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Design for Interaction
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Balancing the Repairability and Recyclability of a Mechanically Durable Agricultural Antenna

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Preface

I came to TU Delft with the intention of being exposed to different types of design and learning to design for positive change. Though I initially set out to distance myself from my technical engineering background when I got to Delft, I found myself back to craving the practicality of it during my first year of the DFI program. After taking on technical roles in the DFI group projects and realizing how much of the hands-on work I liked, I found myself in the repair and recycling class taught by Ruud. Finding the intersection of designing for positive change and technical engineering through circular design helped me find a new avenue of interest that led to this project. This project and my courses at Delft also helped me find that I don't have to fit into just engineering or design.

Acknowledgements

I would like to foremost thank my family and friends and the "repair table bros" for their continued support during this project. Thanks for always pulling me back out to the big picture and reminding me that life is about much more than a thesis.

I'd also like to thank my supervisory team for the time they took to help me learn the details of the world of circular design and reminding me that there's only so much you can do in a few months. I really enjoyed learning from you.

Additionally, I'd like to thank Nedap, and especially Jules, for welcoming me so warmly even though I was often a few hours away. The culture and commitment to constantly improving is so evident at Nedap, and I'm inspired by the way people at Nedap support each other without hesitation.

(Nedap, 2024)

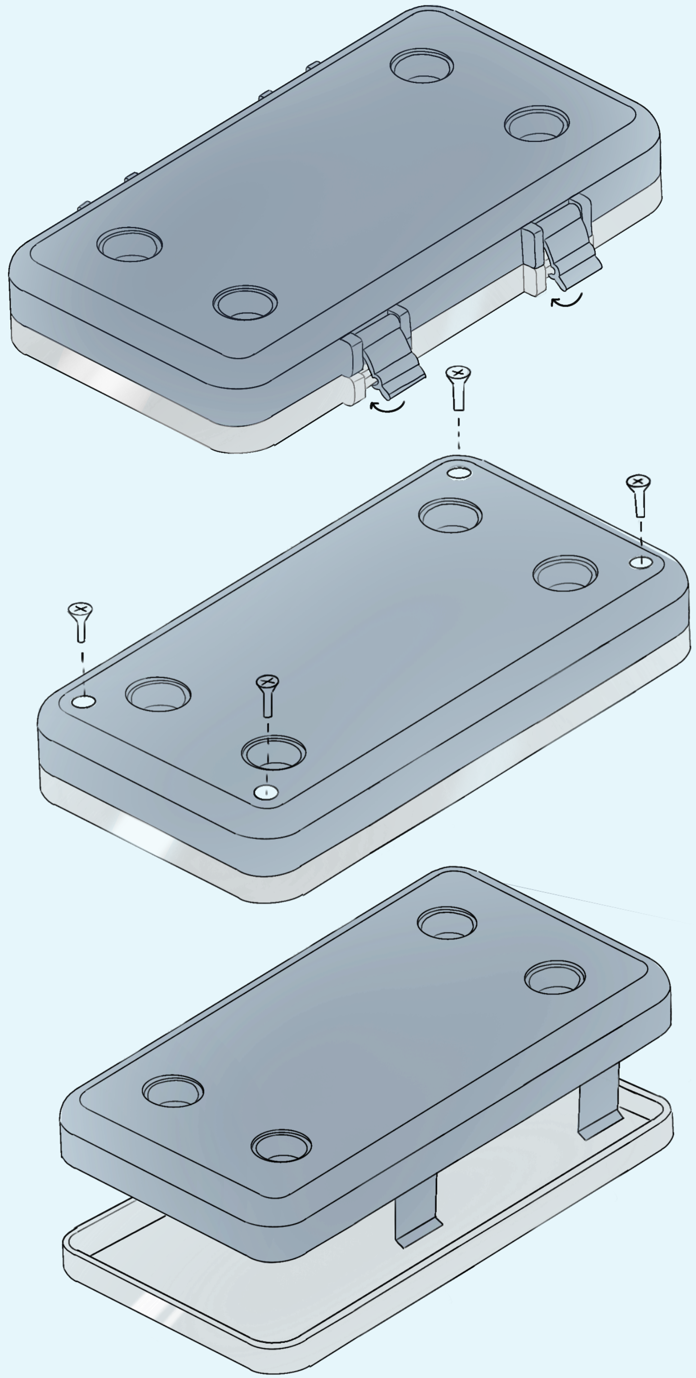
Abstract

This project aims to explore the balance in maintaining durability while redesigning a highly durable, potted electronic product for repair and recycling. The research analyzes and redesigns both the product journeys and the product architecture of an agricultural antenna.

Stakeholder and field research revealed that the farmer is largely in control of the end of life of the antenna. However, they are often unaware or unmotivated to properly dispose of it. Stakeholders have an opportunity to better inform, guide, and motivate the farmers towards initiating the best-case end-of-life of their antenna.

The repairability analysis first identified the electronic components, namely the PCB and copper wire, as priority parts because of their value and functional importance. The bonding attribute of the potting material completely prevents any access to those priority parts for repair. A shredding experiment further exposed the harmful effects of the potting material in the recycling of the product, as it prevents almost any liberation of the copper components during recycling. Additionally, discussions with recyclers and existing recyclability guidelines helped assess the theoretical and practical recyclability, as well as the liberation during recycling, of the other materials in the antenna.

To explore the tensions between the repairability, recyclability, and durability requirements found during the analysis, the redesign section presents alternatives for improving the circularity of the product's architecture. A hardware subscription model and recycling additions to an already existing software interface are presented to address the farmers' lack of recycling knowledge. Finally, a prototype combining alternatives in the product architecture categories is shown and evaluated against the old prototype and the new durability, repairability, and recyclability requirements.



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Terminology

Obsolescence
The process of becoming unused or outdated

WEEE
Waste electric and electronic equipment

Disassembly
''A systematic approach that allows removal of a component of a part or a group of parts or a subassembly from a product (i.e. partial disassembly); or separating a product into all of its parts for a given purpose” (Cui & Forssberg, 2003)

Fragments
The resulting pieces of a product or material after the shredding process in recycling

Fractions
Specific collections of fragments in the recycling process as a result of sorting and separation methods

Liberation
The separation of materials from each other during the recycling process

Homogeneous
Fragments composed of a single material

Heterogeneous
Fragments composed of multiple materials

PCB
Printed Circuit Board

OEM
Original equipment manufacturer

RFID
Radio Frequency Identification, the technology used by this antenna

ROI
Return on investment, meaning the ratio between the income and investment into something

Chapter 1: Introduction

1.1 Problem Definition

This project is focused on exploring the tensions between the repairability, recyclability, and mechanical durability of a product within the company’s animal health monitoring system. The antenna hardware box is part of an RFID (Radio Frequency Identification) system that allows dairy farms to manage, track, and trace each cow wearing a label. The antenna recognizes the ID tag of the cows and sets off actions such as feeding, milking, or sorting of a cow based on which machine or gate the cow walks up to.

As durability is the company’s biggest competitive advantage in the agricultural technology market, with this product often lasting 20 years past the 10 year warranty, the challenge of maintaining durability is crucial. Potting the product (i.e. filling the void space with a poured rubbery material) is key to the product’s current mechanical durability. However, potting the antenna has a large negative effect on the recyclability and repairability of the product as the filling strongly bonds to many of the other components. The antenna box was designed for durability and reliability as it sits within a harsh environment and must withstand physical stress within livestock barns. As potting is a key aspect of some of the company’s top sold livestock products, this case study is able to inform the sustainable redesign of its other products as well. Another motivation for this topic and product choice is the lack of research on the circular redesign of potted electronics products. This provides an opportunity for researching how to maintain reliability while redesigning mechanically durable products like the antenna for better recycling yield and improved repairability.

1.2 Research Questions

The major aim of this assignment is to explore the tensions between designing for repair, recycling, and durability of electronic products. In order to find out these tensions, the project utilizes a case study of an agricultural antenna box used in dairy farms.

First, we must find out what the current journey of the product is, especially at the end of its life. A large influence on the repair and recycling of the product is the user's behavior and the guidance from the stakeholders during and after the product's life.

RQ1: How does the company's involvement and user's behavior affect the end of a life cycle of the product?
Methods: User interviews, stakeholder interviews, desk research, survey, end of life journey mapping

Additionally, it is important to know what about the physical antenna currently causes its lack of recyclability and repairability.

RQ2: How do the design requirements and product architecture of the hardware box affect its recyclability, repairability, and durability?
Methods: Product journey map, disassembly map, hot spot map, shredding test and yield

Then we can identify the tensions between the recyclability, repairability, and mechanical durability of the product and discuss the trade-offs involved.

RQ3: What tensions exist between the requirements for improving repairability, recyclability, and the optimal mechanical durability of the product?
Methods: Expert interviews, requirement comparison table

With information on the tensions gathered, prototyping is performed to test and provide examples of those and other conflicts that arise when redesigning.

RQ4: How can the product be redesigned to enable the repair and recycling of the product?
Methods: Morphological chart, Granta Edupack material selection, prototyping

Chapter 2: Background

2.1 Intro to E-waste

Our world is producing an increasingly large quantity of devices connected to the internet, producing a waste stream composed of waste electrical and electronic equipment (WEEE) harboring hazardous and valuable materials. These are materials such as rare earth metals, precious metals like gold, silver, and platinum, and secondary raw materials like copper and iron. In the EU and globally, WEEE is one of the fastest growing waste streams and is expected to double by 2050 (Anastas & Zimmerman, 2003; Sonego et al., 2022). Only 22.3 percent of the 62 billion kg of e-waste generated in 2022 was documented as collected and recycled properly. Economically, less than one third of the USD 91 billion worth of material is currently recovered by e-waste management. The increase of e-waste generation is outpacing the growth of formal recycling by a factor of 5 (Baldé et al., 2024). This presents a crucial need for stakeholders like businesses, governments, and consumers to increase material recovery by raising awareness, creating services, and better designing products for integrity and recycling.

2.2 Circular Economy Strategies

The linear economy is a major contributor to climate change and resource scarcity, as the extraction and processing of raw materials caused 50% of greenhouse gas emissions (Oberle et al., 2020). This prompts the need for a circular economy that narrows and closes material loops and slows the speed of the life cycles of materials and products (Richter et al., 2023).

The European waste framework presents the framework of prevent, reduce, reuse, and recycle (European Union, 2012). Bakker et al. (2019) introduces four strategies based on this framework: (1) avoiding the use of critical materials, (2) minimizing the use of critical materials, (3) designing products for prolonged use and reuse, and (4) designing products that are easy to recycle. Design strategies can either help prolong or close the product resource loop in a circular economy (Balkenende et al., 2017). While closing a resource loop is related to recycling, other strategies like designing for repair, reuse, and refurbishment prolong a product and material's life. In this section, we will discuss which strategies are utilized throughout this project.

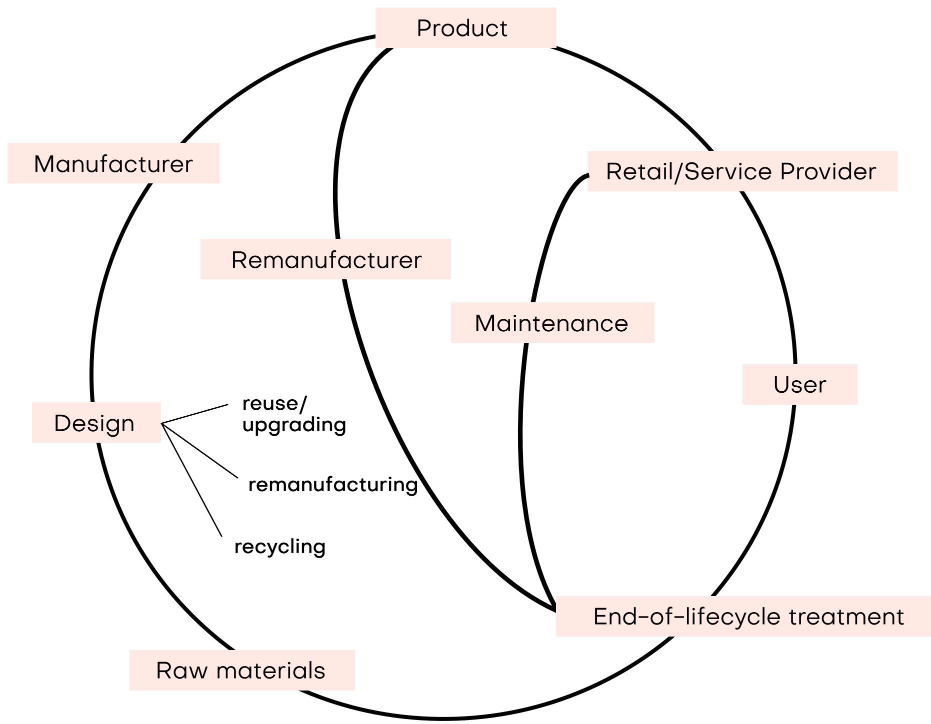


Figure 1: Product lifecycle in a circular economy context (Balkenende et al., 2017)

Contrary to the other strategies, recycling is a mandatory requirement for every product as it is the last resort when a product is obsolete, or no longer useful (Stahel, 2006). While other methods fall into the category of delaying a product's end of life, recycling should always be the final destination because of its material recovery. Therefore, design for recycling is a large focus of this project.

Designing a product for repair aids in slowing the resource loop of the product, as long-lasting products are often supported by a high level of repairability and maintenance (Balkenende et al., 2017). New policy developments, such as in the European Union, are encouraging the high repairability of products through policies such as right-to-repair rules (Baldé et al., 2024). This project will utilize recent design for repair guidelines and methods such as designing a product for disassembly in order to maintain the long life of the antenna.

This thesis is also based on the premise from Bakker et al. (2019) that preventing a product's obsolescence and reversing the eventual obsolescence of a product should be the two main goals of designers working toward a circular economy. The Inertia Principle from Stahel also argues for starting from the highest level of product integrity and keeping the product as close to its original state as long as possible (Stahel, 2006). This project tackles the goal of reversing eventual obsolescence through the previously mentioned design for repair and design for recycling methods. The goal of preventing a product's obsolescence is also tackled by the project's focus on maintaining physical durability, or robustness, which will be explored through existing durability guidelines, impact simulations, and material selection.

While improving the relationship between users and products, or emotional durability (Chapman, 2005), also can prevent a product's premature disposal, this project mainly focuses on the physical durability of the product because of its business to business journey.

(Nedap, 2024)

2.3 E-waste Recycling Process

As recycling processes are highly dependent on the recycling center, part of this project involved visiting two local recyclers to inform the recyclability of the product. Here we will discuss the recycling process of one of the largest e-waste recyclers in the Netherlands and where the antenna's materials would most ideally end up in their process. The process is based on meetings with expert engineers at the e-waste recycling facility and explains the different separating techniques of the process that creates fractions of different materials.

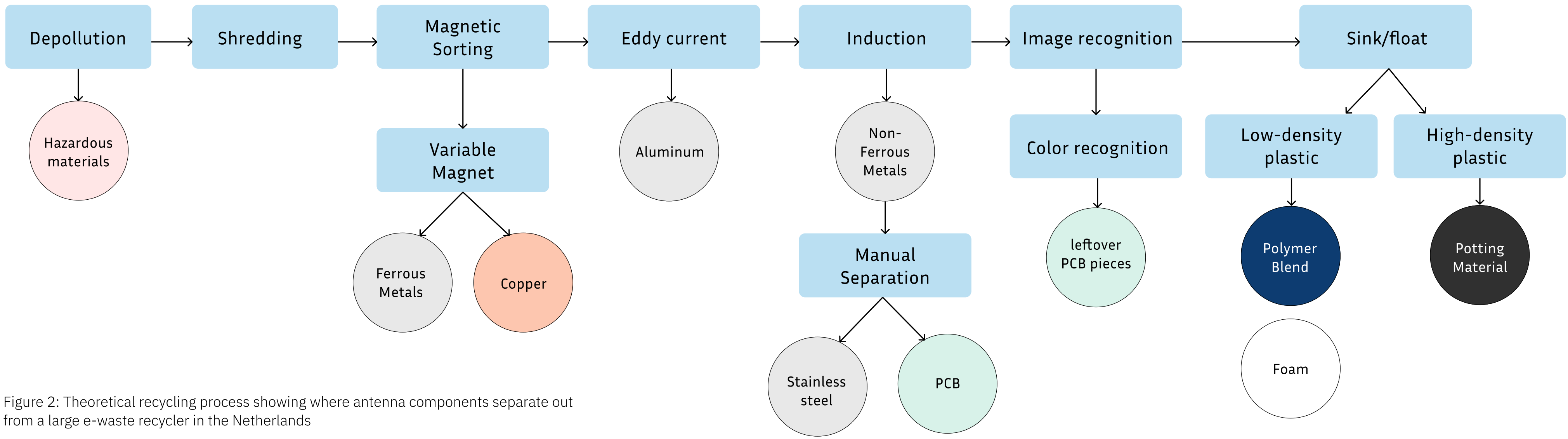


Figure 2: Theoretical recycling process showing where antenna components separate out from a large e-waste recycler in the Netherlands

The recycling process usually begins with a manual depollution of hazardous materials. After the hazardous materials are removed, the waste is shredded and sorted through various separation techniques.

Ferrous metals are first sorted out through magnetic separation, aluminum is separated through eddy current, and the remaining metals are sorted through induction. Figure 2 shows how each of the metals in the antenna would ideally be sorted out through the current recycling process. Copper is also targeted in the magnetic sorting, but the image recognition is trained to pick up the color of the leftover PCB pieces.

The final stage in the process is the sink or float bath, where plastics denser than 1.1 kg/L are sorted out as they often contain brominated flame retardants or other unrecyclable or hazardous additives. These plastics that sink are most likely burned while the other plastics are separated for additional recycling. The recyclability chapter will further discuss the theoretical, practical, technical, and realistic recyclability of the materials in the antenna.

2.4 Agricultural Technology and the Digital Farm

On top of the rising global demand for animal products, dairy farmers globally are facing pressure about the environmental impact and welfare of their animals (Bianchi et al., 2022). In response, farmers are adopting Precision Livestock Farming (PLF) to not only save time but also to improve their resource efficiency by adopting more sustainable products and systems. At dairy farms, this looks like adopting automated systems like milking robots and ID tags acting as behavior, location, and health monitors. Collecting data on their cows' daily activities, milk yield, and feed weight are examples of ways farmers are utilizing new technologies to improve the efficiency of their farms. The dependence of farmers and cows on the quick and accurate functionality of the antennas and processing units within the RFID system, especially when it comes to feeding and milking, highlights the need for high durability or quick repairability of the product.

Agricultural technology companies, like this company, are subject to new sustainability reporting legislation such as the Corporate Sustainability Reporting Directive (CSRD) and the Ecodesign for Sustainable Products Regulations (ESPR), which are predecessors to potentially much more practical product legislation. OEM's like Nedap that produce B2B products are currently conducting LCA's, creating company-wide sustainability objectives, and creating sustainable design policies in lieu of upcoming legislation such as the ESPR.

While legislation is heading towards acting on business to business markets as well, much of current repair and recycling legislation, such as the Right to Repair, is focused on consumer products such as household appliances and display devices. Most countries within the EU have policies that demand B2B producers to register their company if they import to that country and/or report their EEE weights and units (Sphera Global, n.d.). These policies, coupled with reporting directives like the CSRD, are the only type of sustainability regulations affecting Nedap's livestock department at the moment.

Agricultural products are not specifically mentioned in recycling or repair legislations enacted in the USA and the EU. Recycling legislation is generally split between WEEE, batteries, and packaging legislation. The recycling legislation in the US mainly pertains to display devices like computers, monitors, and TV's (Sphera Global, n.d.); the EU is setting strict targets for collection and recycling of many different categories of WEEE to inform regulations and compliance (European Union, 2012).

2.5 Nedap

The case study product of this thesis sits within the livestock department of the company sponsoring this project, Nedap, which provides technological solutions for animal monitoring and management. The company is a Dutch technology innovation company specializing in IoT, RFID, Vision, AI and SAAS to bridge the digital and physical words. With over 1000 employees, it has offices in ten countries and is headquartered in Groenlo, the Netherlands. The company itself is interested in the circular redesign of products like the antenna, as sustainability regulations will only become harsher and more practical for OEM's.

Figure 3: Common Milking Parlor Use of the Antenna (BouMatic, 2022)

2.6 The Antenna

The subject of this case study is one of the company's antennas, a Per-Place Identification antenna that recognizes a cow's ID ear or neck tag and sends the identification to a processing unit to activate actions such as a milking robot starting up or a sorting gate opening for the cow. The antenna is part of an RFID system that enables the identification of unique objects wirelessly and automatically through radio signals. The antenna is mechanically durable, lasting 30 years, but it is filled with an epoxy that also makes the antenna irreparable and not reusable when the covered electronic components break.

To gain an understanding of the components that make up the antenna, an exploded view is seen to the right (Figure 4). The exploded view shows the antenna before being fully encapsulated by a potting material.

As an overview, the copper wire wraps around the extruded parts on the housing and the wire adjuster assembly. The PCB is connected (soldered) to the copper wire and cable. There is a wire adjuster assembly that when screwed a few times can adjust the tightness of the wire, as you can see the copper wire wrapped around it in Figure 4. The aluminum plate sits on top of the components and secures the cable. A strain relief component screws into the aluminum plate to also secure the cable (Figure 5). Stainless steel bushings press into the holes to prevent degradation from bolts. All of the components are encapsulated in potting after assembly.

