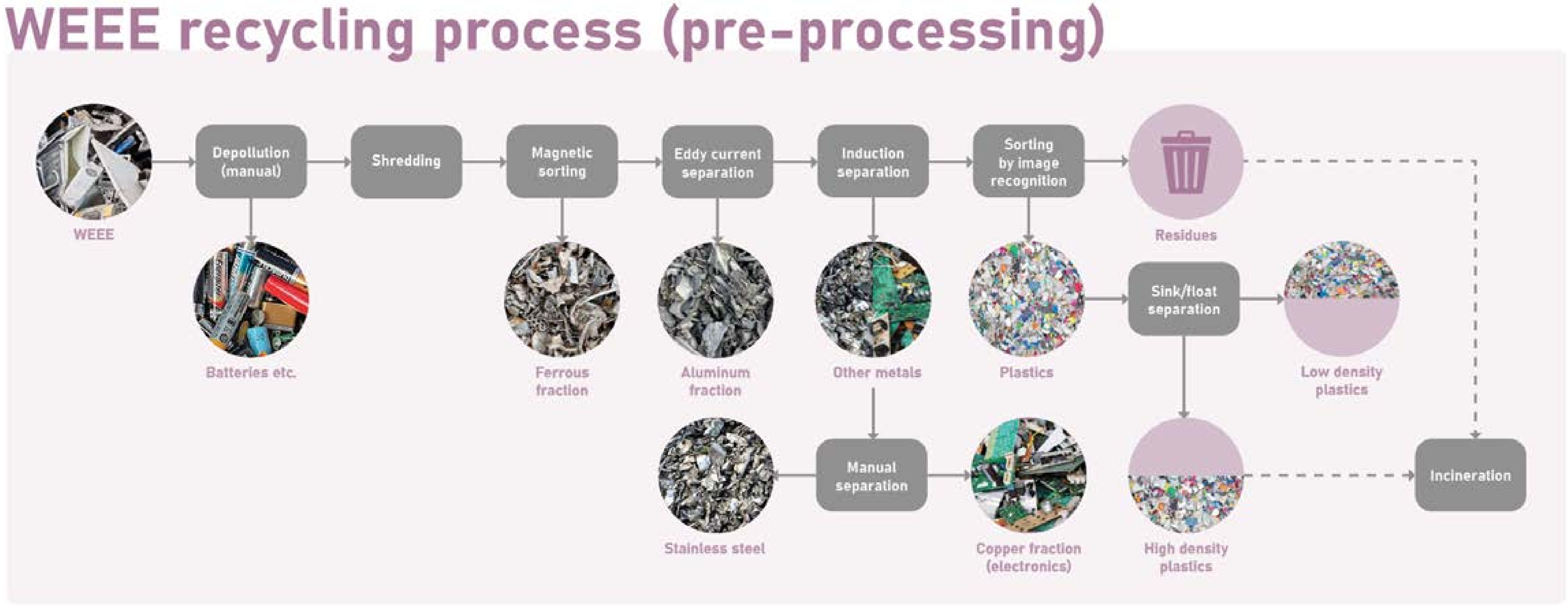


Figure 143. First part of guideline poster: WEEE recycling

The guidelines concerning component connection are shown in Figure 144. The insights resulting from the shredding experiments are incorparated into this section.

Component connection

Do not connect components of different materials in a way that will not liberate when shredded.

Mixed fragments will cause loss of material and pollution of recycling streams, e.g.:

L2s glued to steel often do not liberate during shredding. This results in loss of the L2 materials and pollution of the steel fraction.

If a piece of plastic with a steel screw goes into the plastic fraction, the steel is lost and the plastic stream gets polluted.

When a bit of polymer enters a metal fraction, this is not a big problem because it will burn and serve as fuel. Some rubber joining the aluminum fraction, for example, is not such a problem.

- ✔ snap fits
- ✔ tape with low adhesive force
- ✔ plastic fasteners in metal components
- ✘ glue
- ✘ screws without fracture lines
- ✘ multiple-K processes (e.g. overmolding)

- ✔ connect components of same material, e.g.
  - steel screw in steel frame
  - wo PS components welded together

- ✔ epoxy-based L2s
- ✘ aluminum-based L2s

Figure 144. Second part of guideline poster: material selection.

The final part of the poster concerns material selection (see Figure 145). Although this topic has not been fully explored within this project, two main factors of importance have been identified and are important to grow awareness of among Signify employees. Both PA and PC are indicated as materials that will not be recycled. This is based on the observation that three major Europe based recyclers do not recycle these plastics (MGG Polymers, n.d.), (Enva, n.d.), (Galloo, n.d.).

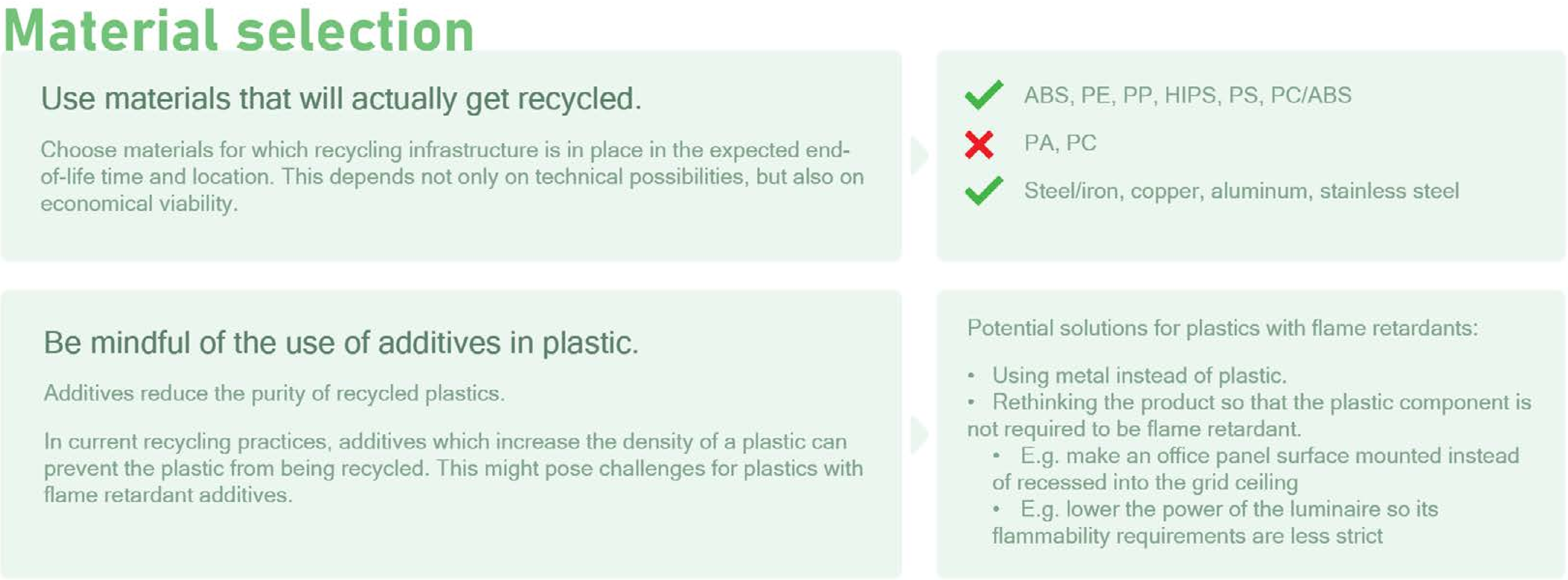


Figure 145. Third part of guideline poster: material selection.

7. Conclusion

In conclusion, the existing CoreLine office luminaire has been redesigned for improved recycling. Shredding experiments have shed light on the recyclability of the current product. The main issues have been identified and are solved in the proposed redesign.

Besides improved recyclability, the proposed redesign offers additional benefits to Signify. Replacing the steel of the backplate and the aluminum of the frame by polystyrene is expected to significantly reduce the cost price of the product. Also, moving away from metals can make Signify less vulnerable to potential metal scarcity in the future.

An important challenge in further development of the concept is the issue of flame retardants and their impact on recyclability of the product. Given that the intention of redesigning the CoreLine luminaire was to improve its recyclability, it would be a shame if the redesigned product would actually be worse for recycling due to flame retardants. A range of directions to address this problem have been proposed.

Lastly, a set of guidelines have been created which serve to aid designers in designing recyclable luminaires. These guidelines are based on all the learnings acquired throughout the project regarding component connection and material selection.