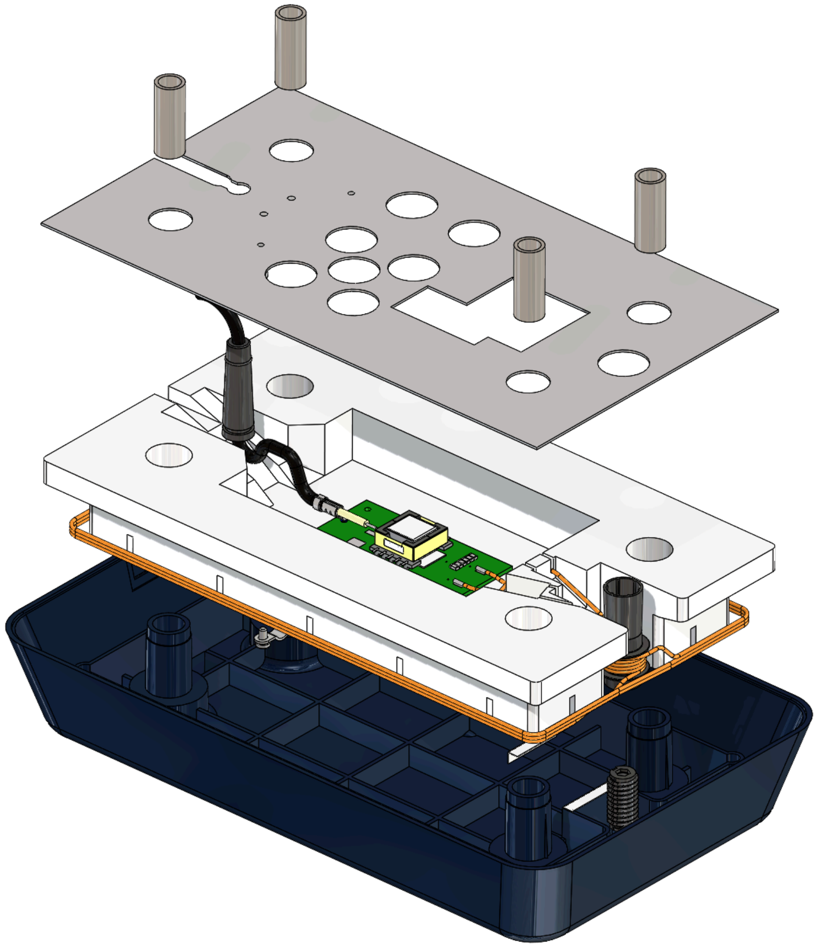


Figure 4: Exploded view of unpotted antenna

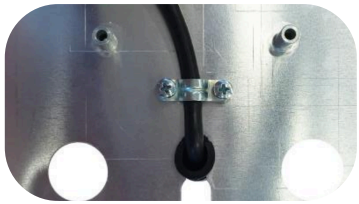


Figure 5: Strain relief holding the cable down

How the antenna works

An overview of how the electrical and electronic components work together is as follows (Figure 6).

1. The processing unit sends a current to the copper coil through the PCB.
2. The coil generates a magnetic field. The addition of the ferrite core increases the inductance of the coil and guides the magnetic lines of the field.
3. When an RFID tag (with its own tiny antenna and chip) enters the field:
   - The field induces a current in the tag's antenna
   - The tag uses this power to transmit data
4. The coil (now functioning as a receiver) picks up the modulated signal.
5. The PCB sends the data back to the processing unit through the cable.
6. The processing unit identifies the cow, performs any actions needed, and displays the data on an interface

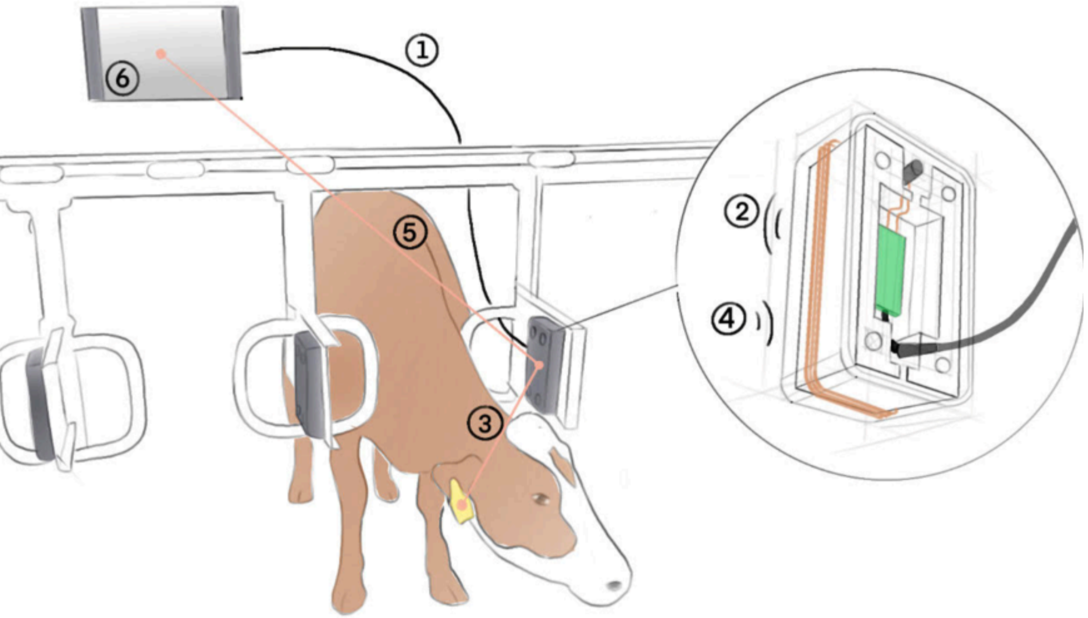


Figure 6: Step by step functional explanation of antenna performance

2.7 Technological Developments Affecting the Redesign

As this product was developed 30 years ago, there are also many aspects of the antenna's architecture that can be upgraded based on more recent technological developments. These developments are concluded from conversations with senior electrical and mechanical engineers at the company.

The ferrite core and entire coil adjuster can be removed as newer PCB's and other software upgrades are able to support tuning the frequency of the antenna in place of the coil adjuster that aided in tuning the frequency before.

The replacement of the **copper wire with a copper strip** allows for a smaller amount of copper to be inside of the antenna. This lowers the value of the antenna's recycling value but also means less copper would be lost when the product is not disposed of or has a lower than 100% yield in the recycling process.

Because of the developments in the hardware of the antenna, the **change in the amount of potting material** will not affect the electromagnetic function of the antenna. It was originally thought that the change in the potting material or other materials in the antenna would largely affect its function, but the low frequency of the antenna also prohibits any large electrical interactions with the other materials. A low dielectric constant is generally preferred for optimal antenna performance.

The **length of the PCB** will decrease by half of its current length. This decreases the size of the area that should be most protected inside the antenna.

Chapter 3: Product Journey and Disposal

Designing a product's architecture for better repair and recycling doesn't improve a product's circularity if the product never reaches a recycling facility or is not repaired when needed. In this chapter we will explore what factors influence farmers' repair and divestment behaviors, the stakeholders involved in the product's journey, the current reselling journeys, and the different disposals of the antenna that currently happen. Then, we will discuss the pain points in the different journeys that negatively affect the disposal or reuse of the product and the resulting redesign requirements. This chapter addresses the first research question.

RQ1: How does the company's involvement and user's behavior affect the end-of-life of the product?

- What are the different end-of-life scenarios of the antenna?
- How are the stakeholders and other third parties involved in the end-of-life journeys of the product?
- What is their influence on the disposal behavior of the users?
- What else influences the user's behavior in their choice between different ways of disposal connected to the end-of-life scenarios?

3.1 Interviews

In order to understand the factors affecting the antenna's end-of-life, one interview with a global application manager at the company, one interview with an agricultural engineer at the company, two interviews with Dutch farmers, two survey responses from an American and Dutch farmer, and two farm visits in the Netherlands were conducted (Table 1, Table 2).

Two type of dairy farms were visited or talked with, a "housing farm" meaning the cows stay in a barn while "composite" means the cows both graze in a field and are housed in a barn. No grazing-only farms, where cows are predominantly at pasture, were involved due to lack of grazing farms locally and likely the smaller amount of them globally. Additionally, an organic farm was visited where no synthetic chemicals are used, the cows have regular access to a pasture, and the cows keep their horns are opposed to other farms. One of the farms was an aspiring circular farm, as the cows eat from organic waste streams from the local city.

Once these interviews and surveys were conducted, quotes and paraphrases were categorized by which of the following stakeholders they related to most (Appendix C). The stakeholders involved in the journey of this product mainly include Nedap, the business partners, the dealers, the recycling middlemen, and the dairy farmers. While the product journey does start earlier with the material extraction and transportation of the materials to Nedap's manufacturers, this project is focused on designing for a better end of life of the antenna, so that is less of a focus in the product journeys. The following is an introduction to the different types of stakeholders involved in the product journey maps.

Table 1: Stakeholders interviewed at the company

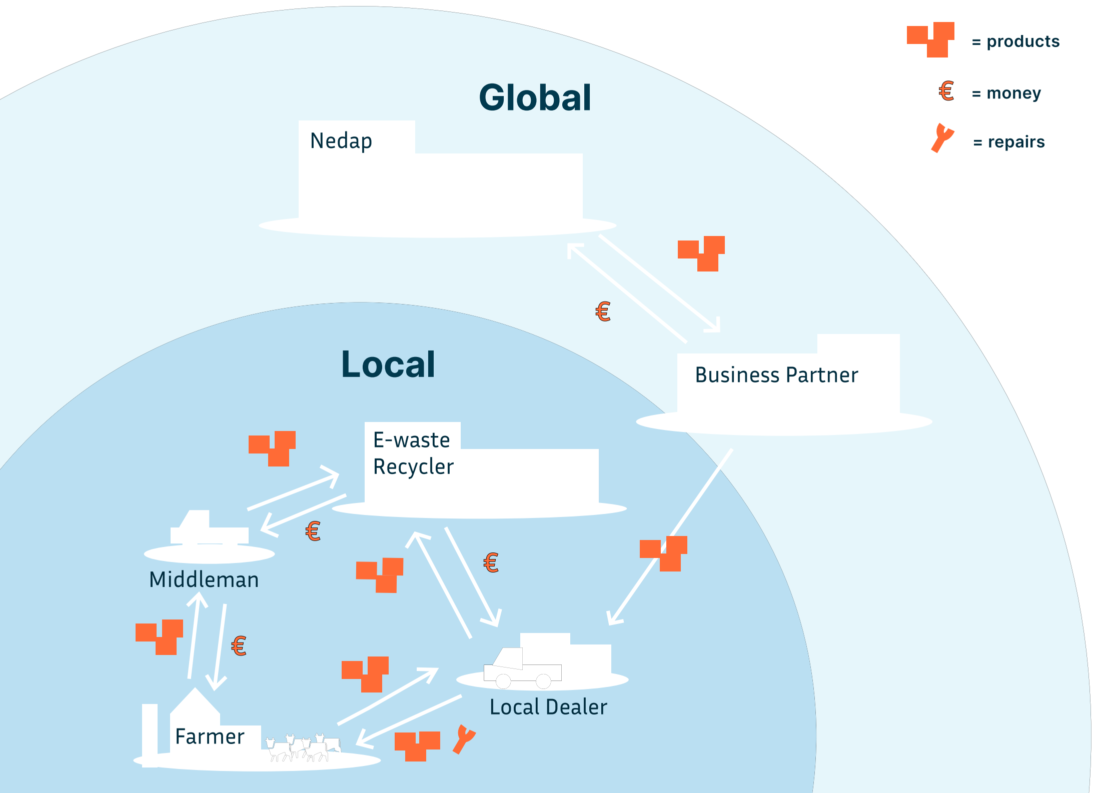
Department	Method
Business Application, Livestock	30 minute interview
Marketing, Livestock	1 hour interview
Engineering, Livestock	30 minute interview

Table 2: Type of dairy farms visited or interviewed

Role	Location	Farm Type	Cow Amount	Method
Herdsman	USA	Housing	600	Survey
Floating farm technical manager	the Netherlands	Composite	31	30 minute call
Organic dairy farmer	the Netherlands	Composite	50	45 minute visit
Test farm farmer	the Netherlands	Housing	300	2 hour visit

3.2 Stakeholder Insights

This section will highlight the stakeholders involved in the product journey and the insights found on their involvement in the different product journeys.



Nedap Livestock

Nedap, the partner of this project, is involved in the design, engineering, manufacturing, assembly, sales, and transportation of the antennas to business partners around the globe. They are the supplier of their livestock products. Nedap does outsource much of the production and manufacturing of the products, but the manufacturing is included in this stakeholder category because some of the manufacturing is done by Nedap owned facilities. Nedap also provides an interface that displays the status of its products, NedapNow. There is generally no direct contact between the company and the farmers.

Business Partners

The business partners distribute the antennas to dealers who are stationed in different regions of many countries. The antennas are shipped to New Zealand, Australia, the United States, China, France, the Netherlands, Ireland, and Germany. The business partners sell the products to dairy farmers and provide the farmers with assistance through the dealers in their region.

Dealers

The dealers assist the farmers during installation, repair, and replacement of the products as will be discussed in the stakeholder maps. They are the farmers' closest contact and can be contacted by the farmers for any issues with the products from the business partners. Their specific duties with the antenna will be seen in the stakeholder maps below. The dealers also have access to the NedapNow software, provided by Nedap.

Figure 7: Stakeholders in the product lifecycle and their interactions with each other

Middlemen

A middleman in the product journey maps is generally a local freelancer who has many side jobs, including transporting goods for farmers and other businesses to recycling facilities. A farmer would know a middleman from the other sides jobs they may perform for the farmers. Additionally, a middleman could also be private recycling transport companies that businesses can book an appointment with and pay for them to pick up their batches of material or electronic products.

Dairy Farmers

The dairy farmers are the users of the antenna (in addition to the cows, of course). The farmers buy the antenna from the dealer and are helped by the dealers to install the antenna (and other products in the system) correctly. The farmers are able to call the dealer for help with repair, replacement, or questions about the antenna and product system. The farmers and their workers are the first to notice malfunctions in the data interface or physically on the antenna and are the final disposers of the products once the product is considered obsolete by the farmers. As the farmers own the product once they buy it, they have the final say on where the product goes at the end of its life.

E-waste Recyclers

E-waste recyclers are recyclers who specialize in processing electronic waste by disassembling and sorting out raw or valuable materials. The middlemen, local dealer, or farmers can drop off quantities of e-waste there for processing.

General Waste Facility

General waste facilities collect, receive, store, and process other non-recycled waste.

3.2.1 Nedap Stakeholder Insights

Nedap's main involvement in the product's lifecycle is the design, manufacturing, production, and selling of the product to business partners. Table 3 displays the insights related to Nedap and the major pain points highlighted in red.

Table 3: Nedap's involvement in the product's lifecycle and the impact on product lifecycle

Nedap's Involvement	Impact on Product Lifecycle
Design of the product/system	Nedap's design requirements that inform the final repairability and recyclability, their focus on repair and recycling during the design, the durability level (and therefore lifetime) of the product, and if there is a notice of failure when the product's performance degrades all impact the final recyclability and repairability of the product.
Business Strategy	Nedap has an influence on the business model of their products and systems. Shifting business models could have a large impact on the end of life of their products if a business model, for example, created economic incentives for the user to correctly dispose of the product.
Availability of Components	The availability of components during manufacturing can impact the availability of spare parts for repair and the need for redesigns of the antenna.
Sustainability Marketing	Nedap has the competitive advantage opportunity to market their product as being designed for sustainability, something being more and more prioritized in the agriculture industry and by their business partners.

*Orange backgrounds indicate pain points

The main pain points found in Nedap's product involvement are the lack of focus on repair and recycling in the original design and the lack of durability of the antenna cable, which are focused on in the following chapters.

Nedap does not generally have direct contact with the farmers and therefore is often far removed from the repair and recycling of their products. But, their software interface, NedapNow, that displays the status of many of their products such as the antenna could lead to business models that increase the repair or recycling of the product if used to economically incentive product repair and recycling or provide access to key information such as fault diagnosis.

3.2.2 Business Partner and Local Dealer Insights

The following are aspects of the business partners and their dealers' involvement in the lifecycle of the antenna (Table 4, 5). The business partners distribute the product to their local dealers who are the main point of contact for the farmers and provide service during and at the end of its life.

Table 4: Business partners' involvement in the product's lifecycle and the impact on product lifecycle

Business Partner Involvement	Impact on Product Lifecycle
Buy-in to sustainability practices	The business partner's commitment to sustainability or recognition of the ROI associated with sustainable strategies significantly influences the extent to which they support and implement repair, reuse, and recycling of products.

Table 5: Local dealer's involvement in the product's lifecycle and the impact on the product lifecycle

Local Dealer Involvement	Impact on Product Lifecycle
Services offered	The offering of repair, reuse, collection, and recycling services enables easier decisions and less effort from the farmer when deciding on how to dispose of the product.
Quality of services offered	The quality of the services offered such as the timeliness of the dealers' responses to farmers' call, the spare part availability, the frequency of check ins by the dealers, and the informing and guiding of the product installation all impact the journey of the product.
Motivating and informing users	How the company motivates users to utilize their repair, reuse, and recycling services impacts the product journey (eg. monetary compensation is a successful motivator for farmers). The communication of the company to farmers about the recycling options available is also impactful.
Ease of Recycling	The ease of the recycling options available to the dealers, such as the cost and distance of the closest recycler impacts their ability to complete the recycling transport.

*Orange backgrounds indicate pain points

Business Partner and Local Dealer Involvement Pain Points

As the business partners that Nedap works closest with do prioritize sustainability and provide many services through the dealers such as their repair and reuse programs, the main pain points were found in the details of:

- The cost and distance of the proper e-waste recycler
- The proper and careful installation of the product
- The company's lack of proper motivating of the farmers to utilize recycling options
- The lack of communication to users about recycling options

3.2.3 Middlemen Insights

The following are insights from the interviews on what influences the middleman's impact on the disposal of the product (Table 6).

Table 6: Middlemen involvement in the product's ;ifecycle and the impact on product lifecycle

Middlemen Involvement	Impact on Product Lifecycle
Location	Middlemen are especially used in rural areas where the distance or access to the recyclers is harder for farmers to reach.
Network	The amount of connections the middleman has influences how much they are used for recycling transportation.
Value of Parts / Compensation	The value of the parts/products being picked up and the monetary compensation from the farmer may determine how likely the middleman is to pick them up.

It is assumed by the farmers that the middlemen transport the products to a recycling center, therefore no major pain points were found. But further research and discussion with middlemen on how this specific product and other potted products is received at recycling facilities should be done. The value of the parts, relating to the monetary return of recycling, is also reflected in the insights from the business partners and farmers.

3.2.4 User Insights

The following are the aspects found that influence the user's behavior during the lifecycle of the product (Table 7).

Table 7: Farmer's involvement in the product's lifecycle and the impact on product lifecycle

Farmer Insights	Impact on Product Lifecycle
Repair Skills of Farmer	The farmer's confidence and experience in repair impact how soon or if they utilize the dealer for repairs.
Farmer's Connection to Locals	The farmer's connection to locals impacts their options of recycling (eg. If they know a recycling middleman that can help them transport materials).
Farm Type	The size of the farm can influence the farmer's dependence on the technology- a bigger farm generally means the farmer depends on the antenna's data more. A larger dependence on the antenna can have an impact on the urgency of repair or replacement/disposal of the antenna.
Farm Location	The location of the farm influences the type of regulations that affect the farmer, the sanitary level of the region, and the farmer's connectedness to resources for repair and recycling.

State of the Industry	A low economic state of the industry can lead other farms to shut down, causing an increase in used products on the market or cause the farmer to not have the funds to pay a middleman to transport the antenna to recycling.
Farmer's Awareness of Available Services	The farmers' awareness of available services like the dealership's services, middlemen recyclers, or the local recycler's location impact how they choose to divest from the product.
Farmer's Awareness of the Recyclability of the Product	The farmer's awareness of the recyclability of the product can impact if they even think to recycle it at end of life.
Return on Investment (ROI)	A large motivator for the farmers to recycle is the ROI from recycling the product. Monetary compensation from valuable parts motivates farmers to properly recycle the product.

*Orange backgrounds indicate pain points

User Pain Points

The biggest pain points of users found in the interviews were:

- The lack of awareness of recycling options
- The lack of awareness of recyclability of the antenna
- The lack of ROI from recycling the antenna
- The effort of recycling the material left over if the dealer or middleman picks up the valuable parts

The final pain point does not currently relate to the antenna specifically as the antenna does not have the ability to disassemble because of the potting. For other products such as robots, the farmers mentioned having to take apart the steel to handover to dealers or middlemen for recycling.

Now that we have the pain points and insights from farmers and stakeholders' experiences with the end of life of the product, we can view the different product journeys found in the interviews and see where in the journeys these pain points happen.

3.2.5 Conclusion

The stakeholder interviews led to the discovery of pain points in the design and manufacturing, the installation, and the motivation for utilizing the recycling options (Table 8). As the lack of focus on repair and recycling in the company's design of the original antenna will be addressed in later chapters, the remaining pain points are to do with the farmers' lack of awareness of recycling options and recyclability and the motivation of the farmers to utilize the recycling options. Additionally, the high cost or distance of the recycling facilities is a demotivator for business partners to properly recycle products, but this is not a pain point focused on in the redesign because of the lack of access to business partners for this project.

Table 8: Stakeholder pain points converted to redesign requirements

Stakeholder Pain Point	Redesign Requirement
Farmers are unaware of the recycling options.	The user (farmer) should be notified of recycling options at the product's obsolescence.
Farmers are unaware of the recyclability of the product.	The user (farmer) should be aware of recyclability of the product.
Farmers are unmotivated to use the recycling options.	The farmers should be motivated to utilize the recycling options.
The current ownership business model does not incentivize sustainable practices.	The product's business model should incentivize sustainable practices.

3.3 Product Journey Maps

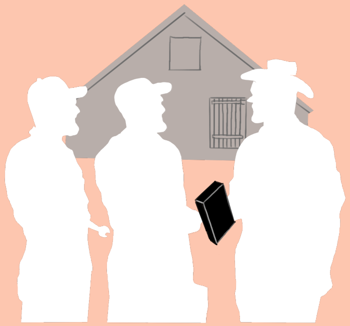
Overview of Product Journeys

The following are the different types of reuse and end of life journeys of the antennas found in the interviews, farm visits, and survey responses. There are two different journeys for the reselling of the product when it is still considered to have life left and two journeys for the final end of life of the product (Figure 8).

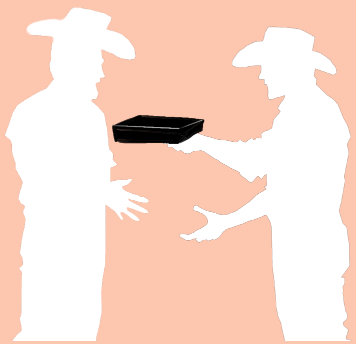
Figure 8: Two reuse and two end of life product journeys found in interviews, surveys, and visits

Reuse Product Journeys

Farmer contacts the dealer after about 10 years of use



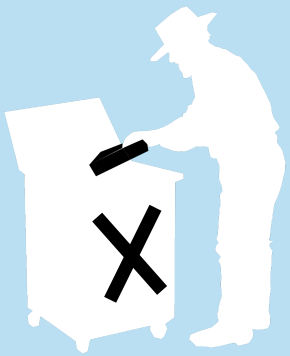
OR *Farmer sells the antenna to another farmer locally*



End of Life Product Journeys

Farmer calls local middleman to take the product to recycling

OR *Farmer puts product in the trash and it is incinerated*



3.3.1 Reuse Product Journey Maps

Every antenna produced is initially sold to a farmer through a dealer of a business partner. Scenario 1 and 2 focus showcase the two reuse options used by farmers when they are finished utilizing the antenna and hope to get rid of the hardware.

In the first reuse scenario, the farmer contacts a dealer about replacing the product (Figure 9). An antenna generally lasts at one farm for 10 years, therefore it is common for the dealers to pick up the antenna and keep it in stock to resell to another farmer later on.

The 30 year lifetime of one of these antennas means the antenna could be used for 10 years at three different farms. A farmer may get rid of the antenna after around 10 years because of replacing their whole system, including more updated or different functioning antennas.

In this scenario, the pain points are mainly found within the design, manufacturing, and proper installation of the product. There are many factors that could influence why a farmer may not choose this scenario, which should be further quantitatively researched. It could be that they receive more money for the old antenna by selling it themselves locally or at an online marketplace, seen in Scenario 2.

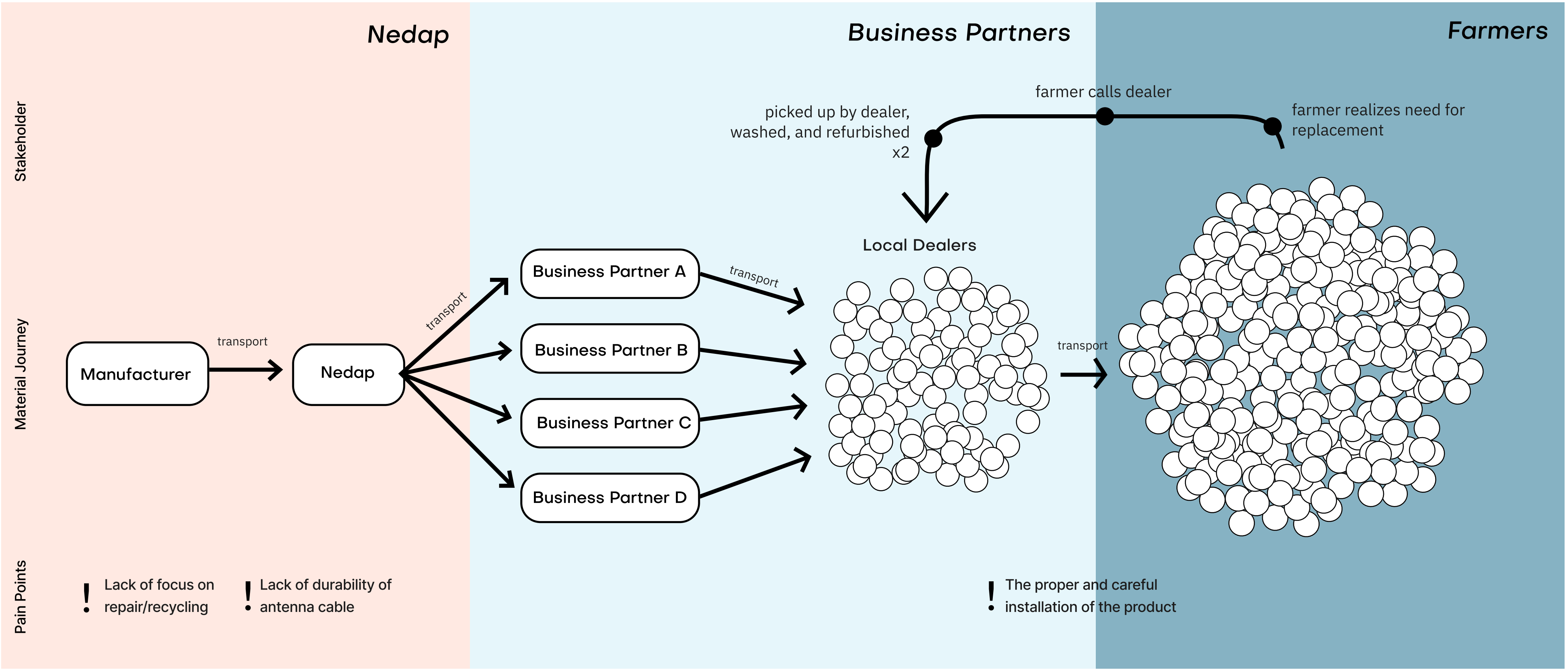


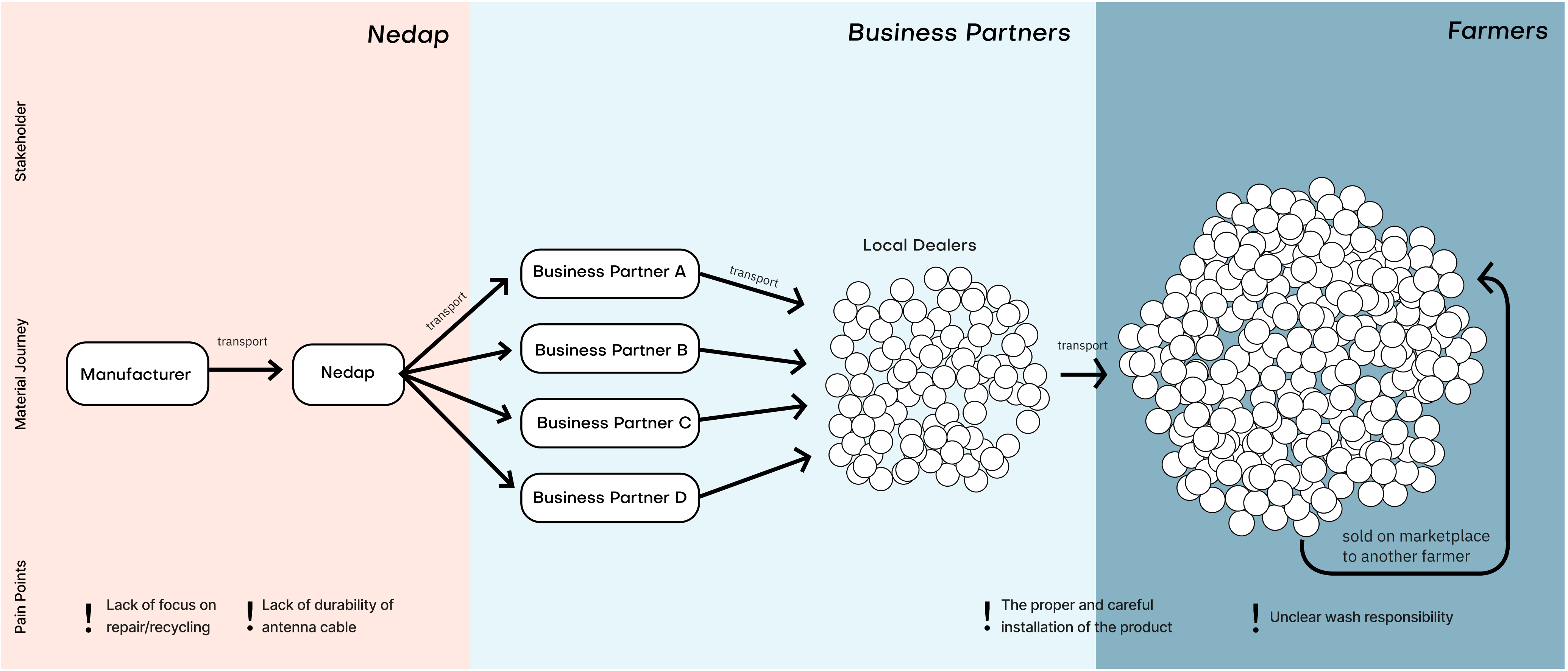
Figure 9: Reuse Scenario 1 where farmer contacts dealer about product replacement after 10 years (eg. upgrading entire system or antenna is broken and needs replacement)

Reuse Scenario 2: Local Resale

In the second reuse scenario, the farmer sells the antenna to another farmer locally. A few of the ways the farmers from the interviews and survey sell their electronic products is through an online marketplace, word of mouth, and even at a local auction.

In this scenario, the added pain point from the former scenario is the unclear wash responsibility of the product. As informed by the business manager, this could become especially dangerous in countries with a lower buy security standard. An unwashed antenna could harbor bacteria, viruses, or chemical residues that could negatively affect the next farm. This is one way that a farmer taking on the responsibility of reselling the antenna and not utilizing the services of a dealer could turn out negatively. As the Netherlands and most of the countries Nedap sells to generally have high buy security standards, meaning sanitization would be a higher priority to those countries, this pain point is not as focused on in the redesign phase. Other pain points could be the loss of dealer support for the next farmer, though this is currently an assumption.

Figure 10: Reuse Scenario 2 where a farmer sells the antenna to another farmer locally (eg. an online marketplace, word of mouth, or auction); the amount of shapes symbolize the stakeholders' ratio locally



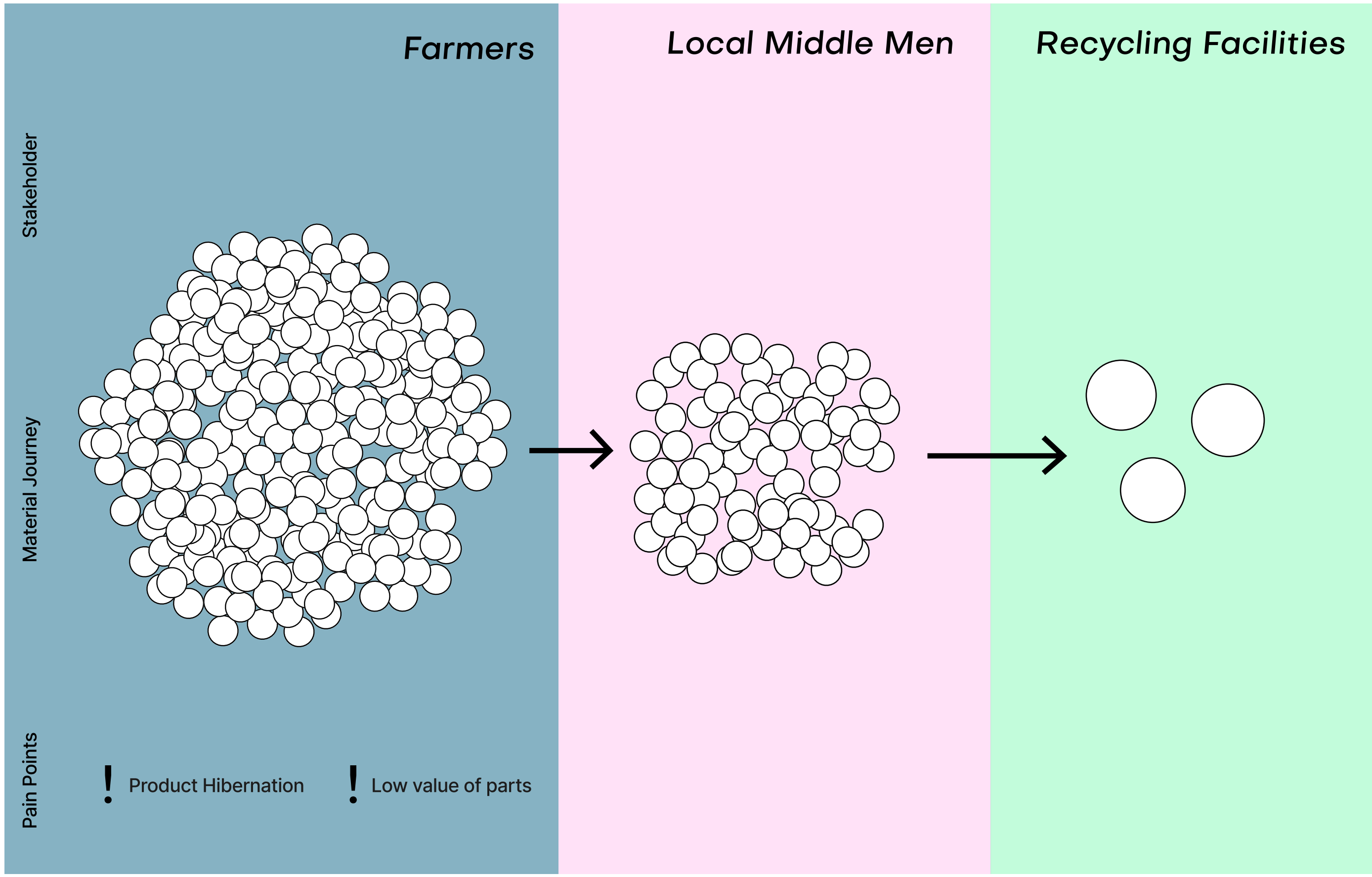
3.3.2 End of Life Product Journey Maps

Scenario 1 and 2 of the end of life product journey maps show overviews of the different options of the antenna's very end of life: the farmer utilizing a local middle man or the farmer throwing away the product leading to most likely, incineration. These scenarios were created from the real-life scenarios of the farmers interviewed and surveyed.

In Scenario 1, the farmer pays a local middle man to transport a batch of electronic goods or other materials to a recycling facility (Figure 11).

This scenario assumes that the farmer is locally connected and has a contact for a private recycling transporter, but all of the farmers interviewed were. In the interviews, one farmer noted that it is more likely that the farmer would add an antenna to a pile of discarded materials or products to be taken by the middle man. The middle man charges a fee, picks up the product, and transports it to the correct recycling facility that processes e-waste.

Figure 11: End of Life Scenario 1 where farmer pays local middleman to transport e-waste



The farmers interviewed also often try to gain back the money paid to the middle man from the money the middle man receives from the recycling facility for the material transported. The issue is that the current antenna has very little recycling value, which may also cause the farmer to not recycle the product if they receive very little back monetarily from doing so. This also showcases the need for monetary or other types of motivation for farmers to correctly dispose of the antenna.

One Dutch farmer mentioned that he would keep the antenna in the batch of electronics or materials in a shed that should be recycled. He would schedule an appointment for pickup from a middleman about 4 times a year. Because his farm was a circular farm with a focus on sustainability, other farmers may not schedule pickups as often, leading to the product's hibernation and possible loss of the product's material recovery.

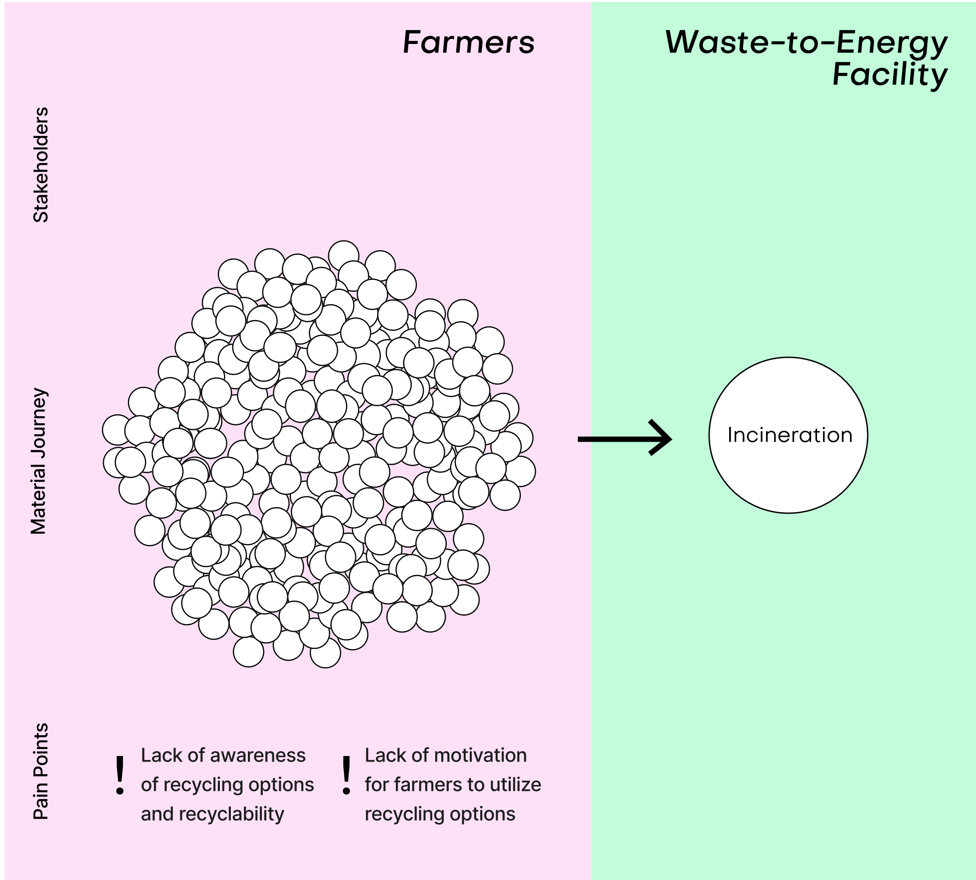
End of Life Scenario 2: Product is thrown away

In Scenario 2, the farmer may hibernate or keep the antenna in an "old museum" in their barn of old products, most likely leading to the burning of the products either by the farmer or by a waste facility if the farmer throws the product away.

The largest pain point in this scenario is the farmer's lack of awareness of recycling options or the lack of motivation for the farmers to utilize the recycling options.

As all of the farmers and business interviewees mentioned in some way the importance of the return on their investment for a farmer, it would most likely be most motivating for a farmer to know he would receive some kind of value back from recycling the product.

Figure 12: End of Life Scenario 2 where farmer stores then throws away product after use



3.3.3 Conclusion and Reflection

The scenarios are highly connected to the ownership-based aspect of the antenna. Because the farmer is the ultimate owner of the product after buying it, they have the final say on where the product and components go at its obsolescence or end of life. Therefore, the farmer has the most impact on if the antenna is reused and if the materials of the antenna are recovered in the end. This is also seen by the pain points mainly being positioned at the disposal of the product. Because of this, redesigns will first be focused on the disposal point in the product journey.

The product journey maps are focused on the different reuse and end of life journeys that the antenna may go through. Larger technological products in agriculture that can be disassembled, such as a milking robot, would additionally have the scenario where the dealer may come pick up the valuable or still working components of the product like electronic components and steel and leave the farmer with the other components to dispose or recycle. The lack of ability to disassemble the antenna because of it being potted, as discussed in the chapters following this one, assumedly causes the lack of similar prioritization of recovering the valuable materials like copper within the antenna by the business partners.

The maps are the result of the interviews and survey done with Dutch and American farmers, but other countries may have different product journeys. For example, the business partners in other countries in the EU may be fully involved in the end-of-life of the antenna by taking it to the recycling facility when asked by the farmer.

Chapter 4: Durability

This section will discuss design guidelines seen in existing literature, design requirement originally defined by Nedap for the antenna's environment and function, and attributes of the current antenna that allow it to last up to 30 years. Additionally, it will discuss how the current materials fulfill the design requirements and how the antenna's environmental context influenced the original focus on designing the antenna for durability.

RQ2: How do the design requirements and product architecture of the hardware box affect its recyclability, repairability, and *durability*?

4.1 Existing Durability Design Guidelines

Existing research highlights how reliable products with mature, stable technology are well-suited for life extension strategies (Bakker et al., 2014). Additionally, products with high use-phase energy compared to their embedded energy should only be replaced more often if a "significantly more energy efficient alternative is available" (Bakker et al., 2014). This antenna houses relatively mature (meaning a lack of breakthrough innovations happening), yet still effective Per Place Identification (PPID) RFID technology. It's ability to interface with other non-proprietary processing units and ID tags also enhances its long-term compatibility. While life cycle assessments are the most effective in determining an optimal product lifespan, these aspects point to designing for durability as a valuable environmental strategy for this product.

As part of analyzing the antenna's durability, we compared the antenna's conformity to existing "Design Aspects Influencing Physical Durability/ Robustness of Products" (Balkenende et al., 2022). Balkenende et al. identified 5 categories of common failures related to robustness and physical durability: Mechanical, Thermal, Electrical, Liquid, and UV (Sunlight) which led to these design principles in Table 9 (Balkenende et al., 2022). The colors of the conformity indicate blue for "good", light blue for "partial", or white for "bad" conformity of the antenna to each principle.