References

Berwald, A., Dimitrova, G., Feenstra, T., Onnekink, J., Peters, H., Vyncke, G., & Ragaert, K. (2021). Design for circularity guidelines for the EEE sector. Sustainability (Basel), 13(7), 3923. https://doi.org/10.3390/su13073923

Bluhm, H., Frey, W., Giese, H., Höppe, P., Schultheiss, C., & Sträßner, R. (2000). Application of pulsed HV discharges to material fragmentation and recycling. IEEE Transactions on Dielectrics and Electrical Insulation, 7(5), 625–636. https://doi.org/10.1109/94.879358

Chancerel, P., Meskers, C., Hagelüken, C., & Rotter, V. S. (2009). Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment. Journal of Industrial Ecology, 13(5), 791–810. https://doi.org/10.1111/j.1530-9290.2009.00171.x

Charles, R. G., Douglas, P., Dowling, M. R., Liversage, G., & Davies, M. L. (2020). Towards Increased Recovery of Critical Raw Materials from WEEE– evaluation of CRMs at a component level and pre-processing methods for interface optimisation with recovery processes. Resources, Conservation and Recycling, 161, 104923. https://doi.org/10.1016/j.resconrec.2020.104923

De Tommaso, J., & Dubois, J. (2021). Risk Analysis on PMMA Recycling Economics. Polymers, 13(16), 2724. https://doi.org/10.3390/polym13162724

Enva. (n.d.). Buy plastic compounds. Retrieved June 17, 2024, from https://enva.com/resource-recovery/plastic/products

European Commission. (n.d.). Waste from Electrical and Electronic Equipment (WEEE). Retrieved March 13, 2024, from https://environment.ec.europa.eu/topics/waste-and-recycling/waste-electrical-and-electronic-equipment-weee_en

Faludi, J., Bakker, C., & Balkenende, R. (n.d.). Sustainable Design From Vision To Action. IMAGINE. (n.d.).

Galloo. (n.d.). Plastiek. Galloo. https://www.galloo.com/nl/materialen/plastiek

IMAGINE. Retrieved April 9, 2024, from https://imagine-h2020.eu/

ImpulsTec. (n.d.-a). E-Waste recycling - ImpulsTec. Retrieved April 9, 2024, from https://impulstec.com/en/e-waste-recycling/

ImpulsTec. (n.d.-b). Technology - ImpulsTec. Retrieved April 9, 2024, from https://impulstec.com/en/technology/

Malooly, L., Daphne, T., & Circularise. (2023, November 9). R-Strategies for a Circular Economy. Circularise. Retrieved April 8, 2024, from https://www.circularise.com/blogs/r-strategies-for-a-circular-economy

Márquez, C., Martín, C., Linares, N., & De Vos, D. (2023). Catalytic routes towards polystyrene recycling. Materials Horizons (Print), 10(5), 1625–1640. https://doi.org/10.1039/d2mh01215d

MGG Polymers. (n.d.). PS | MGG Polymers. Retrieved June 17, 2024, from https://mgg-polymers.com/ps

NWO. (n.d.). Circular Circuits: design of next generation electronics for a circular economy. Retrieved March 13, 2024, from https://www.nwo.nl/en/researchprogrammes/perspectief/perspectief-grants/circular-circuits-design-next-generation

Okwu, P. I., & Onyeje, I. N. (2014). Extraction of Valuable Substances from E-Waste. American Journal of Engineering Research. https://www.ajer.org/papers/v3(1)/ZK31299304.pdf
Parajuly, K., Habib, K., Cimpan, C., Liu, G., & Wenzel, H. (2016). End-of-life resource recovery from emerging electronic products – A case study of robotic vacuum cleaners. Journal of Cleaner Production, 137, 652–666. https://doi.org/10.1016/j.jclepro.2016.07.142

Parajuly, K., Habib, K., Cimpan, C., Liu, G., & Wenzel, H. (2016). End-of-life resource recovery from emerging electronic products – A case study of robotic vacuum cleaners. Journal of Cleaner Production, 137, 652–666. https://doi.org/10.1016/j.jclepro.2016.07.142

Pestalozzi, F., Eisert, S., & Woidasky, J. (2018). Benchmark comparison of high voltage discharge separation of photovoltaic modules by electrohydraulic and electrodynamic fragmentation. Recycling (Basel), 3(2), 13. https://doi.org/10.3390/recycling3020013

Peters, H. A., Toxopeus, M. E., Jauregui-Becker, J. M., & Dirksen, M. (2012). Prioritizing 'Design for Recyclability' Guidelines, Bridging the Gap between Recyclers and Product Developers. In Springer eBooks (pp. 203–208). https://doi.org/10.1007/978-3-642-29069-5_35

PolyCE. (2021). Design for and from recycling: Practical guidelines for designers. In PolyCE Project. Retrieved April 10, 2024, from https://www.polyce-project.eu/wp-content/uploads/2021/04/PolyCE-E-book-Circular-Design-Guidelines-2.pdf

Shittu, O. S., Williams, I., & Shaw, P. J. (2021). Global E-waste management: Can WEEE make a difference? A review of e-waste trends, legislation, contemporary issues and future challenges. Waste Management, 120, 549–563. https://doi.org/10.1016/j.wasman.2020.10.016

Signify. (n.d.-a). About us. Retrieved March 13, 2024, from https://www.signify.com/nl-nl/our-company/about-us

Signify. (n.d.-b). Lighting for circularity. Retrieved March 13, 2024, from https://www.signify.com/nl-nl/sustainability/lighting-for-circularity

Signify. (n.d.-c). Substance management | Signify. Retrieved April 9, 2024, from https://www.signify.com/global/sustainability/product-compliance/substance-management

Vogtlander, J. (n.d.). Idemat2023 (V1.0) [Dataset]. https://nexus.openlca.org/database/IDEMAT

Weima. (n.d.). Shredding metal. https://weima.com/en/shredding/metal/

Appendices

Appendix A: Luminaire LCA data

	A	B	C	D	E	F	G	H	I
1	GWP total								
2		CoreLine [kg CO2e] (weight_CoreLine / weight_Ledinaire * GWP Ledinaire)	Ledinaire [kg CO2e] (data from Signify LCA or Idemat2023)	Ledvance [kg CO2e] (weight_Ledvance / weight_Ledinaire * GWP Ledinaire)	weight CoreLine [g]	Weight Ledinaire [g]	Weight Ledvance [g]	IDEMAT Carbon footprint [kg CO2e/kg]	
3	Frame	5.355355878	3.484824877	4.586644508	209	136	179		
4	Backplate	4.37783366	4.058015872	4.089473359	835	774	780		
5	Diffuser	2.014528671	0.937128893	0.949066841	675	314	318		
6	Reflector	0.10865	0	0.06765	53		33	2.05	A.130.04.117 Idemat2023 PET amorphous
7	Lenses	0.1275	0.1275		34	34		3.75	A.130.04.119 Idemat2023 pMMA
8	Driver housing	0.2346	0.1088		69	32		3.4	A.130.04.109 Idemat2023 PC
9	Connector housing	0.4824	0.1474		72	22		6.7	A.130.04.104 Idemat PA 6
10	LED strips	2.591716913	2.932732296	5.933667669	38	43	87		
11	Driver electronics	3.541704008	1.942224779		93	51			
12	Connector electronics	0.443476546	0.070022613		19	3			
13	Cable	0.135201966	0.067600983		28	14			
14	Screws	0.056944529	0.022777812		10	4			24 screws CoreLine, 8 screws Ledinaire
15									
16	ADPE								
17		CoreLine [kg Sbe] (weight_CoreLine / weight_Ledinaire * ADPE Ledinaire)	Ledinaire [kg Sbe] (data from Signifiy LCA)	Ledvance [kg Sbe]					
18	Frame	9.21436E-06	5.99595E-06						
19	Backplate	4.38781E-05	4.06726E-05						
20	Diffuser	1.05248E-05	0.000004896						
21	LED strips	0.000544987	0.000616695						
22	Driver electronics	0.000833246	0.000456942						
23	Connector electronics	0.000131974	2.0838E-05						
24	Cable	0.000253651	0.000126826						
25	Screws	4.84E-07	1.94E-07						

Appendix B: Input and output weights per batch

	A	B	C	D	E
1		Input weight [g]	Output weight [g]	Difference [g]	Difference [%]
2	CoreLines with driver	8584	8493	91	1.1
3	CoreLines without driver	7480	7459	21	0.3
4	CoreLine drivers	2484	2551	-67	-2.7
5	Ledinaires with driver	7145	6773	372	5.2
6	Ledvance without driver	7170	7222	-52	-0.7