Design Principle	Current Antenna’s Conformity
Design Simplicity Using basic operating principles that reduce the number of (moving) parts required.	The potting material currently helps fulfill many of the original requirements such as condensation resistance, waterproofing, and impact resistance without the need for additional moving parts for each requirement.
Material and Component Selection Matching type and grade of components and materials to their functional requirements and use environment.	The current materials and component selection performs very well as the antenna lasts up to 30 years.
Over-specifying Ensuring the load on the part will not exceed the load that the part can handle	The current antenna has survived extreme circumstances such as cows stepping on it and can weather through decades of wear.
Shielding Protecting sensitive electronics from water by using a watertight cover; airtight cooling system in refrigerator.	The current antenna protects the inner components very well especially due to the potting material.
Surface Treatment Select surface treatments to prevent degradation from weathering or wear.	There are currently no surface treatments on the antenna.
Redundancy Adding a backup system in case the main one fails. Duplication of critical components.	There is not currently a backup system designed for the inner components in the antenna.
Expendable parts / materials Design of the weakest link; An inexpensive part that is designed to wear out during use, protecting more expensive parts; e.g., brake pads or lubricant.	The processing unit has protective elements that act against large electrical currents or voltage spikes, for example.
Component lifespan match Choosing components to match components with the longest lifespan in the product prevents the “weakest link” in the design and assures a component doesn’t fail until the rest of the product fails [8].	The current components were chosen to last similar lengths as they tend to all last decades long. The cable is the possible weakest link but is reinforced with supports like rubber grommets at cable entry.
Uncoupling/Decoupling Separating components from each other’s influence, e.g., positioning capacitors away from hot transistors,, or damping vibration through a shock absorber.	PCB and copper wire are placed away from each other, but the voltage entering the antenna is so low that separating them is not necessarily needed.
Self-reinforcement Functional performance improves certain design parameters deviating from nominal conditions. [33,36] (E.g., Rubber lip ring sealing which becomes tighter as the pressure increases.)	There are currently no components of the antenna improving performance during functionality.

Flexibility (interdependent with loose tolerances) Flexible parts can absorb parameter variation and therefore reduce the performance variation. It is worth noting that flexibility is a function of both material properties and geometry [32].	The current antenna is composed of inflexible materials near the bolting holes, such as stainless steel bushings, but is otherwise mainly composed of plastic.
Controlled tolerances Choosing tolerances of parts or between parts to reduce internal variations in load, thus reducing fatigue from stress cycles.	Tolerances are taken account in the current antenna design, but are not necessarily needed internally because of the potting material bonding the inner components.
Proper Use and Maintenance Encouragement Whilst this principle also falls under repair and maintenance, encouraging product maintenance and proper use has shown to induce fewer failures over its lifetime (Eg. Indicator light in coffee maker when descaling is required).	There are failure alerts on the NedapNow system and repair support available from local dealers, but the proper installation of the cable antenna is crucial and not communicated through the product or system.
Condition maintenance feature Features to stay within safe operating conditions, e.g., cooling of computer chip, load balancing in a washing machine, throttle valve against overpressure.	There are minor adjustments made for functionality within the PCB and connected processing unit, and environmental conditions are not in need of adjustment because of the potting material's high quality performance in harsh environments.
Design to avoid dropping: For products that can be easily moved by the user (under 10kg), having ergonomic handling features (e.g., Handles for a vacuum cleaner, grips for phones), assure that the product transported during its use phase.	The current antenna does not have features that prevent mishandling the product.

Table 9: Design principles for robustness (Balkenende et al., 2022) and the antenna's conformity with light blue meaning partial conformity and blue meaning good conformity

As the potting material bonds most of the inner components together, the current antenna's design strengths lie in the design simplicity, material and component selection, over-specified loads, and protection of the inner components. By attempting to decrease or remove the potting material, one challenge of the redesign lies in maintaining the simplicity of the original design as the potting mixture fulfills many performance requirements through one material. The principle of over-specifying the load on the antenna is also a principle that will be used in the redesign of the antenna through FEA simulations.

4.2 Original Durability Requirements

The antenna was originally designed with durability and long lifetime as the main goal. The design requirements in Table 10 show the different types of environmental and functional requirements from the original design of the antenna. These were gathered from discussions with a Nedap senior engineer, Livestock Head of Marketing, and product owner. A lifetime of 10+ years was the aim when designing the product for durability, as there is also a 10 year warranty on the product.

Table 10: Original durability requirements of the antenna

Type	Durability Requirements	Criteria	Standard
Environmental	Waterproof	See Appendix D	IP65
	Dustproof	See Appendix D	IP65
	Condensation Resistant	See Appendix D	
	Chemical Resistant	See Appendix D	
	Impact Resistant	See Appendix D	
Functional	Frequency Stability	Frequency stays at 134 kHz	ISO 11785
	EMC Stability	Power input stays at 1 watt	ISO 11785

4.2.1 Environmental Influence on Requirements

The durability requirements of the antenna are unique because of the exceptionally challenging agricultural environment it sits in. Livestock barns present challenges including high humidity, ammonia exposure, temperature fluctuations, and physical impacts from animals and equipment. The harsh environment is what caused the original engineers to focus on durability when designing the antenna.

4.3 Cable Durability Field Finding

The cable was the only part identified in stakeholder and user interviews as having the potential of failing due to wear and tear or frequent or sudden impact from cow heads to cleaning robots. Farmers and stakeholders mentioned that the only malfunction they've seen happening to the antenna and competitor antennas are brief lacks of internet connection and the wear and tear of the antenna's cable.

One visit to a farm led to a farmer showing how one of his antenna cables (from a competitor's antenna) had broken after the horn of the cows using the milking station wore down the cable. The farmer was currently attempting to resolder the cable back to itself and had attached PVC pipes to the side of their antennas in the meantime as seen in Figure 13, but they admitted it would probably end in the complete replacement of the antenna.

Figure 13: A broken and temporarily repaired competitor antenna cable with PVC covering

While other stakeholders mentioned the cable being the weakest point of the antenna, though not commonly being a problem, this incident reflected a worst-case incident of the cable breaking off. As this was a competitor's antenna, this antenna did not include the rubber grommet at the cable's entry that Nedap's antenna contains. The incident shows the importance of protecting the cable entry point and encouraging proper installation of the antenna with the cable facing away from the cow.

4.4 Material Selection

Based on the design requirements defined by Nedap, the following materials were originally selected for the antenna based on their fulfillment of the design requirements and needed functions of the antenna. The materials chosen to fulfill the durability requirements include: housing cover, the plastic ferrite cover, the white foam, the cable coating, the grommet (cable entrance protector), the strain relief and its screws, and the potting material (Table 11).

Table 11: Original material selection of current antenna design, materials fulfilling the durability requirements are shown in blue

Name	Material	Design Requirement Fulfilled
Housing cover	Non-recyclable co-polymer	Waterproof, Dustproof
Coil Wire Adjuster	Ferrite, PA	Frequency Stability, EMC Stability, PA is Impact, Water, and Chemical Resistant
Antenna wire	Copper	Frequency Stability, EMC Stability
White Foam	EPS	Impact Resistant, Low Cost
PCB assembly	FR4, Cu, mixed metals	Frequency Stability, EMC Stability
Cable	PVC, Cu	Impact Resistant
Shield plate	Aluminum	Frequency Stability, EMC Stability
Grommet	Rubber	Impact Resistant For Cable
Strain Relief + Screws	Steel	Impact Resistant
Potting	Polyurethane	Waterproof, Dustproof, Condensation Resistant, Chemical Resistant, Impact Resistant, Quick Manufacturing

All of the environmental and functional requirements are focused on the protection of the PCB, copper wire, and cable. The buildup of water, condensation, chemicals, or impact on the components can lead to corrosion, dangerous electrical malfunctions, or contamination of the valuable components.

While other highlighted materials may help with one or a few of the durability requirements, the potting helps with every durability requirement. It is also the only material within the product that prevents condensation, a key aspect in protecting the electronic components from corrosion and other degradations from temperature changes. Additionally, the backside (bolted to a metal wall) of the antenna is currently only protected by the potting material, so removing or decreasing the potting material also means finding another way of waterproofing that side of the antenna and stabilizing the inner parts

4.5 Conclusion

The main aim of the durability requirements of the antenna are to protect the electrical and electronic components inside. The environmental conditions of a dairy barn are a major threat to the performance of the components as chemicals, water, dust, temperature change, and impacts from animals pose surround the antenna.

The analysis of the current durability of the antenna led to the finding of the potting material being a major contributor to the durability of the antenna. The potting material also increases the design simplicity of the antenna, as it helps or alone fulfills many of the durability requirements. Therefore, decreasing or removing the potting material means problem solving for how to fulfill multiple performance requirements, such as condensation resistance, water resistance, and impact resistance, in other ways.

Table 12: Insights from durability research and implications for redesign

Durability Insight	Redesign Requirements
The potting material is the only material preventing the antenna from inner condensation caused by temperature changes.	The antenna must be **condensation resistant**.
The antenna is closely stationed next to cows.	The antenna must be **impact resistant** (including the cable).
The antenna's weak durability point is the cable.	The antenna's cable should be **out of reach** for the cows.
The durability requirements protect the electronics from damage or degradation (the other durability requirements from the original design should be maintained).	The electronic components must be protected from **water**.
	The electronic components must be protected from **dust**.

Chapter 5: Repairability

In this section, we will analyze the current repairability of the antenna to answer RQ2. As the antenna is fully potted with polyurethane, the repairability is very limited. Nonetheless, this section will cover the repair insights from the interviews in the product journey section, show the current difficulty of the disassembly of the antenna, and address which parts of the antenna would be priority parts for repair if the product wasn't potted.

RQ2: How do the design requirements and product architecture of the hardware box affect its recyclability, *repairability*, and durability?

Methods: Interviews and survey, disassembly map, hotspot map

5.1 Repair Insights from Interviews

The previous chapter on the product's journeys also unearthed insights into what influences the repair of the product and other Nedap livestock products (Figure 14). How quickly the repair services are able to assist to the farmers, the repair skills of the farmers, and the spare parts available through the businesses and at the farms were all mentioned as key aspects of the quality of repairs done at the farm. In the interviews, the farmers also mentioned how they first seek to repair their products themselves, but ultimately call the local dealer if it is beyond their skills or stored spare parts.

Figure 14: Influences on the repair of the product found in interviews and surveys, visuals generated partially using Bing Image Creator

5.2 Bill of Materials

To gain an understanding of the components that make up the antenna, a bill of materials (BOM) is seen below (Table 13). Figure 15 shows the antenna's architecture before the potting material is poured on top to bond the components together.

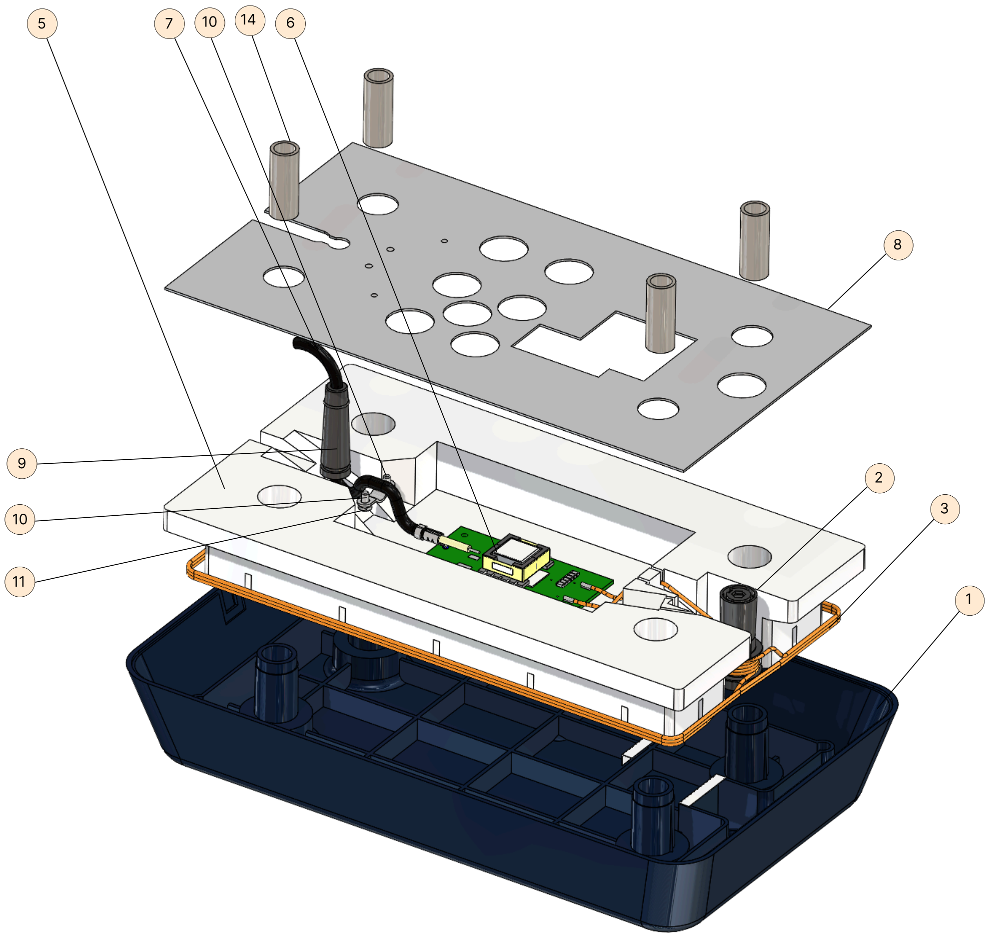


Figure 15: Exploded view of unpotted antenna

Table 13: Bill of materials of the antenna, with components part of assemblies in white

	Name	Material	Amount	Weight (g)	Total Weight (g)
1	Housing cover	Polymer blend	1	312.40	312.40
2	Coil Wire Adjuster Assy		1		7.41
	Ferrite piece	Ferrite	1	4.52	4.52
	Ferrite Holder	PA	1	0.55	0.55
	Plastic Coil Casting	PA	1	2.34	2.34
3	Litz Wire	Copper	1	30	30
4	Glue Loctite	Silicone	1	0.20	0.2
5	White Foam	EPS foam	1	35.80	35.80
6	PCB Assy		1		24.98
	Board	FR4	1	10.80	10.80
	Capacitors	Cu, Mixed Metals	6	0.03	0.18
	TRF Assy		1		14.00
	Wire	Copper	1	2.40	1.40
	Casing + core	Ferrite	1	12.6	12.6
7	Cable Assy		1		302.2
	Solder and Coax Sleeve	PVC	1	224.80	224.80
	Copper wire	Copper	1	77.40	77.40
8	Shield Plate	Aluminum	1	81.8	81.8
9	Strain Relief Grommet	Rubber	1	2.61	2.61
10	Strain Relief	Steel	1	1	1
11	Screw	Steel	2	0.76	1.52
12	Potting Assy		1		1070
	Potting	Polyurethane	1	823	823
	Hardener	Polyurethane	1	247	247
13	Plug Caps	Polyethylene	4	2	8
14	Busses	Stainless Steel	4	12.27	49.08
				Total Weight	1927

5.3 Design for Repair Guidelines

In order to analyze the antenna's conformity to existing repair guidelines, Dangal et al.'s guidelines are presented below with added explanations of the antenna's current conformity. Dangal et al.'s repairability guidelines were developed through analyzing current repairability scoring systems, such as the French Repairability Index and iFixit scoring system, tear-down experiments, and a survey. This resulted in up to date guidelines for EEE. These guidelines along with the other methods in this section informed the requirements for improving the antenna's repairability in the redesign.

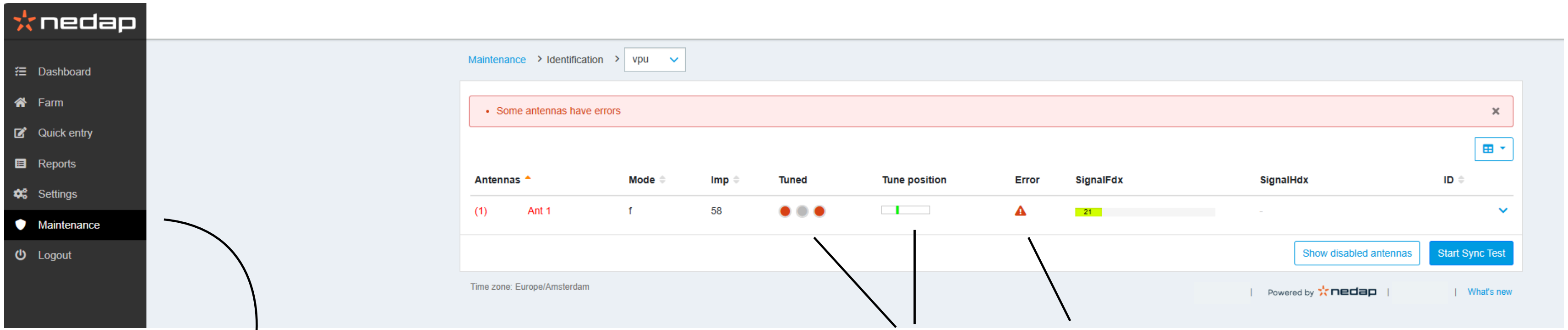
The colors of Table 14 indicate blue for "good", light blue for "partial", and white for "bad" or "no" conformity of the antenna to the principle.

1. Disassembly and Reassembly	
Clumping- clustering non-priority parts for easy removal	Potting material prevents inner component removal due to all components being bonded together.
Surfacing- repositioning priority component earlier in disassembly step sequence	Potting material prevents disassembly.
11 Trimming- optimizing fasteners	The two screws within the antenna are not accessible due to potting material.
Trimming- provide disassembly and reassembly cues	No disassembly or reassembly cues are given.
2. Information Provision	
Passive information important for maintenance, diagnosis, repair in the form of i.e. a manual	Information on if the antenna is correctly tuned and functioning accurately is available in the NedapNow interface, and local dealers are available for repair assistance, but there is no repair guidance or diagnosis help on the interface, product, or manual.
Active information provision to the user, like sound of text signals	Notifications become visible in NedapNow when an antenna is not functioning properly.
3. Accessibility of priority components	
Lid/valve/door	There is no access to the inner components due to potting material.
Wide geometry opening	No opening due to potting material.
Testing points	Testing points are not accessible due to potting material.
Clustering maintenance points	Maintenance points are not accessible due to potting material.
Full view of the components	Components are not visible due to potting material.
Material transparency	Potting material and plastic housing are not transparent.
Symmetric positioning of components	Priority components are positioned symmetrically, though not accessible.
4. Modularity	
Make modules easily removable	Modules are not removable due to potting material
Avoid bundling priority parts to other parts using non removable fasteners	Priority parts are bonded to other materials due to potting material.
Priority parts should be individually removable	Priority parts are not removable due to potting material.
5. Standardized components and interfaces	
Make components interchangeable and compatible across different products or brands	The antenna is compatible with different ID tags or processing units of other brands but the components are not interchangeable into other products due to the potting material's bonding.

Table 14: Existing repairability guidelines and current antenna's conformity (Dangal et al., 2022)

The antenna only fully conformed to active information provision in the information provision principle. The potting material restricts any disassembly, accessibility to the priority components, modularity of the priority parts, and standardized components and interfaces. The information provided for repair and maintenance is solely from the NedapNow interface and includes notifications when the antenna is not tuned correctly or disconnected and a maintenance tab which shows the current tuning status of the antenna. There is no instruction manual or guidance for diagnosis on the interface, but local dealers are available for assistance. Nedap, on the other hand, is not involved in any direct contact with the farmers through the interface or otherwise.

Figure 16: Notification when antenna is disconnected or in need of tuning



tuning status *ambiguous error symbol*

Maintenance tab showing status of antenna

Notification when antenna is disconnected or needing tuning

While the NedapNow interface contains very brief information on the antenna's status, the notifications do allow the farmer to quickly contact a local dealer and utilize the dealer's more extensive knowledge for adjustment or repair. The main issue is the inner components of the antenna are currently not accessible for repair by either the farmer or the local dealer. In the following sections, we will further explore which components are considered priority parts and how the potting material prevents disassembly and access to the priority parts for repair.

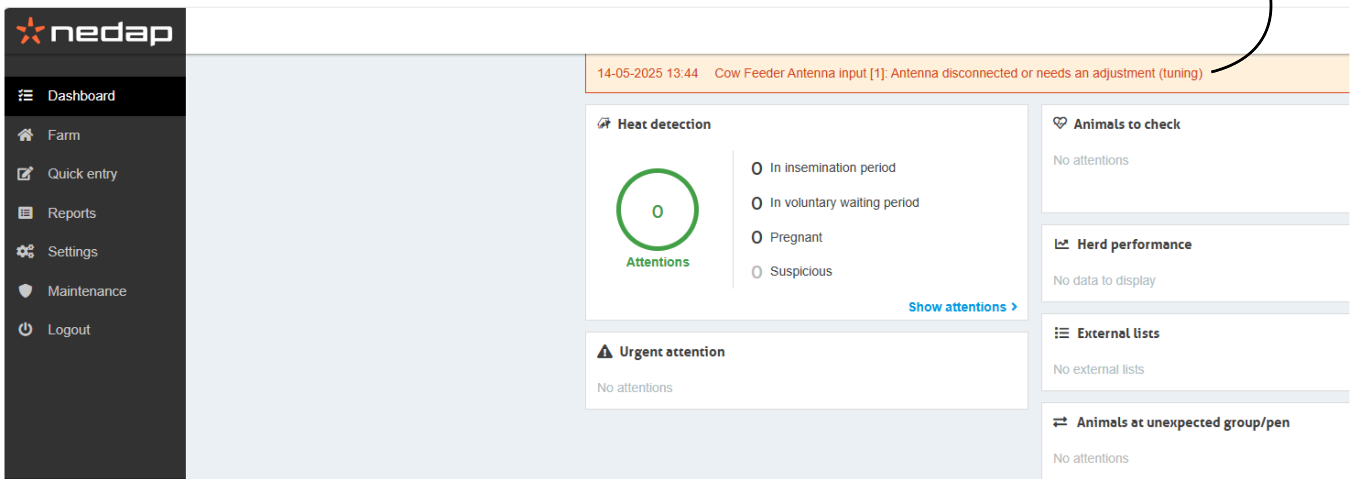


Figure 17: Maintenance tab showing tuning status and error symbol

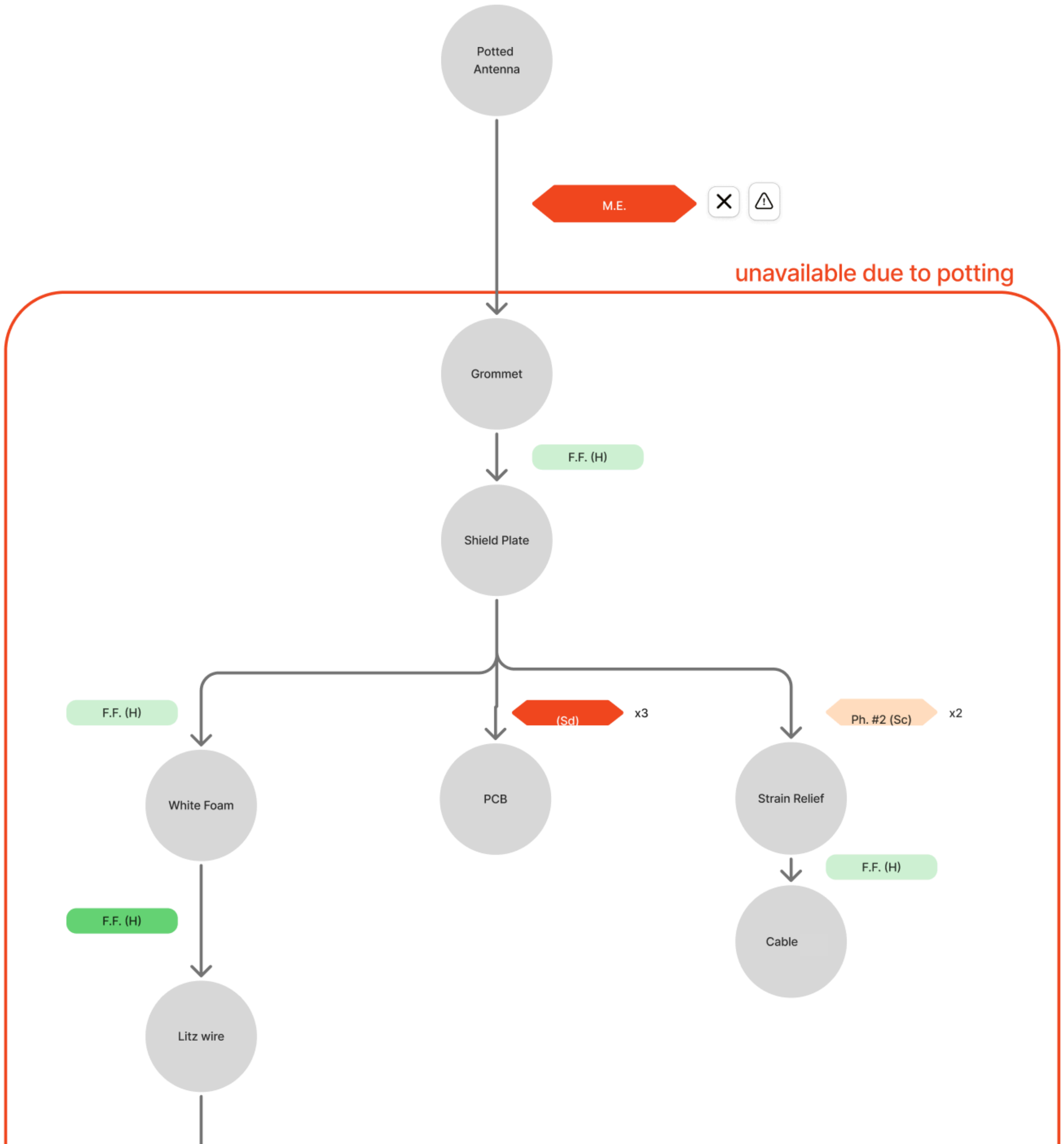
5.4 Dismantle and Disassembly Map

Because of how the potting material encapsulates all of the components except the cable, it is not possible to disassemble the antenna. In order to view the architecture of the product, we attempted to cut open the antenna and created a disassembly map following the method of De Fazio et al. (2021).

Figure 18: Dismantling of the antenna through bandsaw and hammer

We cut the antenna in half with a band saw and hit one side with a hammer in order to separate the halves (Figure 18). The bandsaw could only saw until the ferrite magnet inside of the TRF (Tuned Radio Frequency Receiver) component of the PCB which is why hammering the two sides was needed to separate the two halves (Figure 18). The heavy force dismantle process led to the following disassembly map, as the potting prevents the user or repairmen from accessing any components without extensive processes or time such as using chemicals or heat to separate the potting from the components.

The disassembly map shows how the components covered by the potting are inaccessible for repair. As the tools and time needed to separate the potting from any of the materials are impossible for businesses offering repair services or users, the penalties of uncommon tool and non-reusable connectors are given, which lead to the end of the disassembly map. The other parts of the disassembly map labelled “unavailable due to potting” in Figure 19 display the disassembly steps of the product if those parts were not encapsulated or initially freed from potting, such as in the exploded view.



Type of Tool
(Sci) = Scissors
(H) = Hand
(Pl) = Pliers
(Sd) = Soldering Iron

Connectors
S.F = Snap Fit
F.F. = Friction Fit
M.E. = Material Enclosure

Force Intensity

Low Mid High

Motion Type

= hand motion

= single motion tool

= multiple motion tool

Penalties

= product manipulation

= low visibility / identifiability

= uncommon tool

= non-reusable connector

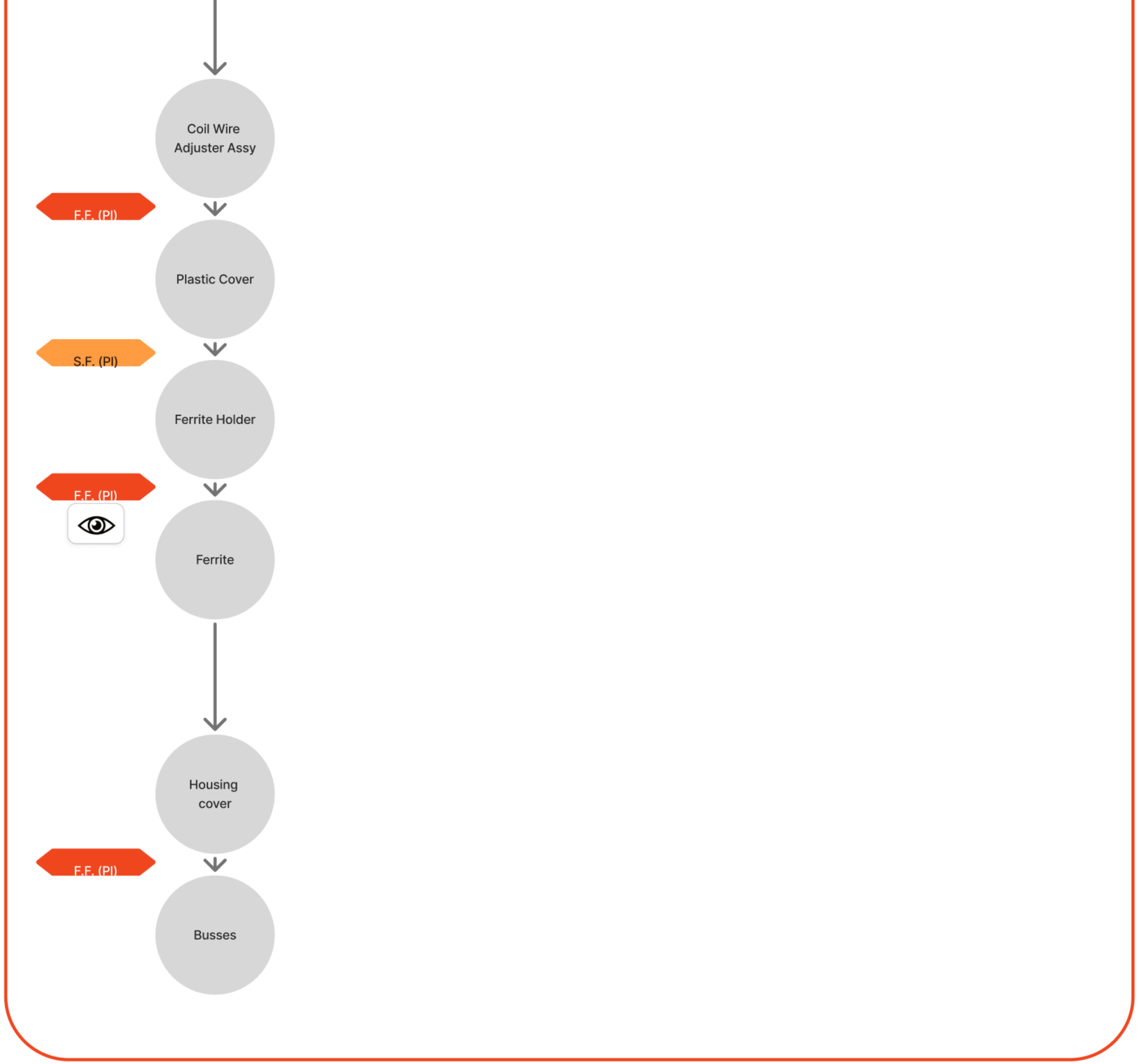


Figure 19: Disassembly map of current antenna

Type of Tool
(Sci) = Scissors
(H) = Hand
(Pl) = Pliers
(Sd) = Soldering Iron

Connectors
S.F = Snap Fit
F.F. = Friction Fit
M.E. = Material Enclosure

Force Intensity

Low Mid High

Motion Type

= hand motion

= single motion tool

= multiple motion tool

Penalties

= product manipulation

= low visibility / identifiability

= uncommon tool

= non-reusable connector

5.5 HotSpot Map

To identify which of the components and materials of the antenna would be considered priority parts if they were accessible, a hotspot map was created using De Fazio's method (Appendix D, (Flipsen et al., 2020)). The environmental impact, economic cost, and functional importance determine which components are priority parts to redesign or design for disassembly. The following priority parts were identified:

Table 15: Priority parts found from HotSpot Mapping

Environmental	**Economic**	**Functional Importance**
Copper wire	Copper wire	Copper wire
Potting	Potting	PCB
PCB	PCB	Cable
		Potting
		Shield plate
		Ferrite core

Table 16: Function of priority parts identified in HotSpot Map

Priority Part	**Function**
Copper wire	Transmission and reception of electromagnetic waves
PCB	Transmission and reception of electromagnetic waves
Potting	Protects against inner condensation, impact, and water and dust
Cable	Power supply
Shield Plate	Shields the other side of the antenna from receiving or transmitting electromagnetic waves
Ferrite core	Increases the induction of the copper wire

The potting, copper wire, and PCB board are the most expensive and environmentally harmful components of the antenna. The potting is expensive because of how much of it is needed per antenna, over 1000 grams.

Table 16 and Figure 20 explain the function and location of each of the priority parts. These are important to take into account in order to understand how closely the positioning and amounts of the components should be maintained in order to maintain the electrical functionality of the antenna in the redesign.

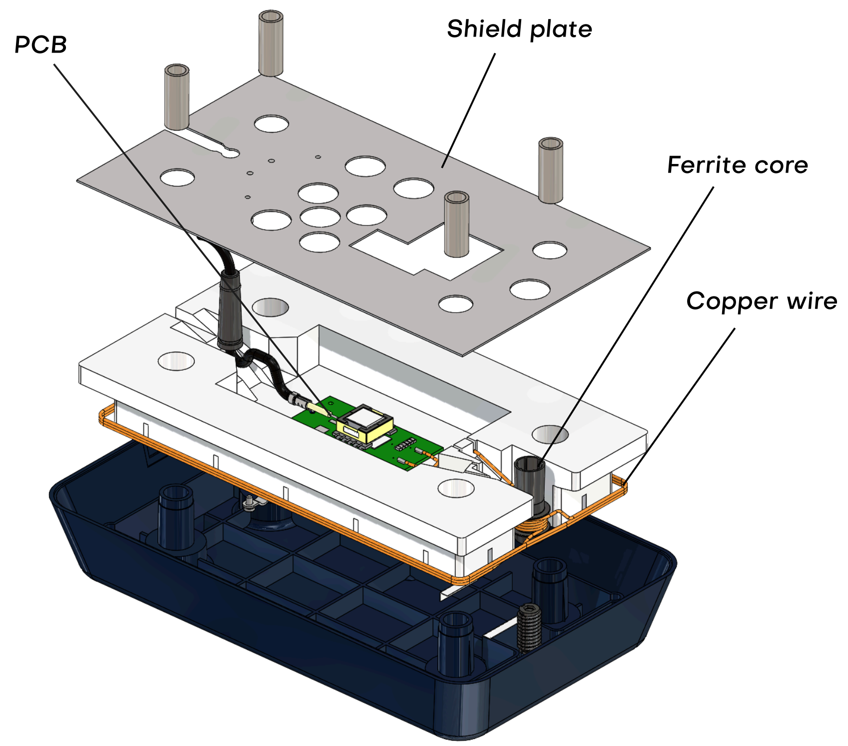


Figure 20: Exploded view of unpotted antenna with priority part call outs

After discussing the electrical functionality of the priority parts with engineers at the company, two requirements were discovered for the redesign in order to maintain the antenna's functionality. The short range of the emission of this antenna, about 30-40 cm, is key to the accurate and precise identification of the cows stepping up to milking robots or milking parlors. In order to maintain this range, the copper wire must be kept the same distance from the aluminum plate and the dimensions of the rectangular shape of the copper wire's coil must stay the same. These are added as requirements for the redesign. While in theory the potting material affects the magnetic field or frequency of the antenna, meetings with engineers at Nedap led to the conclusion that the effect is so minimal it is not taken into account.

5.6 Conclusion

The potting of the antenna prevents accessibility to any of the components of the antenna and prevents any repair activities. The copper wire, PCB, potting material, and cable were all identified as priority parts because of their economic, functional, and environmental impacts. The potting material being one of the priority parts because of its durability function showcases the tension between mechanical durability and repairability and recyclability in this project. The economic and environmental impact of the potting material also point to the need to minimize or remove the potting in the redesign. The functions of the priority parts led to redesign requirements involving keeping the dimensions of the copper wire's positioning the same as the original antenna.

Table 17: Insights found in repairability analysis and redesign implications

Repairability Insight	Redesign Requirements
The potting material leaves the other components inaccessible for repair and has large economic and environmental impacts.	The amount of potting should allow access to the priority parts.
The copper wire's distance to the aluminum plate is important to the electromagnetic radiation of the antenna.	The copper wire should maintain its distance from the aluminum plate.
The copper wire's coil dimensions are important to the antenna's electromagnetic pattern and frequency.	The copper wire should maintain its coil dimensions.

Chapter 6: Recyclability

This section will discuss the theoretical, practical, technical, and realistic recyclability of the antenna in order to answer research question two. This chapter will also include a comparison of the antenna with existing recyclability guidelines in order to further inform the focus points of the redesign.

Theoretical material recyclability indicates if the materials can in theory be recycled.

Practical material recyclability tells if the material is actually recycled in practice by recyclers. Both theoretical and practical recyclability are determined through existing literature and discussions with recyclers.

Technical product recyclability indicates how well the connected materials liberate from each other, which is discovered from shredding the product and analyzing the fragments.

Realistic recyclability takes into account their collection rate and if the product and materials are realistically recovered.

RQ2: How do the design requirements and product architecture of the hardware box affect its *recyclability*, repairability, and durability?

Methods: Shredding test and yield, recyclability map, existing literature

6.1 Theoretical and Practical Material Recyclability

This section will discuss the theoretical and practical material recyclability of the different materials that the antenna is composed of.

The thermoplastics, ferrous and non-ferrous metals, and valuable metals like copper are all theoretically recyclable as there are processes that can recover and reprocess those materials (Berwald et al., 2021). The theoretically unrecyclable materials in the antenna are mainly the thermosets in the antenna, as thermosets are unrecyclable due to their chemical composition (Berwald et al., 2021). The thermosets in the antenna are the small cable grommet and the potting material.

Though many of the materials are theoretically recyclable, there are a few plastics that are not practically recycled by recyclers. The polymer blend, one of the thermoplastics, and the expanded foam are theoretically recyclable as they are thermoplastics, but they are not part of the group of common plastics with economically viable or established recycling streams (Berwald et al., 2021).

6.2 Technical Product Recyclability

The following is the process of the shredding test and results of the sorted fragments. The results of the shredding experiment indicate the liberation of the different materials in the antenna, as we are able to predict if the resulting fragments would end up in their correct fractions for recovery.

6.2.1 The Shredding Test

In order to find out the recyclability of the current antenna's components and materials, a shredding test was conducted. The aim of a shredding test is to discover the technical recyclability of the product. By shredding and hand sorting the pieces, we can see how well separated or polluted the materials are from each other, which impacts if the materials sort correctly during physical and chemical sorting processes at the recycling facilities.

Preparation

Three of the antennas were put through a fine shredding machine, an HSM Powerline HDS 230, at an e-waste recycler in Utrecht, the Netherlands. They were first cut into thirds with a Miter Saw and separated from their cables by cutting at the edge of the rubber grommet. The recyclers performed these tasks so that each piece fit into the entry slot of the machine.

Figure 21: One antenna of three after MiterSaw preparation for shredding

The Shredding

The three antennas were put into the small shredding machine at the e-waste recycler (Figure 22). The cables were also put into the machine after the three antenna boxes. The result was a box full of small (2-8 cm) pieces ready for sorting.

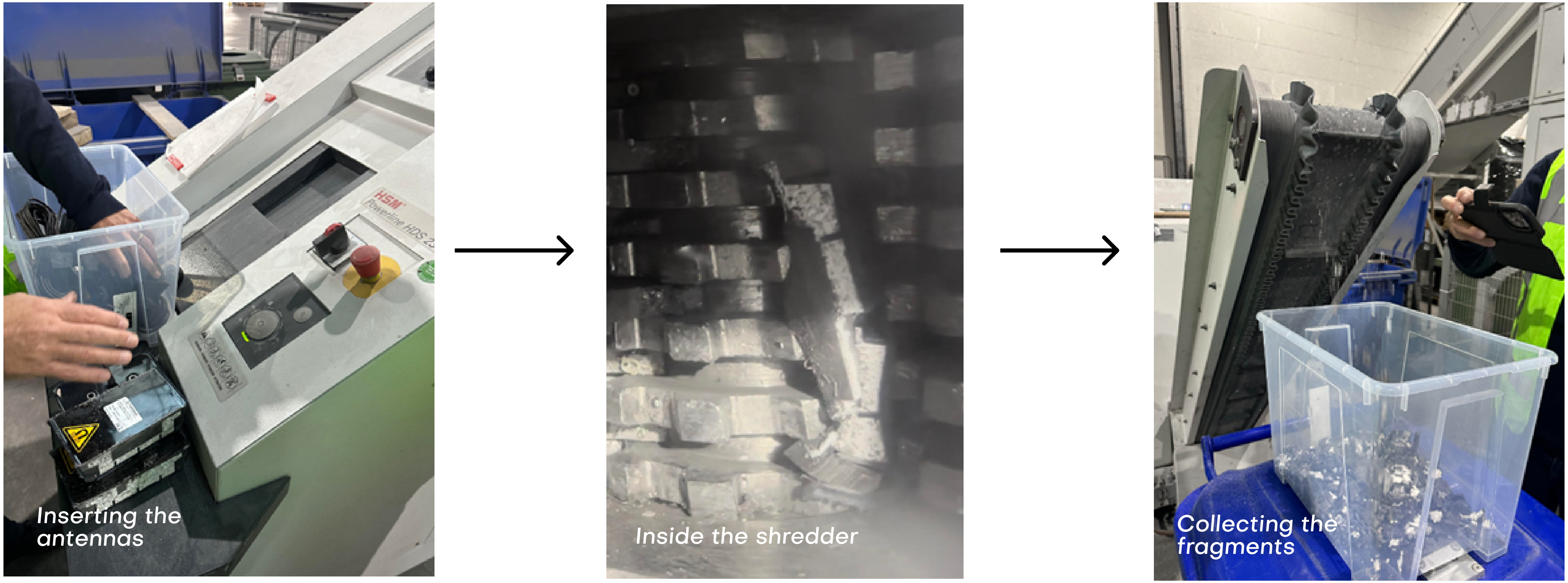


Figure 22: The shredding process of the antennas going through the fine shredder

Sorting the Shredded Pieces

After the pieces were shredded, each piece was sorted into the homogeneous or heterogeneous categories based on whether the piece contained multiple or one material (Figure 23, Table 18, 19).

Figure 23: Sorting the shredded pieces

Homogeneous Categories
Aluminum
Steel
Copper
PCB
Polymer blend
Polyurethane (Potting)
EPS foam
Rubber

Table 18: Homogeneous categories found during sorting

Heterogeneous Categories
Copper and Potting
PCB and Potting
EPS and Potting
Polymer blend and Potting and EPS
Aluminum and EPS
Aluminum and Steel

Table 19: Heterogeneous categories found during sorting

6.2.2 Yield

Mass Recovered

99% of the mass of the antennas was recovered from the shredder, meaning 1% of the material may have gotten stuck in the machine or otherwise lost. The potting, steel, and aluminum separated as one material with much more success than the other materials (Figure 23).

Table 20: Resulting amounts of each material that end up homogeneous, heterogeneous, and how much is ultimately recovered from three shredded antennas

Material	Total Mass (g)	Homogeneous Mass (g)	Mass present in Heterogeneous Fragments (g)	Recovered Mass in Correct Fraction (g)
Ferrous Metals	206	141	52	179
Aluminum	245	210	36	234
PCB (board only)	33	2	28	8
Copper	97	0	97	5
Polyurethane (Potting)	3210	2959	251	Unrecycled
Polymer blend (Housing)	937	637	300	Unrecycled
EPS Foam	107	12	93	Unrecycled
Rubber	8	1	7	Unrecycled

Bolded red meaning materials not practically recycled by recyclers and bolded black highlights most valuable parts

Heterogeneous Connections

A discussion with an e-waste recycling expert allowed for the following analysis and assumptions of the final destinations of the most common heterogeneous fragments. The highest weight and most common heterogeneous fragments were the copper wire connected to the potting material and the housing plastic connected to the potting material (Figure 24). Below we will discuss if the materials ended up in the correct fraction for recovery. When a material does not end up in the correct fraction or is unrecyclable, it means it is not recovered meaning its either incinerated or lost in another fraction.