Appendix C: Input and output weights per fraction, per batch

CoreLines with drivers

Batch (A): 4 Corelines with drivers

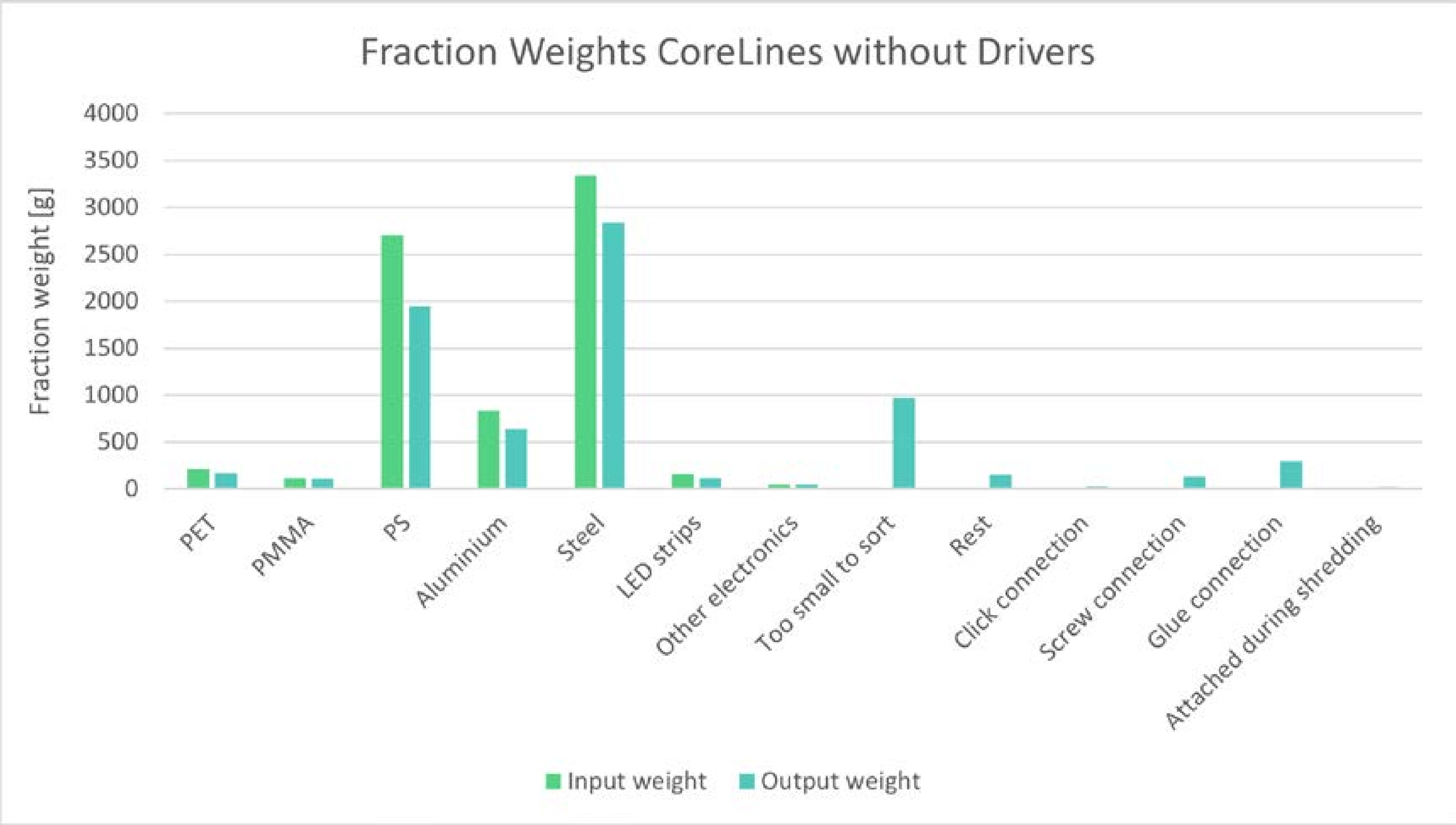
Input weight		**Output weight**			
Weight of 1 CoreLine with driver [g]	2146	Including container [g]	10002	**Difference [g]**	
Weight of 4 CoreLines with drivers [g]	8584	Weight of container	1487		
		Excluding container [g]	8515		69

Weights of fractions	Weight per product [g]	Input weight [g]	Output weight [g]	Difference [g]	Percentage lost [%]	Percentage unmixed [%]	Comments
Unmixed fragments							
PET	53	212	191	21	10	90	most went into steel fraction
PMMA	34	136	106	30	22	78	One lens weighs 0.71 g; most went into click connection (24 lenses; 17 g). No lenses found in other fractions
PS	675	2700	1920	780	29	71	most went into "too small to sort"
PA	72	273	167	106	39	61	green and white plastic (all plastic in connector)
PC	69	276	195	81	29	71	17 g went into screw connections (including 10 screws, 17-10*0.6=11 g)
Aluminum	209	836	676	160	19	81	107 g went into "screw connections" (including 29 screws; 107-29*0.6 = 89.6 g aluminum)
Steel	835	3340	2915	425	13	87	part of it went into glue connection
Other							
LED strips	40	160	99	61	38	62	97.5 g LED strip completely liberated, 21.6 g LED strips with lenses still attached (weight of lenses excluded)
Other electronics	141	564	411	153	27	73	PCB weighs 93 g
Too small to sort			1132				1050g fragments; 82g dust
Rest			80				
Connections							
Click connection			36				
Screw connection			150				screw_alu=107g; screw_pc=17g; screw_pa=12g; screw_steel=3g
Glue connection			167				
Electronics connections			95				
Attached during shredding			245				
TOTAL			8585				
Total weight in connections			693				
Percentage of weight in connections			8	%			

CoreLines without drivers

	A	B	C	D	E	F	G	H	I
1	Batch (D) 4 Corelines without drivers								
2									
3	**Input weight**		**Output weight**						
4	Weight of 1 CoreLine without driver [g]	1870	Including container [g]	8968		**Difference [g]**			
5	Weight of 4 CoreLines without drivers [g]	7480	Weight of container [g]	1486					
6			Excluding container [g]	7482		-2			
7									
8									
9	**Weights of fractions**	Weight per product [g]	Input weight [g]	Output weight [g]	Difference [g]	Percentage lost [%]	Percentage unmixed [%]		Comments
10	Unmixed fragments								
11	PET	53	212	166	46	22	78		
12	PMMA	29	116	106	10	9	91		
13	PS	675	2700	1947	753	28	72		
14	Aluminium	209	836	632	204	24	76		
15	Steel	835	3340	2834	506	15	85		
16	Other								
17	LED strips	40	160	118	42	26	74		118 g LED strip completely liberated, 9 g LED strips with lenses still
18	Other electronics	12	48	49	-1	-2	102		Just the cable from the panel to the driver
19	Too small to sort			970					
20	Rest			152					
21	Connections								
22	Click connection			27					
23	Screw connection			133					all in aluminum
24	Glue connection			292					
25	Attached during shredding			21					
26									
27	**TOTAL**			7447					
28	Total weight in connections			473					
29	Percentage of weight in connections			6	%				