1. PCB + Potting

These pieces come from the center of the antenna where the PCB sits under potting material. The large amount of potting in the heterogeneous pieces means the density separators and eddy current separator will most likely not catch the small amount of PCB embedded in potting material. If the green PCB color is clearly visible to the image recognition machine, the PCB-containing fragment will be correctly sorted for copper refinement. Therefore, the pieces with visible green PCB colors larger than 1 cm x 1 cm led to 60% of the heterogeneous pieces most likely being correctly picked out through image recognition. Otherwise, the pieces with a tinier amount of PCB showing could lead to the sink or float plastics separator and the copper within the PCB would most likely be lost. In the end, 7.7 grams of the 33 grams of PCB, only 4.3% of each antenna, is likely to end up in the correct copper fraction for recovery.

2. Copper + Potting

The copper wire trapped inside the potting material would also lead to a small chance of the copper being picked out by the density or magnetic sorting machines and therefore end up at the sink or float station for plastics. The magnetic sorting is highly dependent on the level of magnetism set by the recyclers on a day to day basis. There is a chance that the copper may be recovered if lost in the sorting process if the e-waste recyclers notice it and decide to send it to a metal refinery for smelting, but the large amount of potting left on the small amount copper may be decided as not worth it by the recycler for economic reasons. Less than 1% of the copper heterogeneous fraction had a copper mass that outweighed the potting mass, leading to only 5.4 grams total of the 97 grams of copper ending up in the copper fraction for recovery. This is only 18% per antenna shredded.

3. Ferrous and Aluminum

These pieces come from the connection of the steel screws to the aluminum plate, as the strain relief uses screws to hold the cable in place and the ferrite core attracts to those metallic pieces (Figure 5). The ferrous (steel screws, ferrite magnet) and aluminum shred pieces risk the loss of aluminum, as the higher weight and magnetism of the screws, for example, could pull the aluminum into the ferrous mixture. 86% of the heterogeneous metal connections' weights were ferrous, which makes the loss of the attached aluminum likely. Fortunately, only 2% of the total aluminum would be lost by these connections.

4. Aluminum + EPS foam

42 grams of these fragments were found as aluminum folding over the EPS foam, but the aluminum's larger weight in most pieces means that the aluminum would likely not be lost and would be recovered in the eddy current. These pieces are the result of the aluminum shield plate placed over the EPS foam.

5. Plastic and Ferrite Core

The plastic and ferrite pieces originate from the wire adjuster assembly, where a ferrite core is fitted inside two plastic outer casings. This ferrite core along with the ferrite magnet inside of the TRF in the PCB contribute greatly to the mixed ferrous and aluminum pieces because of their magnetic properties. Out of the three encasings, one set was completely separated from the ferrite core. The other two shredded antennas led to the ferrite core either being halfway stuck or completely stuck in the nylon casings. 3.1 grams of the ferrite were lost to the plastic fraction.

Results of the Shredding Experiment

The Sankey diagram visualizes how much of the copper does not make it to the copper fraction but instead is lost in other fractions, how a large part of the materials are technically unrecyclable, and the small amount of ferrous or non-ferrous metal that are lost in other fractions.

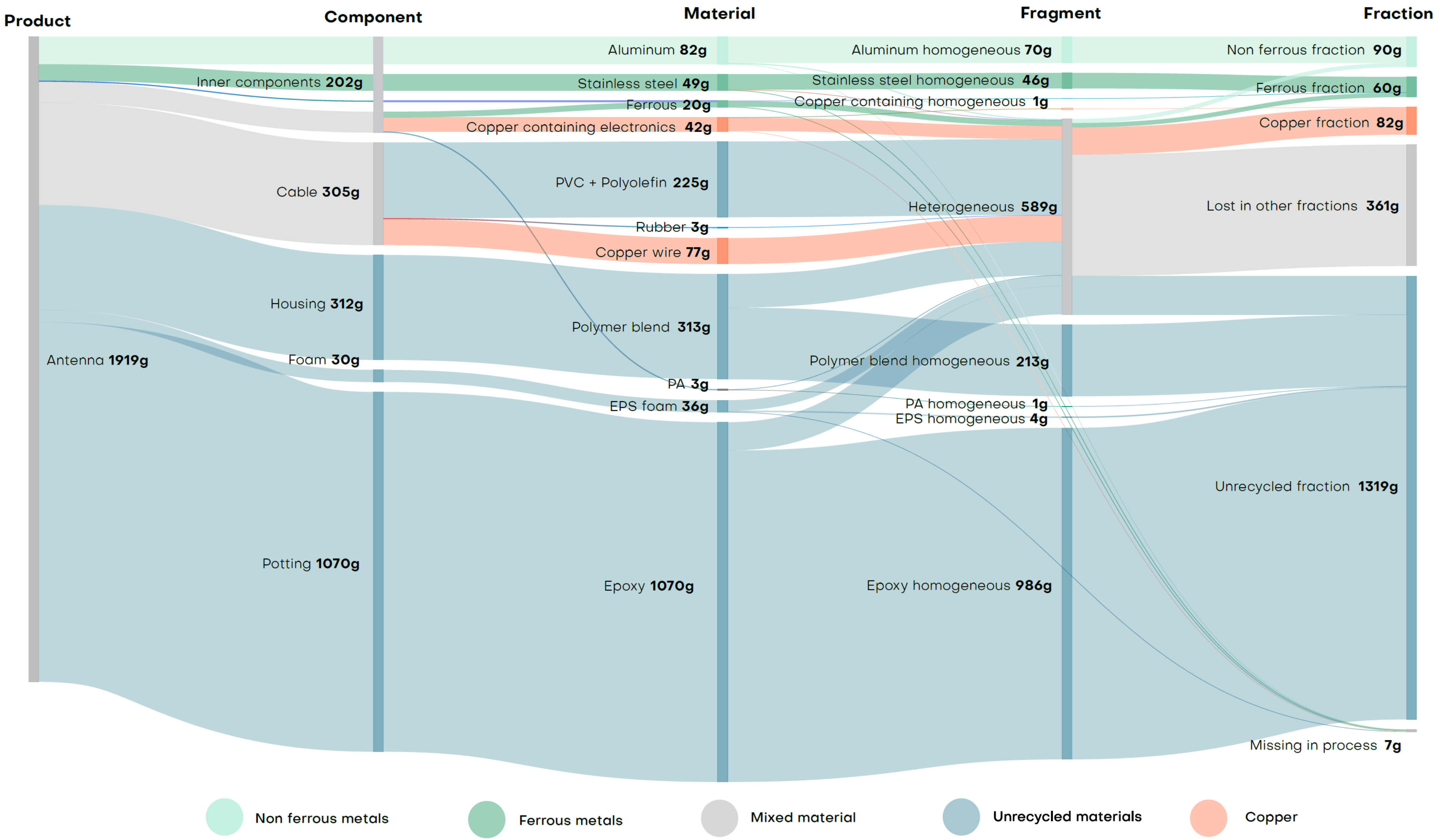


Figure 24: Sankey diagram of results of one antenna from shredding experiment

6.2.3 Recyclability Guideline Conformity

In order to review the antenna's conformity with existing recyclability knowledge and further explore the realistic recyclability of the antenna, the antenna was compared with the recyclability guidelines of Berwald et al. (2021). Dorien van Dolderen's literature review of published Design for Recycling guidelines found that a limited amount of methods and guidelines focused on Designing for Recycling have been developed (Van Dolderen, 2024). Berward et al. (2021) was one of the few guidelines found in Dorien's review developed in collaboration with recyclers recently, which is key considering the inconsistent and evolving nature of recycling practices. The colors of Table 21 indicate blue for "good", light blue for "partial", and white for "bad" conformity of the antenna to the principle. Notice the large amount of white in the table due to the potting material.

Table 21: Current Antenna's Conformity with Existing Recyclability Guidelines (Berwald et al., 2021)

Recyclability Guidelines	Current Antenna's Conformity
Product Level	
1. Enabling easy access and removal of hazardous or polluting parts	
1.1. Use click/snap solutions to fix batteries in a product. Avoid permanent fixing such as glued, welded, and enclosed solutions. 1.2. Fix valuable parts (e.g., printed circuit boards (PCBs), cables, wires, and motors) in a product with metal screws, click fingers, press-fit, shrink foil, self-screwed/tapering, or connectors. Avoid permanent fixings such as pressure sensitive adhesive (PSA) tapes, glue, and welded solutions. 1.3. Use drains for operating liquids and gasses and enable easy removal of parts such as oil tanks, compressors, and hoses 1.4. Use detachment possibilities for hazardous and polluting parts/materials (e.g., dust bags, lamps, cord sets, cord winders, paper, cardboard, textiles, wood, foams, glass, and ceramics). 1.5. Use one module for hazardous parts in the product structure to enable taking out one non-recyclable module instead of searching for several different hazardous parts	Potting material prevents inner component removal due to all components being bonded together.
2. Use of recyclable materials that will be recycled by WEEE recyclers	
2.1. Avoid thermosets and composites.	The potting material, PCB, and grommet are all thermosets.
2.2. Do not use plating, galvanizing, and vacuum-metallization as a coating on plastics.	No coatings are used on the current antenna.
2.3. Avoid the use of coatings on plastics.	No coatings are used on the current antenna.
2.4. Minimize the use of thermoplastic elastomers.	The cable sleeve is made of a thermoplastic elastomer.
2.5. Avoid the use of foam.	Thermoplastic elastomer foam is used in the antenna.
2.6. Minimize the use of magnets.	Magnetic ferrite metals are used in the electronic components.
3. Use of material combinations and connections that allow easy liberation	
3.1. Avoid molding different material types together by multiple-K processes (different plastic materials injected into the same mould, over-molding, or in-mold decoration). 3.2. Avoid connections that enclose a material permanently. Avoid methods such as molding-in inserts into plastics, rivets, staples, press-fits, bolts, bolt and nuts, brazing, welding, and clinching.	The potting material bonds copper, other metals, and plastics to itself permanently.

4. Use of recycled materials	
4.1. Consider more textured surfaces for injection molding plastic parts. Avoid uniform high-gloss surfaces.	The parts are not glossy.
Part Level	
5. Avoidance of hazardous substances	
5.1 Avoid the use of brominated flame retardants (BFRs) such as polybrominated diphenyl ethers (PBDEs), tetrabromobisphenol A (TBBPA), polybrominated biphenyls (PBBs), Hexabromocyclododecane (HBCD), etc., in the product.	There are no BFR's present.
5.2 Avoid the use of substances of very high concern (SVHC) according to the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation [40] and substances classified as carcinogenic (Carc. 1A or 1B), mutagenic (Muta 1A or 1), or reprotoxic (Repr. 1A or 1B) by the Classification, Labelling and Packaging (CLP) Regulation in housing/housing parts [41].	The company complies with REACH (Nedap Annual Report 2024, 2024).
5.3. Avoid the use of substances that are listed on the 'SIN list' [42].	SVHC's are avoided by the company.
5.4. Do not use halogenated polymers (e.g., Polyvinyl chloride (PVC), Polytetrafluoroethylene (PTFE)).	PVC is used in the cable sleeve.
6. Enable easy access and removal of hazardous or polluting parts	
6.1. Avoid magnetic parts on printed circuit boards (PCBs)	The PCB includes a magnetic ferrite component.
7. Use of recyclable materials that will be recycled by WEEE recyclers	
7.1. Use common plastics in the product such as ABS, PP, PA, PC, PC/ABS, HIPS, PE (polyethylene), where possible.	PA is used in the antenna, but all other plastics used are not common plastics.
7.2. Avoid polymer blends.	The housing cover is made of a polymer blend.
7.3. Avoid glass fiber-filled plastics.	The plastics are not glass fiber-filled.
7.4. Minimize the use of thermoplastic elastomers.	The cable sleeve is made of a thermoplastic elastomer.
7.5. Avoid the use of thermoset rubbers.	The grommet is made of a thermoset rubber.
7.6. Minimize additives in plastic materials.	There are no additives in the plastics.
8. Use material combinations and connections that allow easy liberation	
8.1. Avoid fixing ferrous metals to non-ferrous metals in either parts or fasteners. For example, do not use a screw (ferrous metal) to attach a part to aluminum (non-ferrous)	Two ferrous screws and other ferrite magnets attach to some of the aluminum in the antenna.
8.2. 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.	No metals are permanently fixed to each other.
9. Use of recycled materials	
9.1. Choose geometries for injection-molded parts that allow easy flow paths. Avoid tight and narrow geometries.	N.A. to this project
9.2. For injection mold plastic parts, do not use long injection paths.	N.A. to this project
9.3. For injection mold plastic parts, consider more or wider venting ports.	N.A. to this project
9.4. Use virgin plastics for very demanding parts (e.g., transparent light guides).	The plastics in the antenna are virgin plastics.

6.3 Conclusion

Theoretically all of the materials except the thermosets are recyclable, and therefore recoverable, though the foam, one thermoplastic, and the polymer blend in the housing cover are also not generally recycled due to low economic or non-established recycling streams.

The shredding test revealed that the use of the potting material and ferrous to non-ferrous connections lead to a large loss of the valuable materials and some loss of other metals. The copper wire and PCB, the most valuable materials, were almost completely encapsulated in the potting material. Their bonding to the epoxy would technically prevent almost all of those materials to end up in the correct recycling fraction for recovery. All of the copper wire and 96% of the PCB would not be recovered in the copper fraction. The other heterogeneous connections resulted in 5% of aluminum and 14% of the ferrous material being lost because of their connection to each other or plastic, which is not a large

In terms of its realistic recyclability, the collection rate of agricultural WEEE such as the antenna is unknown. A discussion with one of the largest electronical device collectors and the only Producer Responsibility Organization in the Netherlands, Stichting Open, resulted in the knowledge that the antenna could be handed in to a recycling center or at collection points in the Netherlands, but there is no known hard data on the collection rates or amount of agricultural antennas recycled. This highlights a large issue, as collection data would enable the company and other agricultural technology producers to better track and pinpoint how and where to improve collection and disposal.

Table 22: Insights found in recyclability analysis and redesign implications

Recyclability Insights	**Redesign Requirements**
The PCB and wires' copper are at large risk of not being recovered because of their encapsulation in potting.	The copper components should be separatable from other components during shredding.
Steel screws attached to aluminum lead to aluminum going down the ferrous stream instead of the non-ferrous stream.	The aluminum pieces should separate from ferrous metals when shredded.
If too much plastic is left around the ferrite core, the ferrite core will be sorted incorrectly into the plastic fraction.	The ferrite and plastic should liberate when shredded.
The aluminum folding over the EPS foam prevents the EPS foam from being recycled.	The aluminum should not fold over when shredded.
The housing cover and potting material are not recyclable.	All materials should be recyclable (including the housing cover and potting material).

Chapter 7: Design Requirements

This chapter will discuss the redesign requirements compiled from the insights concluded in the previous chapters and tensions foreseen for the redesign stage.

RQ3: What tensions exist between the requirements for improving repairability, recyclability, and the optimal mechanical durability of the product?

Table 23: Redesign requirements based on insights from previous chapters with blue highlighting the highest priority requirements

Design for	No.	Priority	Design Requirement	Criteria	Standard
Environmental Durability	D.1	1	The electronic components must be protected from **water**.	Water jet test	IP65
	D.2	1	The electronic components must be protected from **dust**.	Dust chamber test	IP65
	D.3	1	The electronic components must be protected from **condensation**. (temperature change)	Temperature change test	
	D.4	1	The antenna must be **impact resistan**t up to 1000 kg/10 cm^2.	Drop test and withstanding 1000 kg/cm^2	
	D.5	2	The antenna's cable should be out of reach for the cows.	The antenna's cable should be on another side of the antenna than where the cow faces.	
Functionality	F.1	1	The copper wire should maintain its distance from the aluminum plate.	See Appendix F	ISO 11785
	F.2	1	The copper wire should maintain its coil dimensions.	See Appendix F	ISO 11785
	F.3	1	The copper wire, cable, and PCB must maintain their connections.		
Repairability	RP.1	1	The priority parts (PCB, copper wire) should be accessible.	Each priority part should be removable by common tools and low force.	

Recyclability	RC.1	1	The copper components (PCB and copper wire) should be separatable from other components during shredding.	The weight of the copper in heterogeneous fragments should outweigh the potting in the fragments.
	RC.2	2	The aluminum plate and ferrous metals should separate from each other when shredded.	The aluminum and ferrous materials should be connected in a way where they are likely to separate from each other when shredded.
	RC.3	2	The ferrite and plastic should liberate when shredded.	The ferrite and plastic materials should be connected in a way where they are likely to separate from each other when shredded.
	RC.4	2	The aluminum should not fold over (the EPS) when shredded.	The aluminum and EPS foam should be connected in a way where they are likely to separate from each other when shredded.
	RC.5	1	All materials should be recyclable.	Every material should be confirmed as theoretically, practically, and technically recyclable by recyclers.
	RC.6	1	The user should be notified of recycling options at the product's obsolescence.	
	RC.7	1	The user should be aware of recyclability of the product.	
	RC.8	1	The user should be motivated to utilize the recycling options.	

Design for	No.	Priority	Design Requirement	Criteria
Business	B.1	2	The production cost of the antenna should be maintained.	The antenna should cost less than or equal to its current production price.
	B.2	2	The antenna should be quickly manufactured.	The antenna should take less than or equal to the current time it takes to be manufactured.
	B.3	1	The product's business model should incentivize sustainable practices.	The farmers should be monetarily incentivized to correctly dispose of the antenna.

7.1 Categories and Priority Levels of the Requirements

The redesign requirements fit into broader categories of environmental durability, functionality, repairability, recyclability, and business requirements (Table 23). The requirement table also includes priority numbers based on their level of urgency or importance. The highest priority requirements are also marked in blue.

The repairability section should be prioritized based on the expected longevity of the redesign. For example, if the redesign lasts the warranty of 10 years instead of the current 30, it would be more important for the redesign to be repairable. But if the redesign can also last decades long, the recyclability should much more be prioritized than the repairability. For this project, we will aim to design for both in order to find the tensions that arise.

Within recyclability, the most priority is given to requirements with the largest impact on the recovery of the valuable and highest volume materials, like copper and the outer housing of the antenna. The last three recyclability requirements related to the user's involvement are high priority because of their large impact on if the product makes it to the correct recycling facility as seen in Chapter 3.

The business requirements are also there because of their importance in the feasibility of the redesigns. While there could be solutions that are more sustainable, if they economically or from a manufacturing perspective are infeasible, then the business requirements give reason to focus on other more feasible solutions. These requirements are not as focused on in this project, because of lack of time, but would be a large focus in the continuation of the project.

7.2 Insights for the Redesign

The high priority recycling requirements and repair requirement both indicate the need to redesign the amount or use of the potting material, as currently the potting material's bonding to the copper and PCB components prevents access and the recovery of those materials during repair and recycling.

Additionally, the potting material currently enables the first four environmental durability requirements, so redesigning or removing the potting activates the need to fulfill those requirements through different solutions.

The functional requirements also somewhat strictly limit the redesign of the shape and size of the antenna, as the copper wire and aluminum shield dimensions must relatively stay the same because of their importance in the electromagnetic function of the antenna.

7.3 Conclusion

The potting material fulfills many of the durability requirements yet causes much of the unrecyclability and irrepairability of the priority parts. This presents the challenge of finding a new design that maintains the environmental durability while allowing the liberation of the valuable and high volume materials within the antenna. New technological developments such as the ability to remove the coil adjuster assembly and the potting material's lack of effect on the antenna's electromagnetic capabilities enable some flexibility in the material and product architecture redesigns. These requirements and tensions set the stage for finding solutions for the antenna that better enable its recyclability and repairability while maintaining its long-lasting durability against its harsh environment of cow and weather in outdoor barns.

Chapter 8: Redesign

This section will discuss the process of concept ideation and narrowing concepts and ends with a possible redesign for the antenna. It will also discuss tensions in the requirements of each concept and the tensions that arise from choosing certain concepts together in the case study.

RQ3: What tensions exist between the requirements for improving repairability, recyclability, and the optimal mechanical durability of the product?
Methods: Expert interviews, requirement comparison tables

RQ4: How can the product be redesigned to enable the repair and recycling of the product?
Methods: Morphological chart, Granta Edupack material selection, prototyping

8.1 Product Journey Concepts

This sections discusses the process of brainstorming, evaluating, and developing concepts that address the user requirements found in chapter 3.

8.1.1 Brainstorm and Evaluation of Concepts

The following concepts were ideated based on the main pain points found in the Product Journey and Disposal chapter.