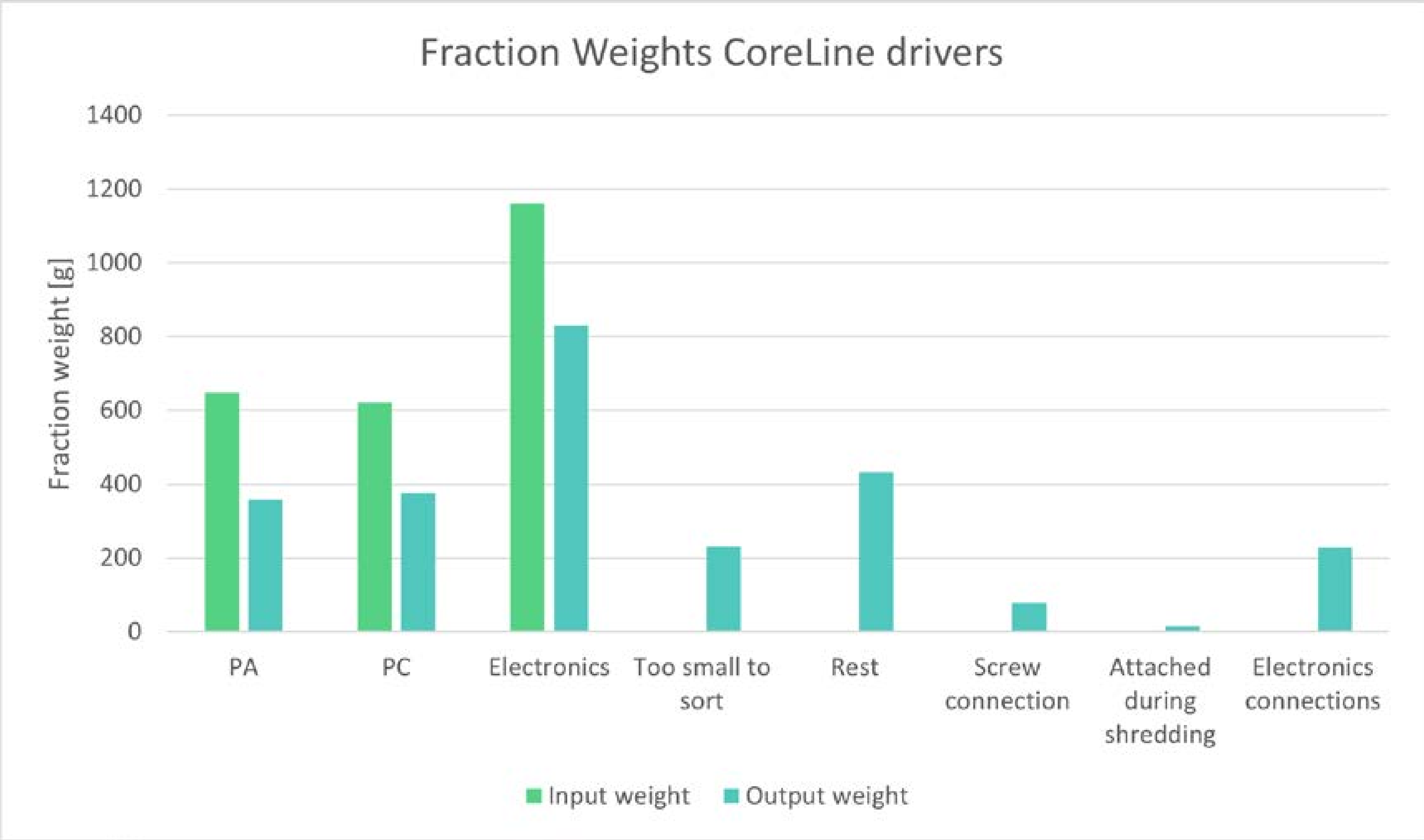
CoreLines without drivers



CoreLine drivers

	A	B	C	D	E	F	G	H	I
1	Batch (E) 9 Coreline drivers								
2									
3	**Input weight**		**Output weight**						
4	Weight of 1 CoreLine driver [g]	276	Including container [g]	4060		**Difference [g]**			
5	Weight of 9 CoreLine drivers [g]	2484	Weight of container [g]	1509					
6			Excluding container [g]	2551		-67			
7									
8									
9	**Weights of fractions**	Weight per product [g]	Input weight [g]	Output weight [g]	Difference [g]	Percentage lost [%]	Percentage unmixed [%]		Comments
10	Unmixed fragments								
11	PA	72	648	358	290	45	55		
12	PC	69	621	376	245	39	61		
13	Other								
14	Electronics	129	1161	831	330	28	72		
15	Too small to sort			231					
16	Rest			433					
17	Connections								
18	Screw connection			79					screw_pc=48g; screw_pa=32g
19	Attached during shredding			15					
20	Electronics connections			228					
21									
22	**TOTAL**			2323					
23	Total weight in connections			94					
24	Percentage of weight in connections			4	%				

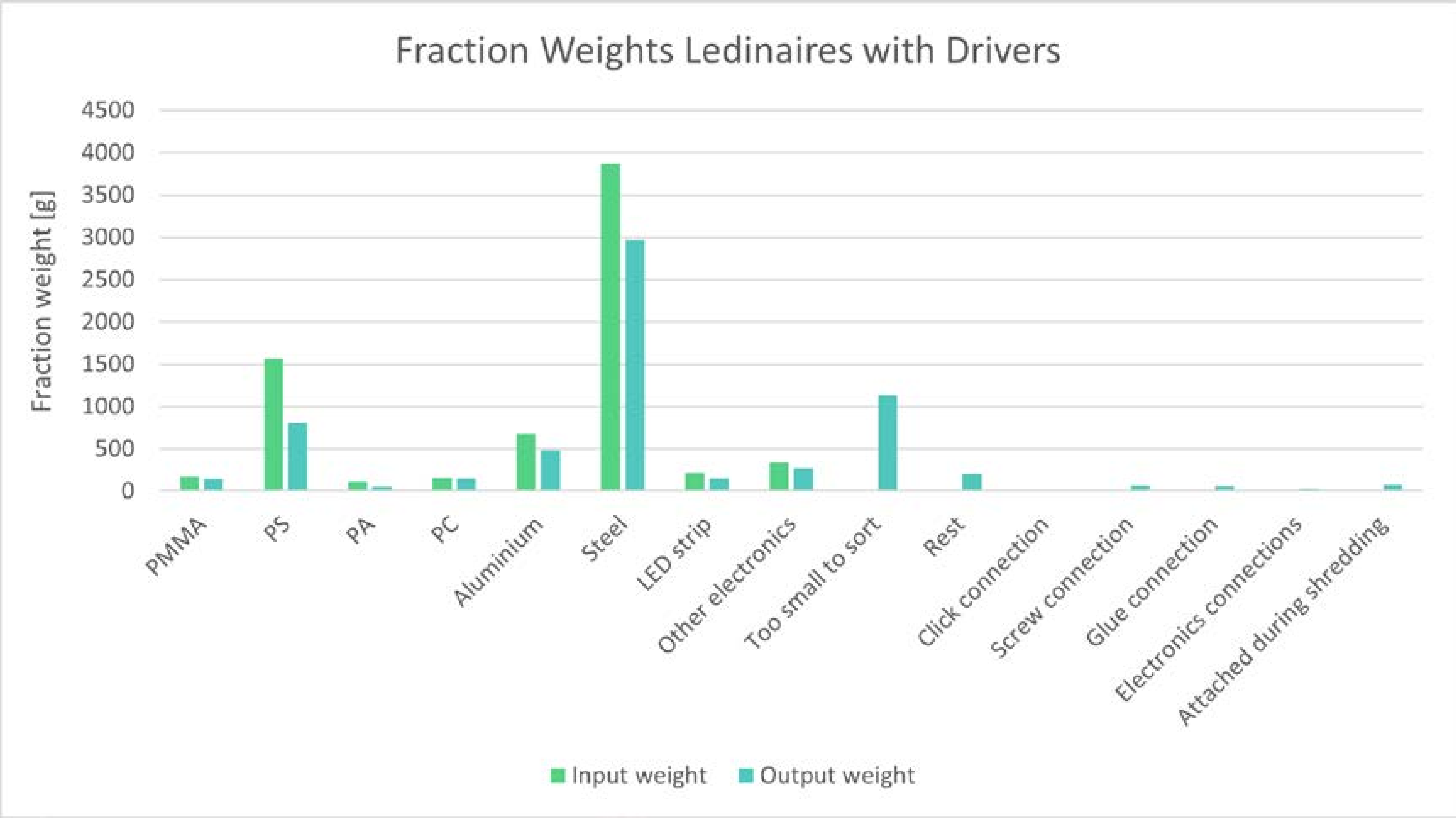
CoreLine drivers



Ledinaires with drivers

	A	B	C	D	E	F	G	H	I
1	Batch (C) 5 Ledinaires with drivers								
2									
3	**Input weight**		**Output weight**						
4	Weight of 1 Ledinaire with driver [g]	1429	Including container [g]	8282		**Difference [g]**			
5	Weight of 5 Ledinaires with drivers [g]	7145	Weight of container [g]	1488					
6			Excluding container [g]	6794		351			
7									
8									
9	**Weights of fractions**	Weight per product [g]	Input weight [g]	Output weight [g]	Difference [g]	Percentage lost [%]	Percentage unmixed [%]		Comments
10	Unmixed fragments								
11	PMMA	34	170	141	29	17	83		one lens weighs 0.71 g
12	PS	314	1570	805	765	49	51		
13	PA	22	110	53	57	52	48		inc sticker
14	PC	32	160	146	14	9	91		
15	Aluminium	136	680	485	195	29	71		
16	Steel	774	3870	2963	907	23	77		
17	Other								
18	LED strip	43	215	150	65	30	70		149 g LED strip completely liberated, 9 g LED strips with lenses still
19	Other electronics	68	340	272	68	20	80		cable weighs 10 g, connector 13 g, PCB 51 g
20	Too small to sort			1141					
21	Rest			200					
22	Connections								
23	Click connection			14					
24	Screw connection			68					screw_alu=48;screw_pa=20
25	Glue connection			62					
26	Electronics connections			25					
27	Attached during shredding			74					
28									
29	**TOTAL**			6599					
30	Total weight in connections			243					
31	Percentage of weight in connections			4	%				

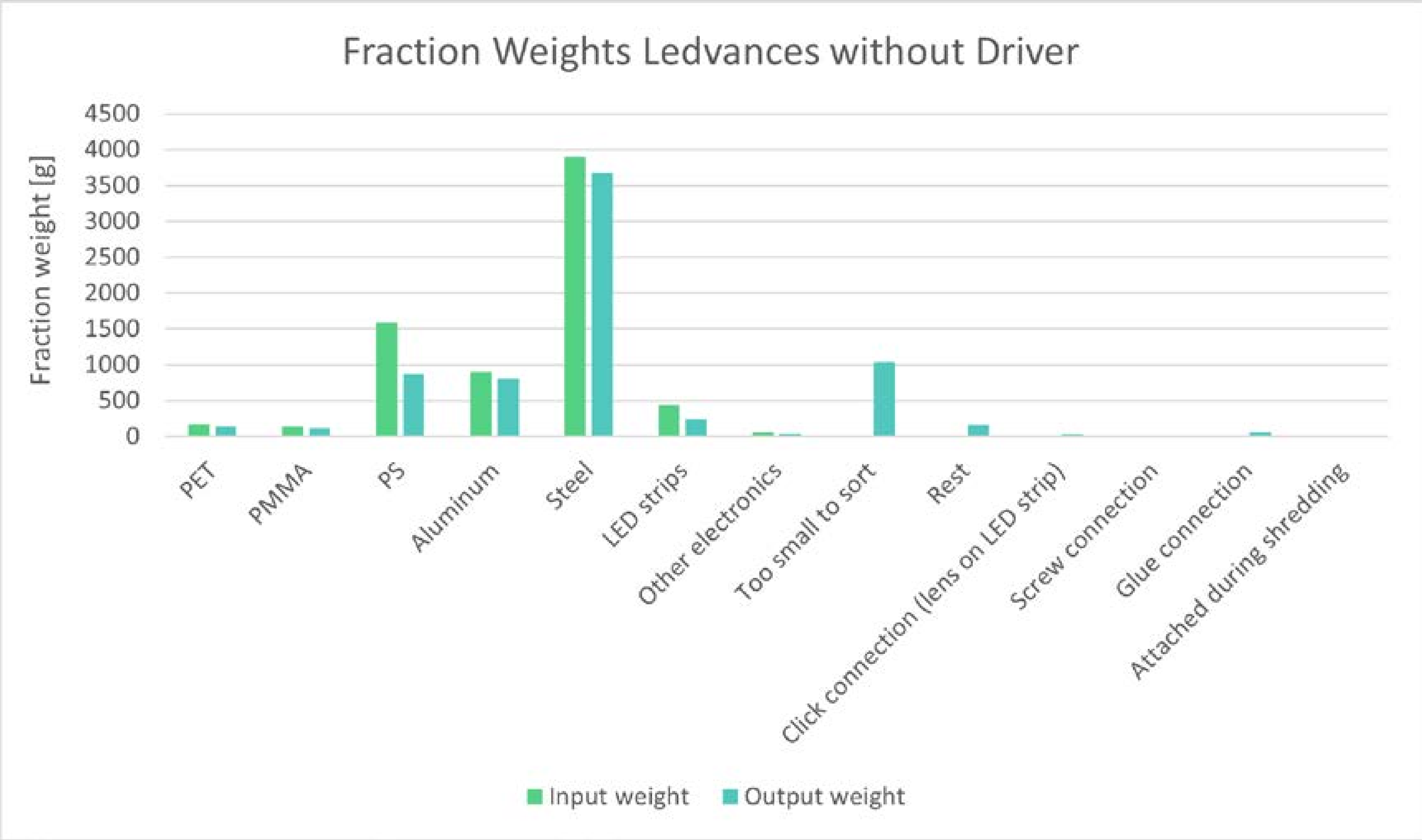
Ledinaires with drivers



Ledvances without drivers

	A	B	C	D	E	F	G	H	I
1	Batch (B) 5 Ledvances without drivers								
2									
3	**Input weight**		**Output weight**						
4	Weight of 1 Ledvance without driver [g]	1434	Including container [g]	8731		**Difference [g]**			
5	Weight of 5 Ledvances without drivers [g]	7170	Weight of container [g]	1510					
6			Excluding container [g]	7221		-51			
7									
8									
9	**Weights of fractions**	Weight per product [g]	Input weight [g]	Output weight [g]	Difference [g]	Percentage lost [%]	Percentage unmixed [%]		Comments
10	Unmixed fragments								
11	PET	33	165	140	25	15	85		
12	PMMA	29	145	112	33	23	77		1 lens weighs 0.68 g
13	PS	318	1590	868	722	45	55		
14	Aluminum	179	895	807	88	10	90		
15	Steel	780	3900	3681	219	6	94		
16	Other								
17	LED strips	87	435	240	195	45	55		239 g LED strip completely liberated, 12.8 g LED strips with lenses still
18	Other electronics	11	55	41	14	25	75		
19	Too small to sort			1038					
20	Rest			164					
21	Connections								
22	Click connection (lens on LED strip)			32					
23	Screw connection			10					
24	Glue connection			59					
25	Attached during shredding			14					
26									
27	**TOTAL**			7206					
28	Total weight in connections			115					
29	Percentage of weight in connections			2	%				

Ledvances without drivers



Appendix D: GWP, ADPE and pollution of identified issues in CoreLine shredding

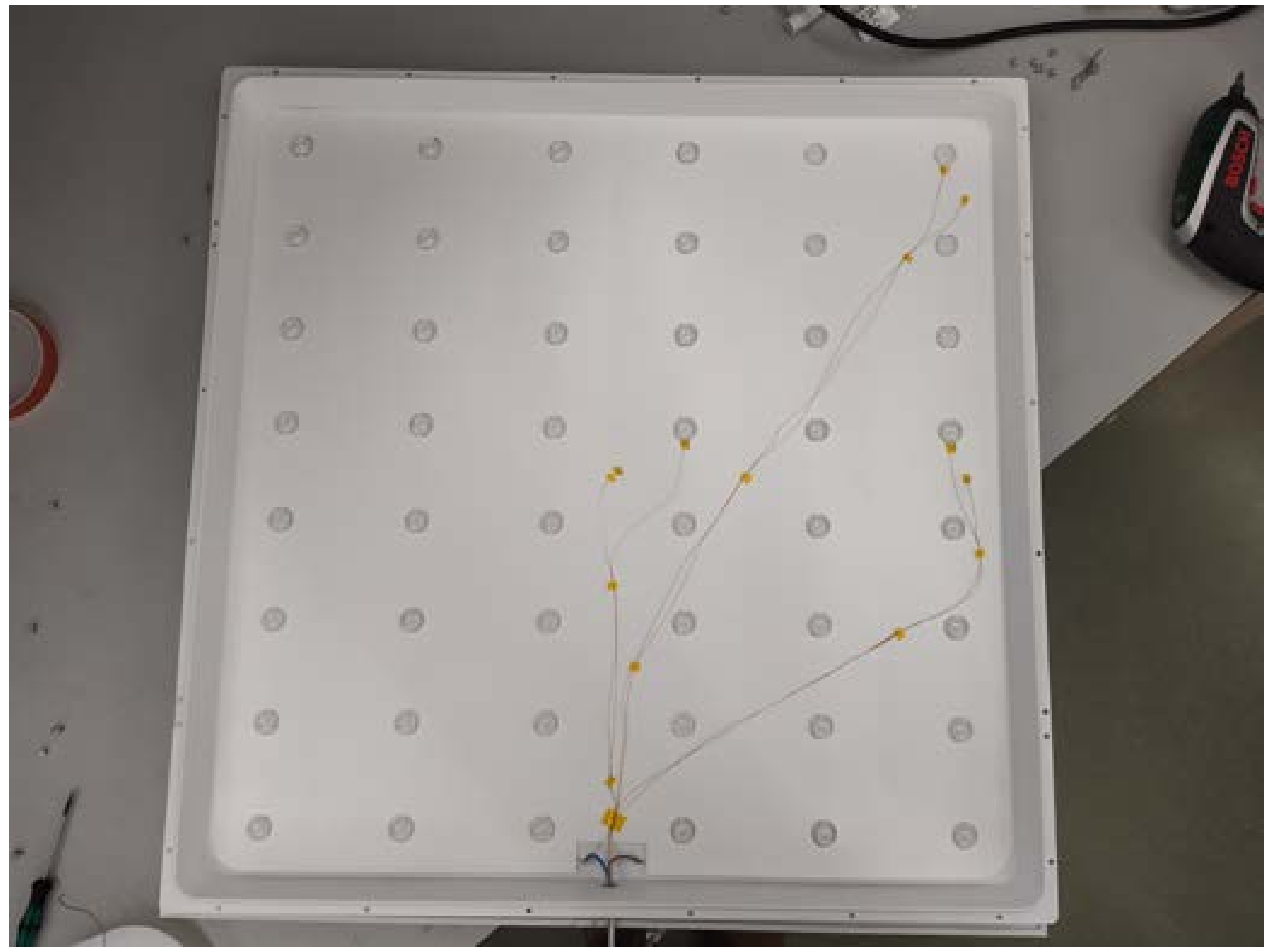
	A	B	C	D	E	F	G	H	I
1	**Material lost**	**material loss per product [g]**	**material loss [%]**	**impact of loss [kg CO2e]** (% lost * GWP as in LCA /100)	**impact of loss [kg Sbe]** (% lost * GWP as in LCA /100)	**Polluted material per product [g]**	**Pollution [%]** (weight of pollution / (weight of pollution + weight of polluted)		
2	Screws in frame	4.0	40	0.0	1.9E-07	209	2		74 screws stuck across the two CoreLine batches (8 products)
3	Screws in driver housing	1.1	11	0.0	5.2E-08	69	2		10 screws stuck across 4 products
4	Screws in connector housing	0.5	5	0.0	2.6E-08	72	1		5 screws stuck across 4 products
5	LED strips on backplate	12.9	34	0.9	1.8E-04	835	2		
6	Sticker on driver housing	3.0				69	4		
7	Reflector on backplate	8.4	16	0.0		835	1		
8	Lenses on LED strips	5.0				178	3		
9	Connector plastic	26.5	37	0.2		178	13		
10	Rubber in frame	9.6				209	4		