Lack of awareness of recycling options and recyclability

4. Recycling introduction unboxing video
5. Recycling options shown on product manual
6. Recycling tabs on NedapNow
7. Quarterly recycling pickup
8. NedapNow recycling notifications activated by product disconnection
9. Recycling stickers
10. Infographic recycling manual barcode
11. Product passport barcode
12. Collection point at local dealer store

Lack of ROI | **Lack of motivation for farmers to utilize recycling options**

1. Design architecture for repair and recycling
2. Subscription based hardware model
3. E-waste bin that calculates recycling value

The cost and distance of the proper e-waste recycler

13. Partner with local middlemen

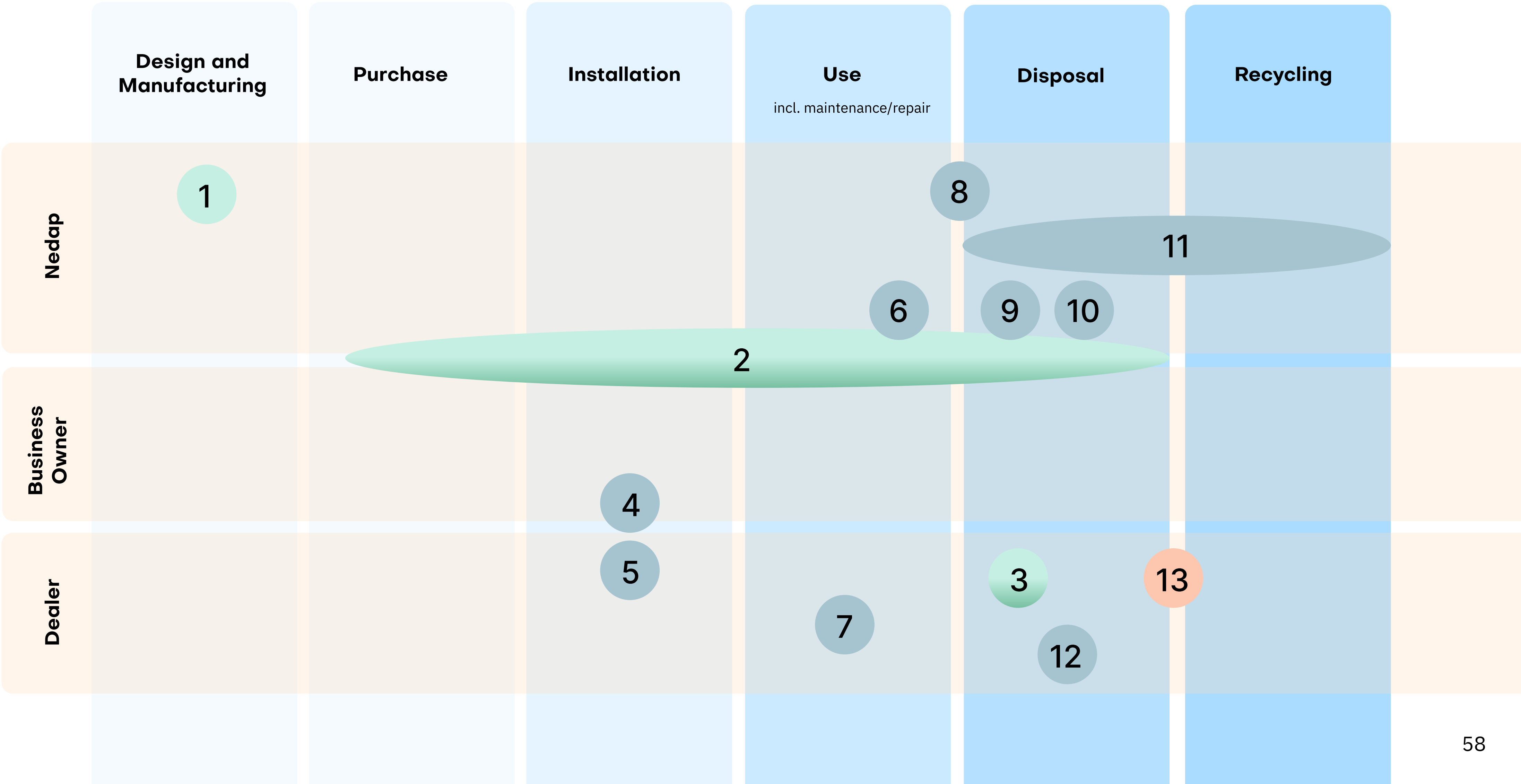
Figure 25: Brainstormed concepts for product journey and disposal pain points

In order to ensure the concepts would solve the requirements that arose from the Product Journey and Disposal chapter (Table 24) and were distributed across the product journey, the concepts were visualized on the different phases of the product journey of the antenna (Figure 26). The visual also displays which stakeholders were involved in the different concepts.

Table 24: Recycling requirements related to the product journey and user

RC.6	The user should be notified of recycling options at the product's obsolescence.
RC.7	The user should be aware of recyclability of the product.
RC.8	The user should be motivated to utilize the recycling options.

Figure 26: Product journey and stakeholder analysis map of brainstormed concepts



As the disposal stage has a large impact on if the product is collected and recycled by an e-waste recycling facility, the location on the analysis map between the use and disposal phases was targeted for selecting concepts to further evaluate. Concept 2, 3, 7, 8, and 11 were chosen from the map because of their location between the use and disposal phases.

As the NedapNow integration and subscription model concepts fulfilled many of the requirements (see Table 25) in combination with being the most feasible for stakeholder implementation, those concepts were chosen to further develop. NedapNow is the interface that displays the data from Nedap's hardware on the farms.

	E-waste calc	Regular recycling pickup	NedapNow integration	Subscription model	Product Passport
Req RC.6 The user should be notified of recycling options at the product's obsolescence					
Nearness to critical point	●	●	●	●	●
Ease of recycling option information access			●		
Req RC.7 The user should be aware of the recyclability of the product					
Ease of recyclability information access	●		●		●
Req RC.8. The user should be motivated to utilize the recycling options					
Motivation for farmer	●			●	
Feasibility					
Ease of Testing			●		●
Ease of Prototyping			●		●
Feasibility for stakeholder implementation			●	●	

Table 25: Narrowing of product journey concepts

8.1.2 Final Concepts

Hardware subscription model concept

Nedap has started exploring a subscription model through a smart tag-as-a-service concept where a smart tag, one of the ID tags that connects to the antenna, is offered at a discounted rate and the software of the tag is based on a subscription model. While this service benefits Nedap financially, a subscription model that encourages the return of the hardware could mean placing a subscription payment on the hardware instead of or in addition to the software.

A hardware-based subscription would mean charging the user monthly or yearly in exchange for keeping their hardware, in this case the antenna (Figure 27). It's important to note that the antenna can last up to 25 years longer than a smart tag, so the subscription cost being yearly or a small amount per month on top of a discounted hardware price would be reasonable alternatives to a high monthly payment. Repair and replacement services can also be offered in exchange for the subscription payment. The goal of this model is to motivate the farmer to ultimately dispose of the antenna by giving it back to the local dealer, as the local dealer can more easily standardize the transport and process of reselling the antenna or transport it to a recycler (Figure 27). This concept also addresses the business requirement B.3.

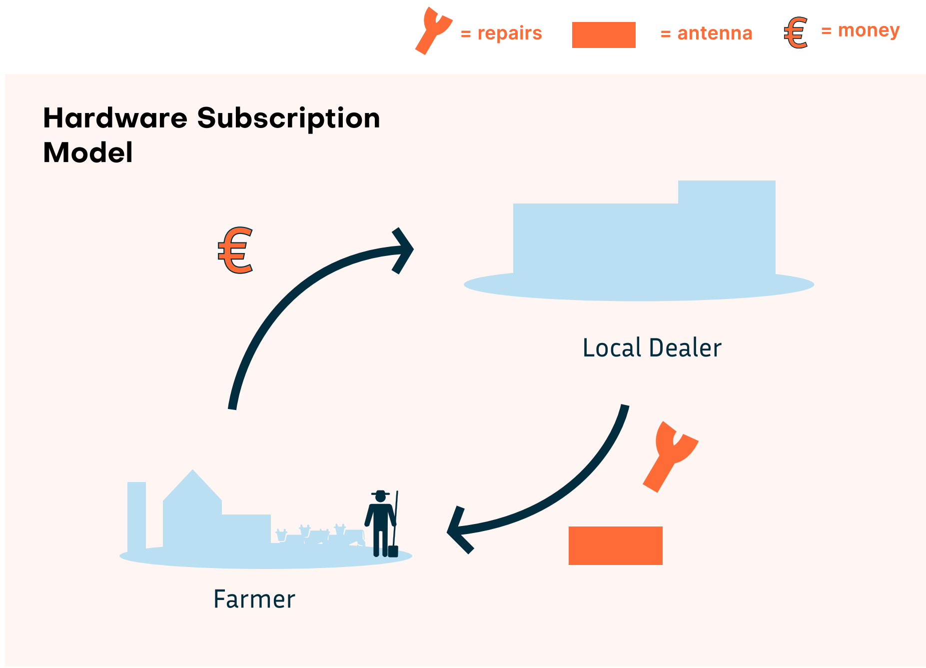


Figure 27: Hardware subscription model incentivizing hardware returns

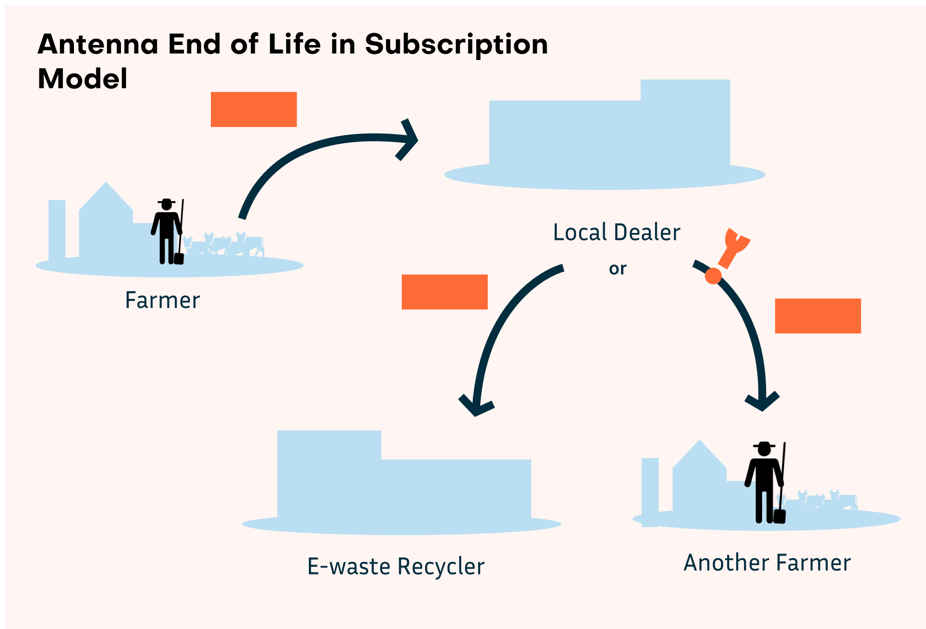


Figure 28: Actions of business partner after receiving antenna from farmer

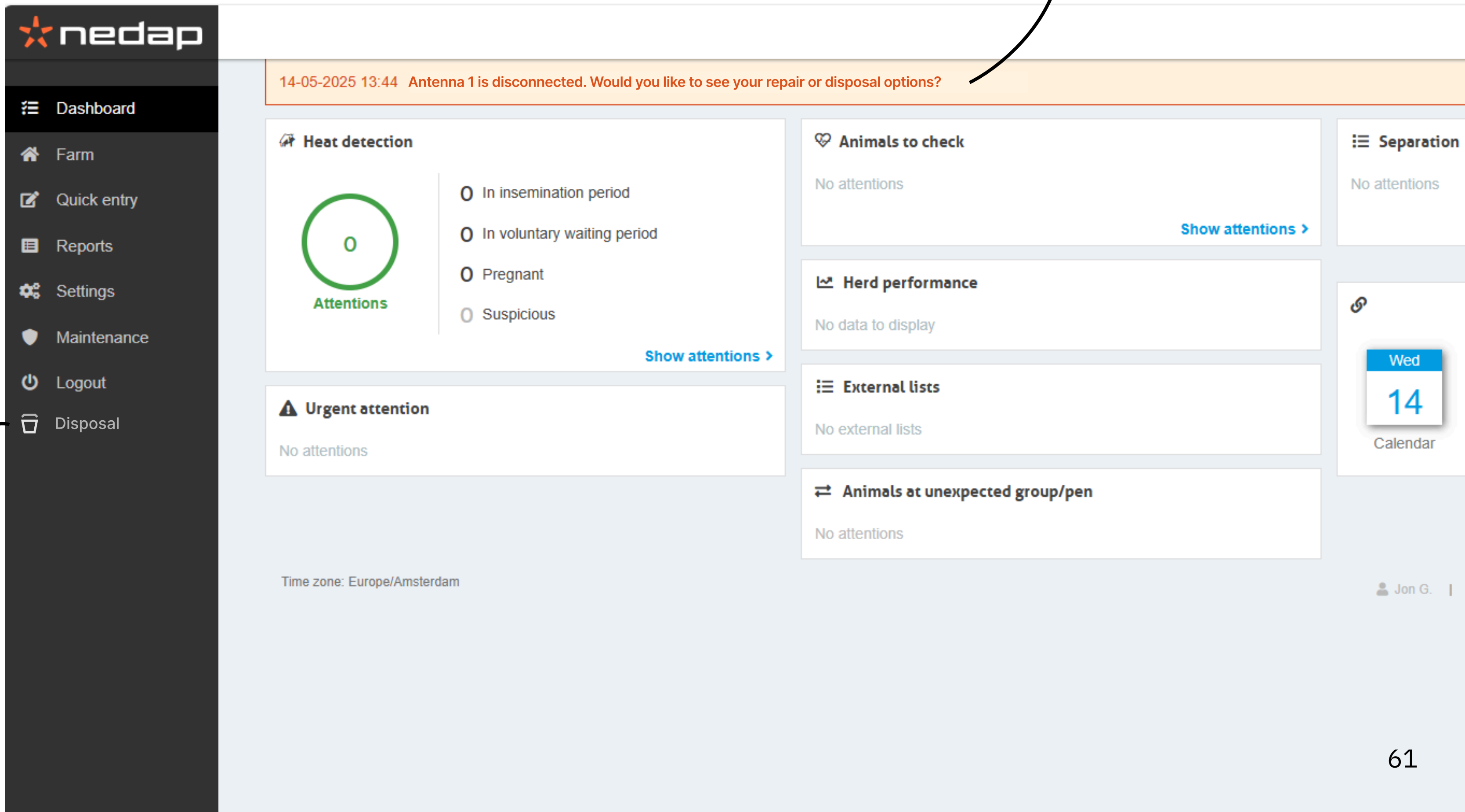
NedapNow Interface Circularity Additions

The current interface that the antenna and other Nedap hardware connects to is called NedapNow. It tracks if the antenna is tuned properly and if it is plugged in. This concept adds a disposal tab to the NedapNow interface and notifications that lead the farmer to the closest business partner or recycler when they navigate to the disposal tab.

In this redesign, when an antenna is unplugged, a notification pops up (Figure 29) that leads to user to the disposal tab when clicked on.

Clickable Notifications prompting disposal of unplugged e-waste

Figure 29: Notification that leads to disposal options on NedapNow interface

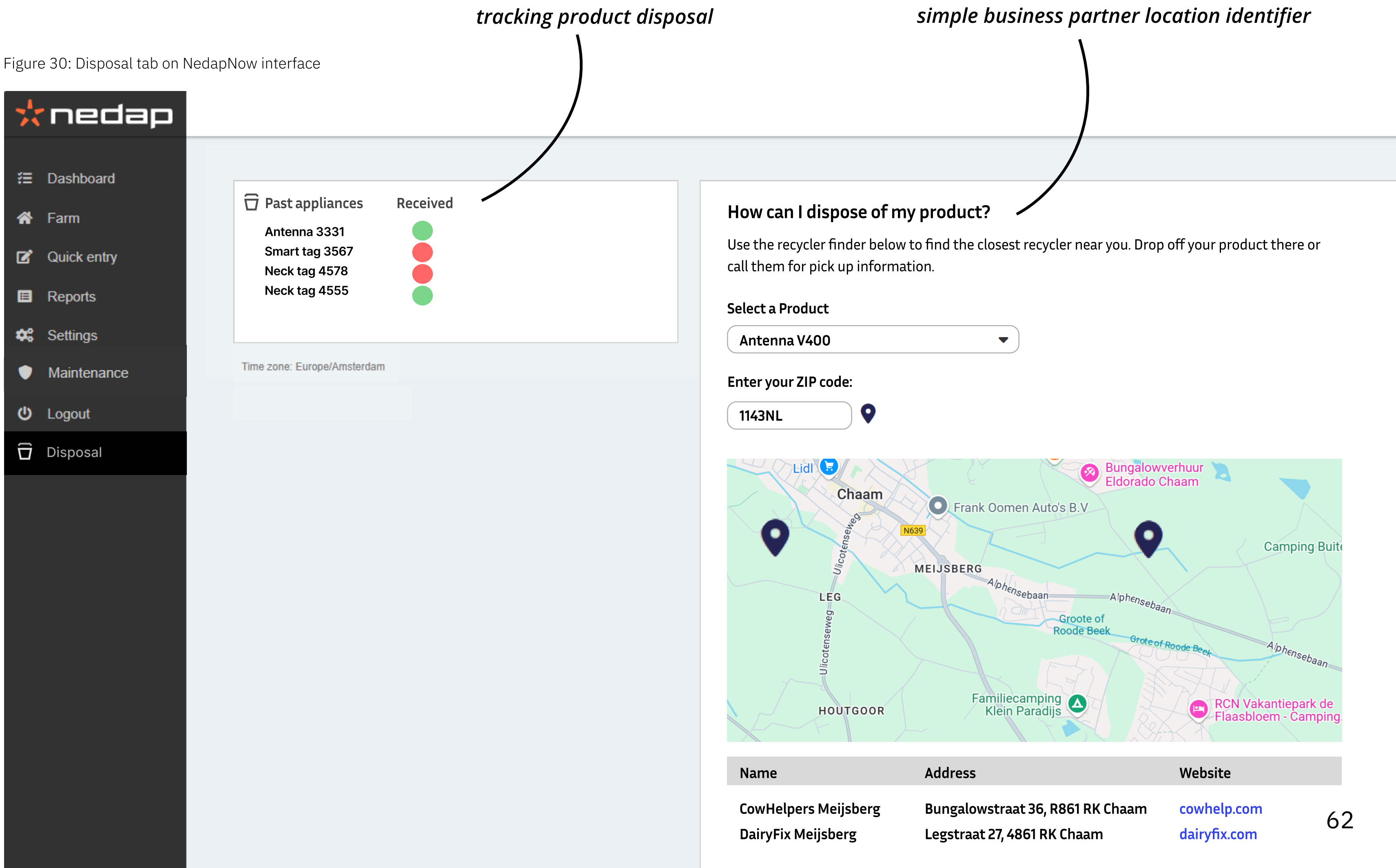


Disposal tab always available

The disposal tab, seen in Figure 30 and added for the redesign, displays if past unplugged appliances have been received by a locaGl business partner or recycler. Another aspect of the disposal tab is a recycler finder where the user can use their zip code to locate the closest drop off point or contact for pick up.

This concept targets redesign requirements RC.6 and RC.7 and aims to notify the user at the product's obsolescence and increase the user's awareness of the recycling options nearby.

Figure 30: Disposal tab on NedapNow interface



8.1.3 Conclusion

When interviewing stakeholders early on in the project, a major insight was the amount of influence the farmers' disposal of the product has on the product and materials' recovery. It became clear that providing services that inform, motivate, and guide the farmer to the correct actions could potentially have a large impact on the life and recovery of the product.

The final two concepts, the hardware subscription model and interface circularity additions, seek to provide an economic incentive for correctly disposing of the products and provide easily accessible disposal guidance through locating the closest dealer and tracking the status of their disposal. As the antenna does not contain as much valuable or hazardous materials as other products, the solutions can be used for the other products in the company's portfolio as well.

In the end, the product journey concepts are initial ideas, as the product architecture redesign was more focused on, and should be further developed with stakeholders.

8.2 Product Architecture Brainstorming

The initial brainstorming consisted of meeting with senior electrical and mechanical engineers at the company, brainstorming concepts for different requirements on a whiteboard with two industrial design colleagues, and drawing or writing all concepts on sticky notes. The concepts were then added under the requirements they corresponded to on the whiteboard. The brainstorm ended with 61 sticky note ideas. The following categories were the focus of the brainstorm, with the priority recycling requirements in mind but more focused on later in the redesign phase.

A large focus of the brainstorm was coming up with solutions that could replace the polyurethane potting material's original fulfillment of the durability requirements. The recyclability requirements were addressed later on through material selection in Granta Edupack and discussions with recyclers.

Water and dustproof | *Impact Resistant*

Access to priority parts | *Condensation Resistant*

Figure 31: Categories for Brainstorming

The ideas were combined based on similarity and made into a morphological chart (Figure 32).

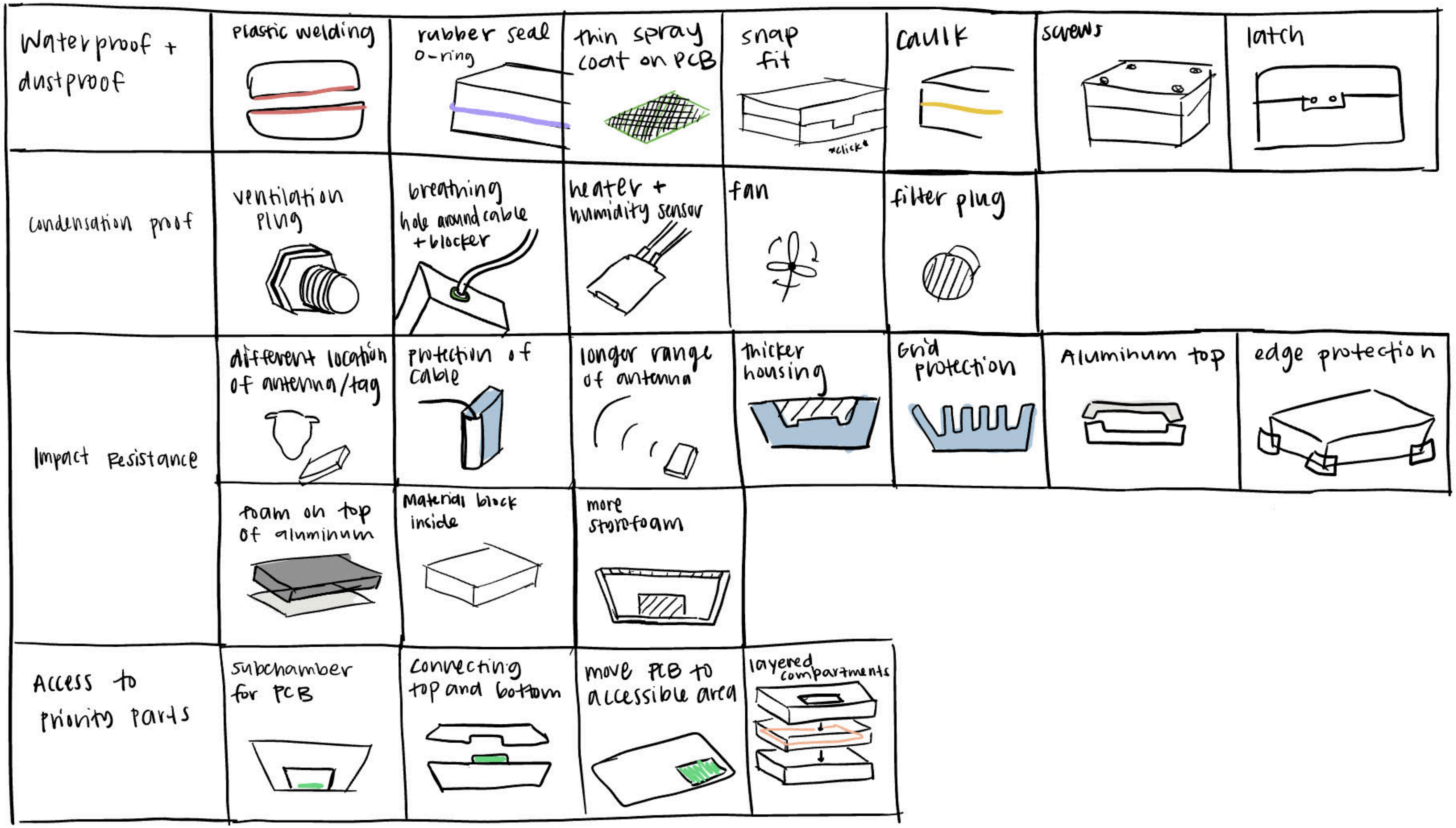


Figure 32: Morphological chart of narrowed brainstorm concepts

8.3 Narrowing the Concepts

This section will discuss the different aspects of the antenna's architecture involved in the redesign, their importance, and the tensions or conflicts that arise in each concept's fulfillment of the redesign requirements. Meetings with an electrical and mechanical engineer at the company were conducted in order to inform the analysis of each concept.