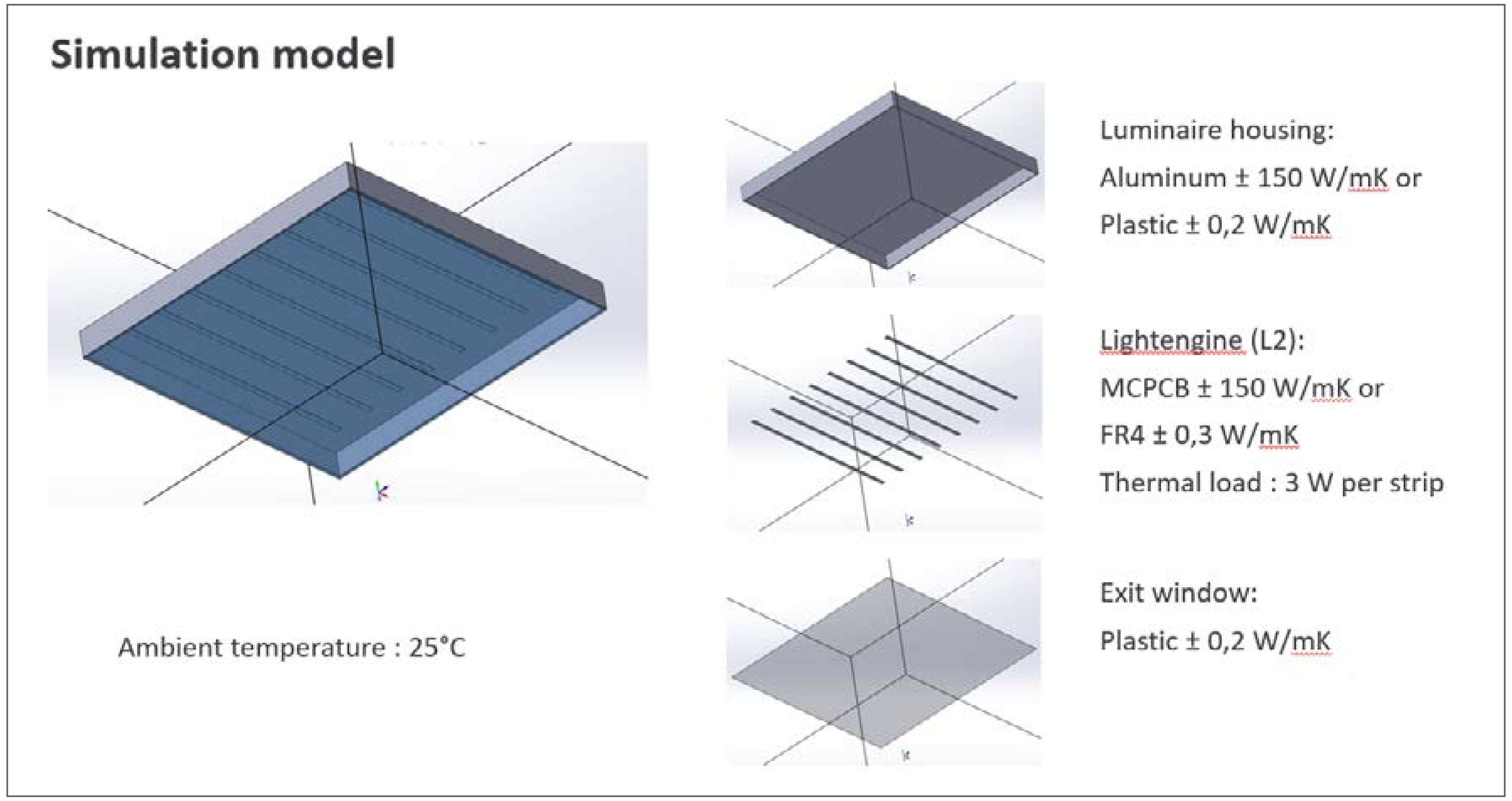
Appendix E: Thermal simulations

A thermal expert at Signify has conducted measurements and simulations to determine whether the CoreLine luminaire would meet thermal requirements if:

- the backplate was made of plastic;
- the L2s were epoxy based instead of aluminum based.

In order for the L2s to remain functional, their temperature may not exceed 85 °C. The simulations show that when the backplate is made of plastic and the L2s are epoxy-based, the L2s remain well below the 85 °C treshold (their maximum temperature is estimated to be 63.7 °C). Thus, from a thermal point of view, there is no issue in changing the backplate to plastic and the L2s to epoxy-based.





Coreline panel	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Housing-1 : Material	-	Aluminum 5052	Plexiglass	Plexiglass	Aluminum 5052
L2-1 : Material	-	FR4 (25% Fibre)	Aluminum 5052	FR4 (25% Fibre)	Aluminum 5052
L2 average	°C	57.3	58.1	59.4	29.6
housing average	°C	28.6	28.9	28.9	29.4
L2 maximum	°C	61.5	58.6	63.7	29.8
housing maximum	°C	29.0	42.5	41.0	29.9

Appendix G: Pugh matrices

L2s to backplate

Weighted Pugh Selection Matrix

Enter "-3" to "+3" (-3=large negative effect, +3=large positive effect, 0=no effect)

Criteria	Rating (1 to 5)	Reference Current CoreLin	Plastic snap fits	Integrated metal fasteners	Screws and fracture lines	Self supporting sandwich	Ultrasonic sandwich	Wire traps					
Good liberation during shredding	5	0	2	3	3	3	3	3					
Look & feel	5	0	0	-2	-1	0	0	-3					
BoM costs	5	0	-1	2	-1	-2	0	0					
Manufacturing costs	5	0	-1	2	-1	1	1	-1					
Use of materials that will actually be recycled	4	0	0	1	1	2	2	1					
Low GWP (make phase)	4	0	0	0	0	-2	0	0					
Demonstrates a design feature that is new to the Signify portfolio	3	0	0	0	2	3	3	3					
Repairability	2	0	-2	0	0	3	-3	0					
note: insert rows above this line to maintain calculations													
Count of Positives Effects (>0)		0.0	1.0	4.0	3.0	5.0	4.0	3.0	0.0	0.0	0.0	0.0	0
Count of Negatives Effects (<0)		0.0	3.0	1.0	3.0	2.0	1.0	2.0	0.0	0.0	0.0	0.0	0
Count of No Effect (=0)		8.0	4.0	3.0	2.0	1.0	3.0	3.0	0.0	0.0	0.0	0.0	0
Weighted Sum of Positive Effects		0.0	10.0	39.0	25.0	43.0	37.0	28.0	0.0	0.0	0.0	0.0	0
Weighted Sum of Negative Effects		0.0	-14.0	-10.0	-15.0	-18.0	-6.0	-20.0	0.0	0.0	0.0	0.0	0
Weighted Net Effect		0.0	-4.0	29.0	10.0	25.0	31.0	8.0	0.0	0.0	0.0	0.0	0

Frame to backplate

		Weighted Pugh Selectio									
	1 to 5	Enter "-3" to "+3" (-3=large negative effect, +3=large positive effect, 0=no effect)									
Criteria	**Rating**	**Reference Current Core**	Plastic fasteners	Clicking	Slide and click	Lunch box	Wire snap	Folding	Steel frame		
Good liberation during shredding	5	0	0	3	2	3	3	2	3		
Look & feel	5	0	1	0	-1	-2	0	1	0		
BoM costs	5	0	-1	-1	-1	0	-1	1	1		
Manufacturing costs	5	0	-1	-1	1	1	1	0	-1		
Use of materials that will actually be recycled	4	0	0	0	0	-2	0	0	0		
Low GWP (make phase)	4	0	0	0	0	0	0	0	3		
Demonstrates a design feature that is new to the Signify portfolio	3	0	0	0	3	3	3	1	1		
Repairability	2	0	-1	1	2	2	0	-3	0		
note: insert rows above this line to maintain calculations											
Count of Positives Effects (>0)		0.0	1.0	2.0	4.0	4.0	3.0	4.0	4.0	0.0	0.0
Count of Negatives Effects (<0)		0.0	3.0	2.0	2.0	2.0	1.0	1.0	1.0	0.0	0.0
Count of No Effect (=0)		8.0	4.0	4.0	2.0	2.0	4.0	3.0	3.0	0.0	0.0
Weighted Sum of Positive Effects		0.0	5.0	17.0	28.0	33.0	29.0	23.0	35.0	0.0	0.0
Weighted Sum of Negative Effects		0.0	-12.0	-10.0	-10.0	-18.0	-5.0	-6.0	-5.0	0.0	0.0
Weighted Net Effect		**0.0**	**-7.0**	**7.0**	**18.0**	**15.0**	**24.0**	**17.0**	**30.0**	**0.0**	**0.0**
		0	-31	-3	8	-3	24	17	30	0	

Driver securement

Weighted Pugh Selection Matrix

Enter "-3" to "+3" (-3=large negative effect, +3=large positive effect, 0=no effect)

Criteria	Rating (1 to 5)	Reference Current CoreLine	Indent and tie wrap	Cage	Partial box	Cable ring							
Good liberation during shredding	5	0	3	3	3	3							
Look & feel	5	0	-2	-3	-2	-1							
BoM costs	5	0	1	1	-1	1							
Manufacturing costs	5	0	1	-1	0	-1							
Use of materials that will actually be recycled	4	0	1	0	1	1							
Low GWP (make phase)	4	0	0	0	-1	0							
Demonstrates a design feature that is new to the Signify portfolio	3	0	3	3	3	3							
Repairability	2	0	2	3	3	3							
note: insert rows above this line to maintain calculations													
Count of Positives Effects (>0)		0.0	6.0	4.0	4.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Count of Negatives Effects (<0)		0.0	1.0	2.0	3.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Count of No Effect (=0)		8.0	1.0	2.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Weighted Sum of Positive Effects		0.0	42.0	35.0	34.0	39.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Weighted Sum of Negative Effects		0.0	-10.0	-20.0	-19.0	-10.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Weighted Net Effect		0.0	32.0	15.0	15.0	29.0	0.0	0.0	0.0	0.0	0.0	0.0	0

Backplate material

Weighted Pugh Selection Matrix

Con

Criteria	Rating (1 to 5)	Reference Current CoreL	Plastic backplate										
		Enter "-3" to "+3" (-3=large negative effect, +3=large positive effect, 0=no effect)											
Good liberation during shredding	5	0	0										
Look & feel	5	0	0										
BoM costs	5	0	2										
Manufacturing costs	5	0	1										
Use of materials that will actually be recycled	4	0	0										
Low GWP (make phase)	4	0	2										
Demonstrates a design feature that is new to the Signify portfolio	3	0	2										
Repairability	2	0	0										
note: insert rows above this line to maintain calculations													
Count of Positives Effects (>0)		0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Count of Negatives Effects (<0)		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Count of No Effect (=0)		8.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Weighted Sum of Positive Effects		0.0	29.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Weighted Sum of Negative Effects		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Weighted Net Effect		0.0	29.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		0	29	0	0	0	0	0	0	0	0	0	0

Appendix H: Pugh matrix scores and rationales

Criterion 1: Good liberation of different materials during shredding (reducing mixed fragments)

Sub-solution	Score	Explanation
L2s to backplate		
Plastic snap fits	2	L2s will probably realease; if the snap fits are glued to a steel backplate, then these might not liberate (but this would only be very little material).
Integrated metal fasteners	3	Shredded a product with L2s connected in a similar way; they liberated completely.
Screws and fracture lines	3	Assuming the L2s will break at the fracture lines, they would liberate well from the screws.
Self supporting sandwich	3	No direct connection between the L2s and any other components.
Ultrasonic sandwich	3	No direct connection between the L2s and any other components.
Wire traps	3	The wires will break during shredding, releasing the L2s.
Frame to backplate		
Plastic fasteners	0	Liberation of plastic screws will be the same as for metal screws.
Clicking	3	A product with metal clicking features was tested in the shredder; good liberation.
Slide and click	2	It is expected that shredding the product will disturb the geometry of the frame and clicking corner to such an extent that they will not be forced together anymore. If the frame is of metal, there might be pieces of plastic clicking corner getting wrapped up in the metal. This would have to be tested.
Lunch box	3	As soon as the wire breaks, the connection disintegrates.
Wire snap	3	As soon as the wire breaks, the connection disintegrates.
Folding	2	There is a risk that some pieces of the backplate or exit windows will remain clamped within the frame.
Steel frame	3	If screws remain stuck, this does not lead to a mixed fragment.
Backplate material		
Plastic backplate	0	No change to current design.
Driver securement		
Indent and tie wrap	3	The tie wrap will get cut in pieces in the shredding and will then fall out of the backplate's eyelets.
Cage	3	The plastic cage will tear in the shredder and then fall out of the backplate's eyelets.
Partial box	3	There is no direct connection between the partial box and the driver. Assuming the partial box can be clicked into the backplate.
Cable ring	3	There is no direct connection between the cable ring and the driver. Assuming the cable ring can be clicked into the backplate.

Criterion 2: Look & feel

Sub-solution	Score	Explanation
L2s to backplate		
Plastic snap fits	0	Not visible from outside of the product.
Integrated metal fasteners	-2	The gaps in the backplate will create the perception that dust can enter the product.
Screws and fracture lines	-1	The screws sticking out of the backplate make the overall look and feel less clean.
Self supporting sandwich	0	Not visible from outside of the product.
Ultrasonic sandwich	0	As long as any visible lines are symmetrical, there is no issue.
Wire traps	-3	The gaps in the backplate will create the perception that dust can enter the product. Also, wires sticking out make the product look less convenient to handle (you can get stuck behind the wires).
Frame to backplate		
Plastic fasteners	1	If fasteners are white instead of grey, they blend in more with the white backplate.
Clicking	0	Small metal clicking features places neatly along the edge will give a similar look and feel as the current screws do.
Slide and click	-1	In the current product, the connections between the four sides of the frame are welded and then coated white, resulting in a seamless result. In the slide and click solution, the seam could be slightly more visible, which is not nice as it will be visible from the room side.
Lunch box	-2	Does not look professional, feels like an improvised solution.
Wire snap	0	The wire integrates well with the edge of the product, things would not get stuck in it and it is not visible from the room side.
Folding	1	No more screws; cleaner look.
Steel frame	0	Will look more or less the same as the current product. It does not matter if the coating looks slightly different.
Backplate material		
Plastic backplate	0	It does not matter if the backplate has a slightly different surface finish (e.g. matte or shiny does not matter).
Driver securement		
Indent and tie wrap	-2	This looks like it takes too much effort on the installer’s side. Installers could hurt themselves on the eyelets on the backplate.
Cage	-3	Even worse because there are more eyelets. And the plastic film does not look high quality.
Partial box	-2	Looks like too much effort because there are two separate elements which have to be unpacked and installed.
Cable ring	-1	Again, separate element which has to be unpacked. Looks more professional than the other options.

Criterion 3: BoM costs

Sub-solution	Score	Explanation
L2s to backplate		
Plastic snap fits	-1	More expensive to produce plastic snap fits than glue.
Integrated metal fasteners	2	Cheaper to create cutouts in the backplate than to buy glue.
Screws and fracture lines	-1	More expensive to buy ~20 screws than the glue.
Self supporting sandwich	-2	To make the sandwich component stiff enough for proper clamping of the L2s, it would likely have to be at least 1mm thick, which is basically an extra backplate worth of material.
Ultrasonic sandwich	0	No extra material needed.
Wire traps	0	Steel wire and glue cost roughly the same.
Frame to backplate		
Plastic fasteners	-1	Plastic fasteners are more expensive than steel screws. Also, more fasteners are probably needed if they are plastic because they are weaker.
Clicking	-1	Custom clicking features have to be produced.
Slide and click	-1	Custom clicking corners have to be produced.
Lunch box	0	Wire probably costs roughly the same as the steel screws.
Wire snap	-1	All the arms need to be created to hold the wire, which makes the frame and backplate more expensive.
Folding	+1	No more screws needed.
Steel frame	+1	Steel is cheaper than aluminum and allows for smaller wall thickness. Coating costs are expected to be the same.
Backplate material		
Plastic backplate	+2	Will be a lot cheaper in plastic than in steel.
Driver securement		
Indent and tie wrap	+1	Tie wrap is cheaper than rubber sticker.
Cage	+1	Making eyelets in metal backplate is cheap. Plastic cage probably cheaper than the current sticker.
Partial box	-1	Custom component has to be produced.
Cable ring	+1	Very simple component, cheaper than rubber sticker.

Criterion 4: Manufacturing costs

Sub-solution	Score	Explanation
L2s to backplate		
Plastic snap fits	-1	More expensive to attach ~20 snap fits than create 6 lines of glue.
Integrated metal fasteners	2	Cheap to use stamping machine. Applying the glue is more expensive, especially because two glue types are used.
Screws and fracture lines	-1	Screws are done manually. Glue is applied robotically. Also added costs of applying fracture lines.
Self supporting sandwich	1	Glueing and L2 positioning would no longer be needed.
Ultrasonic sandwich	1	Ultrasonic welding is cheaper than glueing. Glueing can be skipped twice: L2s and reflector.
Wire traps	-1	It probably takes longer to insert the wire than insert the screws.
Frame to backplate		
Plastic fasteners	-1	If the fasteners are plastic, more of them will be needed and they have to be inserted more carefully than steel screws so it will take longer.
Clicking	-1	More manual labor as compared to the screws.
Slide and click	+1	Clicking 4 corners is easier than inserting all the screws.
Lunch box	+1	Quicker than the screws.
Wire snap	+1	Quicker than the screws.
Folding	0	Using rolling equipment to make folds is expected to be as expensive as inserting the screws.
Steel frame	-1	It will be expensive to integrate the complete roll forming process into the assembly.
Backplate material		
Plastic backplate	+1	Thermoforming is cheaper than metal stamping.
Driver securement		
Indent and tie wrap	+1	The tie wrap does not have to be assembled before sale; the installer will assemble it.
Cage	-1	More expensive to make the eyelets in the backplate and cut the plastic into shape than to attach a sticker.
Partial box	0	Inserting box into backplate expected to be similarly expensive as applying sticker.
Cable ring	-1	The ring will need to be quite strong in order not to bend under 30 N force, so it will likely be more expensive to manufacture than it is to apply a sticker.

Criterion 5: Use of materials that will actually be recycled, if liberated

Sub-solution	Score	Explanation
L2s to backplate		
Plastic snap fits	0	Assuming the plastic of the snap fits will be recycled.
Integrated metal fasteners	1	No glue anymore, no additional material.
Screws and fracture lines	1	No more glue, steel screws will be recycled.
Self supporting sandwich	2	Assuming a plastic is selected which is recycled. No more glue will be needed. The reflector currently does not get recycled because it is foil. If the reflector gets thicker then it will be recycled.
Ultrasonic sandwich	2	Assuming a plastic is selected which is recycled. No more glue will be needed. The reflector currently does not get recycled because it is foil. If it is stuck to the backplate, (part of it) will join the backplate into reprocessing.
Wire traps	1	No glue anymore, steel wire will be recycled.
Frame to backplate		
Plastic fasteners	0	Assuming nylon fasteners will be recycled. No difference as compared to screws.
Clicking	0	Clicking elements will be made from steel, which will be recycled
Slide and click	0	Assuming the plastic corners will be recycled.
Lunch box	-2	The elastic wire will not be recycled.
Wire snap	0	The wire will be steel, which gets recycled.
Folding	0	No new material introduced. The screws will be gone, but these would get recycled.
Steel frame	0	A steel frame would get recycled.
Backplate material		
Plastic backplate	0	Assuming a plastic is used for which there is a recycling infrastructure.
Driver securement		
Indent and tie wrap	1	No more sticker. Assuming tie-wrap will be recycled.
Cage	0	No more sticker, but the plastic cage likely will not be recycled because it is a sort of foil.
Partial box	1	No more sticker. Assuming the box will be made of a material that gets recycled.
Cable ring	1	No more sticker. Assuming the ring will be made of a material that gets recycled.

Criterion 6: Low GWP in make phase

Sub-solution	Score	Explanation
L2s to backplate		
Plastic snap fits	0	Glue and snap fits expected to have similar GWP; both low volumes and non-metal.
Integrated metal fasteners	0	Glue is saved but it is a neglible amount of CO_2e (5 grams).
Screws and fracture lines	0	Glue is replaced by screws; similarly small GWP.
Self supporting sandwich	-2	Assuming a thickness of 1.2 mm (which would be necessary to make the component sufficiently stiff), this would add roughly 2 kg of CO_2e to the make phase.
Ultrasonic sandwich	0	Glue is saved but it is a neglible amount of CO_2e (5 grams).
Wire traps	0	Glue is replaced by steel wire; expected to have similar GWP.
Frame to backplate		
Plastic fasteners	0	Plastic fasteners likely have a smaller GWP, but the GWP of the current screws is only 20 grams, so the difference will be negligible.
Clicking	0	The clicking elements will probably have comparable GWP to the current screws.
Slide and click	0	The clicking elements will probably have comparable GWP to the current screws.
Lunch box	0	The wire will probably have comparable GWP to the current screws.
Wire snap	0	The wire will probably have comparable GWP to the current screws.
Folding	0	The screws are eliminated, but these cause only 20g CO_2e.
Steel frame	3	According to Signify's LCA data, switching to a steel frame reduces GWP by 3 kilograms of CO_2e (as compared to current aluminum frame).
Backplate material		
Plastic backplate	2	Based on the OneClick data that is used in Signify's EPD, 0.5 to 2 kilograms of CO_2e could be saved by switching from a steel backplate to a plastic backplate, depending on the plastic type.
Driver securement		
Indent and tie wrap	0	GWP of tie wrap and current sticker likely comparably low.
Cage	0	GWP of plastic cage and current sticker likely comparably low.
Partial box	-1	The partial boxes consist of a lot more material than the sticker.
Cable ring	0	GWP of metal ring and current sticker likely comparably low.

Criterion 7: Demonstrates a design feature that is new to the Signify portfolio.

Sub-solution	Score	Explanation
L2s to backplate		
Plastic snap fits	0	Already featured in a different Signify product.
Integrated metal fasteners	0	Already featured in a different Signify product.
Screws and fracture lines	2	Not done before by Signify, but L2s have been screwed before (just without fracture lines).
Self supporting sandwich	3	Very different to existing portfolio.
Ultrasonic sandwich	3	Very different to existing portfolio.
Wire traps	3	Very different to existing portfolio.
Frame to backplate		
Plastic fasteners	0	Very similar to steel screws.
Clicking	0	Already featured in a different Signify product.
Slide and click	3	Although the slide and click mechanism already exists in a luminaire accessoire, it is very new to luminaires. To implement such a feature in the frame, there are more con-straints because the frame has to interface with more other components.
Lunch box	3	Very different to existing portfolio.
Wire snap	3	Very different to existing portfolio.
Folding	1	A bit new to the portfolio, but less inventive than previous options.
Steel frame	1	Slightly new.
Backplate material		
Plastic backplate	2	Signify has no recessed luminaire with plastic backplate.
Driver securement		
Indent and tie wrap	3	Very different to existing portfolio.
Cage	3	Very different to existing portfolio.
Partial box	3	Very different to existing portfolio.
Cable ring	3	Very different to existing portfolio.

Criterion 8: Repairability.

Sub-solution	Score	Explanation
L2s to backplate		
Plastic snap fits	-2	Snap fits could break; more difficult to acquire new snap fit than to reglue an L2.
Integrated metal fasteners	0	While it is easier to dis- and reassemble the L2s, the reflector is still glued to the backplate, which will have to be removed in order to reach the L2s.
Screws and fracture lines	0	While it is easier to dis- and reassemble the L2s, the reflector is still glued to the backplate, which will have to be removed in order to reach the L2s.
Self supporting sandwich	3	The self-supporting reflector makes it very easy to dis- and reassemble the L2s.
Ultrasonic sandwich	-3	Both reflector and backplate could break during disassembly. Reassembly would require access to ultrasonic welding tools, which is far from standard.
Wire traps	0	While it is easier to dis- and reassemble the L2s, the reflector is still glued to the backplate, which will have to be removed in order to reach the L2s.
Frame to backplate		
Plastic fasteners	-1	Plastic screws require more care, so slower to replace.
Clicking	1	It is probably quicker to handle 12 click features than 24 screws.
Slide and click	2	A lot quicker than all the screws.
Lunch box	2	A lot quicker than all the screws.
Wire snap	0	Since the wire has to be quite strong, it probably takes as much effort to handle as 24 screws.
Folding	-3	Not repairable.
Steel frame	0	Same as current.
Backplate material		
Plastic backplate	0	No inherent difference with respect to repair.
Driver securement		
Indent and tie wrap	2	Easy to cut the tie-wrap and get a new one; removing the sticker is more difficult.
Cage	3	Use the same component again.
Partial box	3	Use the same component again.
Cable ring	3	Use the same component again.