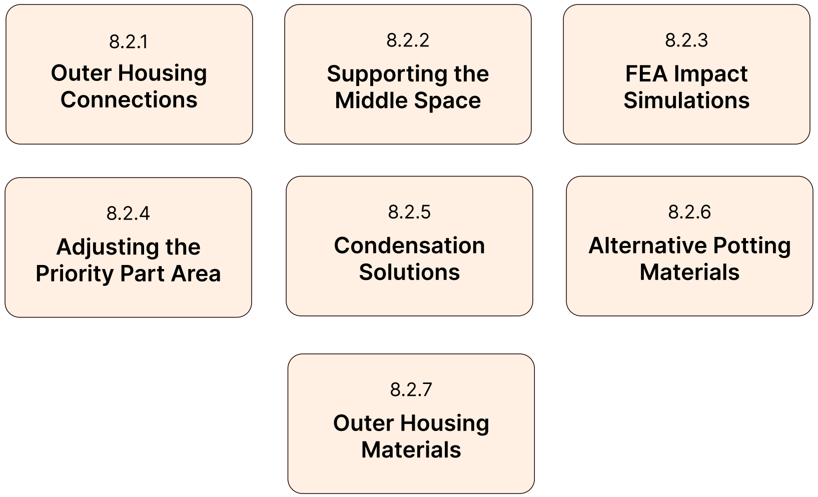


Figure 33: Product architecture concept categories

8.2.1 Outer Housing Connections

By removing or decreasing the potting material, the antenna should now be protected another way in order to stay water and dust proof. Therefore, many connection concepts such as welding, screwed in covers, caulk or glue, and rubber rings or gaskets were thought of during the brainstorm.

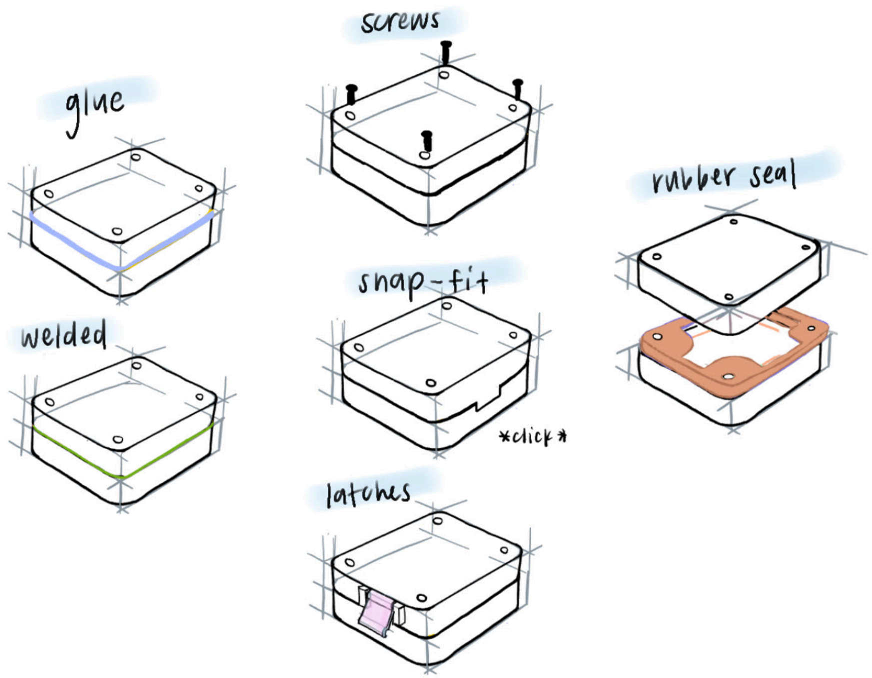


Figure 34: Water and dustproof concept brainstorm drawings

The redesign requirements relating to the seals were considered in order to compare the pros and cons of choosing each options. Table 26 gives an overview of how well each concept fulfills the requirements.

The levels of fulfillment, visualized in color in Table 26, are based off of the following explanations.

The durability levels are based off of the risk of their failure. The repairability levels are based on the difficulty of dismantling of the type of connection with levels being easy access, unpredictable access, and extremely difficult access due to high force or uncommon tools as mentioned in De Fazio's Disassembly Map (De Fazio et al., 2021).

The recyclability requirement was split into theoretical material recyclability, practical material recyclability, and technical product recyclability based off of the redesign requirement RC.5's criteria. The two levels for the theoretical material recyclability were recyclable, possibly recyclable, or unrecyclable. Practical recyclability had the same levels but based on if the materials were recycled in practice. The technical product recyclability levels were based off of Doris Versloot's three groups of liberation (2024). Based off of Table 26, latches and screws were most considered during prototyping.

	Durability	**Repairability**	**Recyclability**		
	Water and dust proof	Access to Priority Parts	Theoretical Material Recyclability	Practical Material Recyclability	Technical Product Recyclability
Welding	Creates a permanent seal through material connection. Easily reaches above IP65.	Extremely difficult dismantling, potentially irreversible	No materials are added in the act of welding	No material added	Welding the same material together leads to easier sorting. Welding different materials together can lead to polluted fractions and material loss (Versloot, 2024)
Glue/Caulk	Creates a semi-permanent seal but may degrade over time. Can perform above IP65.	Difficult dismantling, requires heat gun	Glue itself is most likely unrecyclable as they are generally thermosets	Thermosets are not recyclable (Berward et. al, 2021)	Connecting different materials together can lead to polluted fractions and material loss (Versloot, 2024)
Latches	Highly dependent on design. Typically need rubber seal for waterproofing.	Impermanent connection allows for quick access	Often made of plastic or metal, so the recyclability depends on the purity of the metal (Van schaik & Reuter, 2012) and type of plastic chosen	Dependent on the material chosen. Common plastics or pure metals preferred for recycling.	Plastic-metal connections can lead to pollution or material loss of metals (Versloot, 2024). Same-material connections are more easily recycled.
Screws	Highly dependent on design. Typically need rubber seal for waterproofing.	Impermanent connection allows for quick access	Screws can be made of ferrous metals or nylon (PA) plastic. Ferrous metals are theoretically recyclable, but PA is debated and therefore assumed unrecyclable for now (Mortier, 2025).	Dependent on the material chosen. Pure metals preferred for recycling (Van schaik & Reuter, 2012)	Screws have unpredictable liberation and can keep incompatible materials connected during sorting (Versloot, 2024).
Snap-fit	Highly dependent on design. Typically need rubber seal for waterproofing.	Impermanent connection but can be non-reusable (Balkenende et al., 2022)	Often made of plastics due to their flexibility. Plastics that float in the 1.1 kg/L are potentially recyclable (Bill et al., 2019).	Dependent on material chosen. Common plastics such as PC and ABS are preferred (Berward et. al, 2021).	Snap-fits are expected to liberate well during shredding (Versloot, 2024).

Durability
- low risk
- some risk
- high risk

Repairability
- easy access
- unpredictable access
- no access

Theoretical + Practical Recycl.
- recyclable
- dependent
- unrecyclable

Technical Recycl.
- high liberation
- unpredictable
- low liberation

Table 26: Connection redesign requirement comparison

As latches, snap-fits, and screws typically need a rubber seal to ensure waterproofing, the repairability and recyclability of a rubber seal was also discussed in Table 27. The development of latch design combined with a rubber seal was chosen because of its high repairability and the recyclability potential of the latches.

The type of connections chosen for a product are high determinants of its repairability and recyclability as they determines the level of access to priority parts and the level of liberation of materials from each other for recycling.

While welding and glue provide the most permanent seals, they have the lowest level of expected liberation, or technical recyclability, according to Versloot's shredding experiment and literature review (2024). They are also extremely difficult and potentially impossible to disassemble, inhibiting any access to the priority parts for repair. This is the reason why many guidelines, including Berwald's, specifically mention avoiding glue and welding.

Snap-fits are expected to liberate well during shredding (Versloot, 2024), but their reusability is questionable as they can be prone to breaking when disassembling them for repair. Latches were also assumed as a type of snap-fit for technical recyclability, though the metal-plastic connections may cause issue in technical recycling and should be further researched. Latches could potentially provide an opportunity for a waterproof, technically recyclable, and repairable design if practically recycled materials are selected for them. Screws have unpredictable liberation during shredding, as it also depends what kind of materials they are connected to, but they do allow for disassembly.

While technical product recyclability is the biggest focus of recyclability in Table 26, as the concepts are connectors, a few of the connections are commonly made of the following materials as discussed with a TU Delft researcher and professor. Glue is commonly a thermoset, which is unrecyclable (Berwald et al., 2021), but is also usually a small percentage of product's weight. Screws are commonly made of recyclable ferrous metals or PA, which is currently not commonly recycled according to recyclers (Mortier, 2025). Rubber seals are generally thermosets, which are unrecyclable as mentioned before.

It should also be highly noted that this product is generally bolted to a wall when in the barn, so other, much more temporary connections before being bolted to the wall could be considered for transport. Table 26 showcases more permanent options to prevent the antenna from disassembling to quickly after removing the bolts.

Table 27: Repairability and recyclability of rubber seals for supporting snap-fits, screws, and latches

	Repairability	**Recyclability**		
	Access to Priority Parts	Theoretical Material Recyclability	Practical Material Recyclability	Technical Product Recyclability
Rubber seal	Impermanent connection allows for quicker access	Most rubbers are thermosets and therefore unrecyclable (Berward et. al, 2021)	Thermosets are not recyclable due to their chemical composition (Berward et. al, 2021)	Elastomers are likely to be filtered out (Berward et. al, 2021)

8.2.2 Supporting the Middle Space

As the functionality constraints limit the antenna to relatively stay the same size and height while the PCB and copper wire are able to decrease in size from technological advancements, there still remains a large amount of free space within the antenna that was previously filled with epoxy and EPS foam. When brainstorming, the types of concepts for supporting this space were filling the middle space with a "material block", supporting the space with inner supports, increasing the strength of the housing material, or even removing the empty space to create a donut shaped antenna.

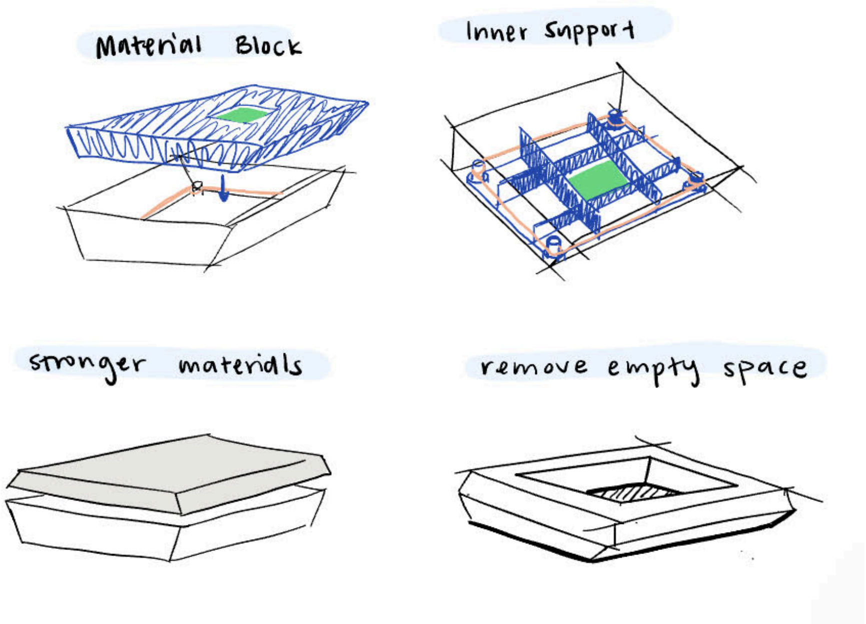


Figure 35: Inner support brainstorm drawings

Material Block Material Selection

In order to find materials that were recyclable and strong enough to support the inner structure, Granta Edupack was used to find materials that could replace EPS foam and epoxy. After filtering materials by a compressive strength above EPS foam's 1 MPa, and their ability to be recycled, a Youngs Modulus vs. compressive strength graph of foam materials was made because of foam's elastic abilities (Figure 36). A higher young's modulus would indicate a stiffer material and a low young's modulus would indicate a more elastic material. High compressive strength would indicate the ability to resist large compressive forces without cracking or collapsing.

In Granta Edupack, materials are given the attribute of "recycle" when the material could theoretically be recycled but not necessarily is in practice. Materials in Granta are considered "functionally recyclable" when the quality of the materials after being recycled is still high enough to be used for the same purpose, but no such materials were found. Additionally, we looked at the "Climate change (CO2-eq), recycling" attribute of the materials, meaning how many kilograms of CO2 is produced per kilogram of the material when it is being recycled.

When looking at foams, cork and polyurethane were selected. Cork was selected because of its slightly higher compressive strength than EPS and its theoretical recyclability and biodegradability. Polyurethane foam was also selected because of its recyclability, higher compressive strength, and its range of density and stiffness options. Open cell polyurethane foam is currently used in other durable products such as Peli cases for its impact absorption and easy "pick and pluck" shape forming, but closed cell polyurethane foam was chosen to offer higher compressive strength and better resistance to heavy impacts.

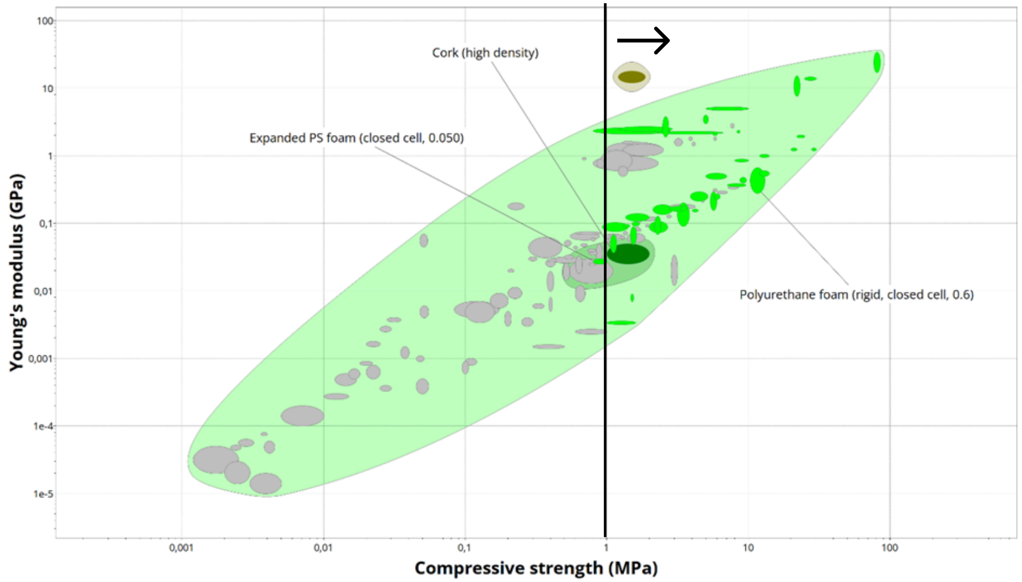


Figure 36: Granta Edupack material block foam selection filtered by 1 MPa compressive strength and theoretical recyclability

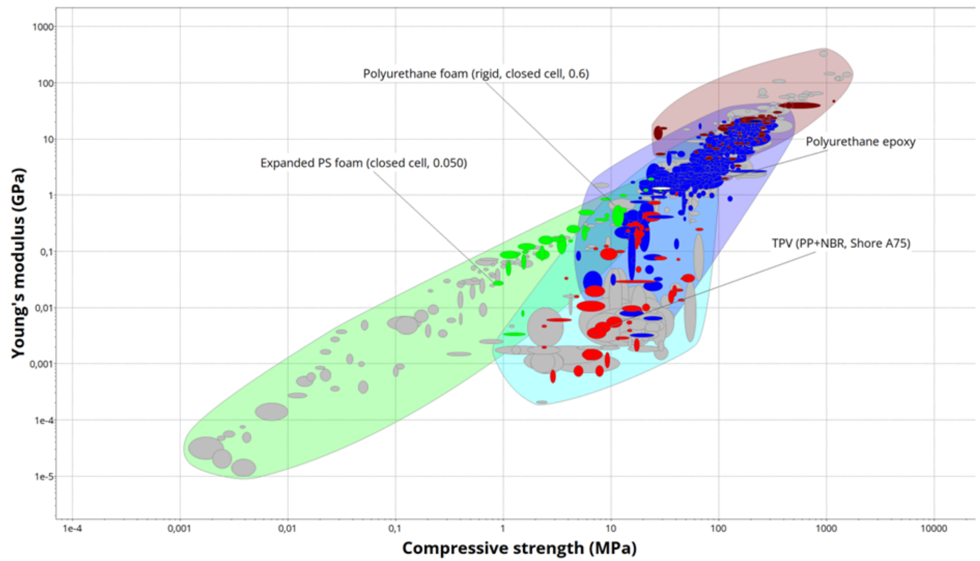


Figure 37: Granta Edupack material block selection from all material categories filtered for theoretical recyclability

When looking at other material categories, TPV (Thermoplastic Vulcanizate) was also chosen because of its low elasticity yet higher compressive strength than EPS foam, therefore giving the selected materials a bigger range in elasticity (Figure 37). TPU (Thermoplastic Polyurethane) was chosen for its high compressive strength yet rubber-like characteristics.

Technical product recyclability was not include in Table 28 as their liberation during shredding largely depends on what the materials are connected to, but epoxy's bonding connection to other materials leads to a low liberation as seen in the shredding experiment. The other materials are expected to have higher liberation with their connections as they do not lead to material enclosures like coating or molding materials do (Versloot, 2024).

Though the chosen materials have lower compressive strengths than the polyurethane epoxy, they generally have lower young's modulus meaning they can recover to their original state much more easily than epoxy. While the materials were originally filtered for their theoretical recyclability, recyclability guidelines from Berwald et al. (2021) and a conversation with a recycling center worker informed the levels of recyclable or unrecyclable in the theoretical and practical recyclability categories. This material selection also revealed the current lack of practically recycled materials with high impact resistance.

	Impact Resistance			**Recyclability**	
	Compressive Strength (MPa)	Youngs Modulus (GPa)	Yield Strength (MPa)	Theoretical Material Recyclability	Practical Material Recyclability
Polyurethane epoxy*	70	4.2	58	Thermosets are unrecyclable due to their chemical composition (Berwald et. al., 2021).	Thermoset polymers are unrecyclable (Berwald et. al., 2021).
EPS foam*	0.9	0.03	1	Thermoplastics can be recycled (Berwald et. al., 2021).	Thermoplastics other than common plastics are not generally recycled (Berwald et. al., 2021).
High Density Cork	0.6	0.05	2	Cork is completely recyclable (Mestre & Gil, 2011).	There are few cork recycling programs (Mestre & Gil, 2011), but cork is bio-based meaning that its incineration is carbon neutral.
TPV ShoreA90	19	0.09	16	Thermoplastics can be recycled (Bill et al., 2019)	Thermoplastics other than common plastics are not generally recycled (Berwald et. al., 2021).
Polyurethane foam 0.6	11	0.4	5	Thermoset foams are not recyclable and is likely to end up in landfills (Berwald et. al., 2021).	Thermosets are not recyclable (Berwald et. al., 2021).
TPU ShoreA85	40	0.02	35	Thermoplastics can be recycled (Bill et al., 2019)	Thermoplastics other than common plastics are not generally recycled (Berwald et. al., 2021).

recyclable

unrecyclable

Table 28: Mechanical properties and requirement comparison of the chosen materials
*materials currently used in the antenna

Inner Support and Stronger Material Variations

For the inner support concept, the following modifications and variations of the current inner grid were made to test in the FEA impact simulations. As the thickness of the grid walls could not be adjusted by a large amount because of the injection molding constraints, the variations mainly involve increasing the density of the grid, adding cylinder supports, and experimenting with the outer material by simulating a metal cover for the antenna for added support. Each model had top and bottom covers of the original polymer blend except for the zinc alloy top cover with cylinder inserts model (bottom model, Figure 38).

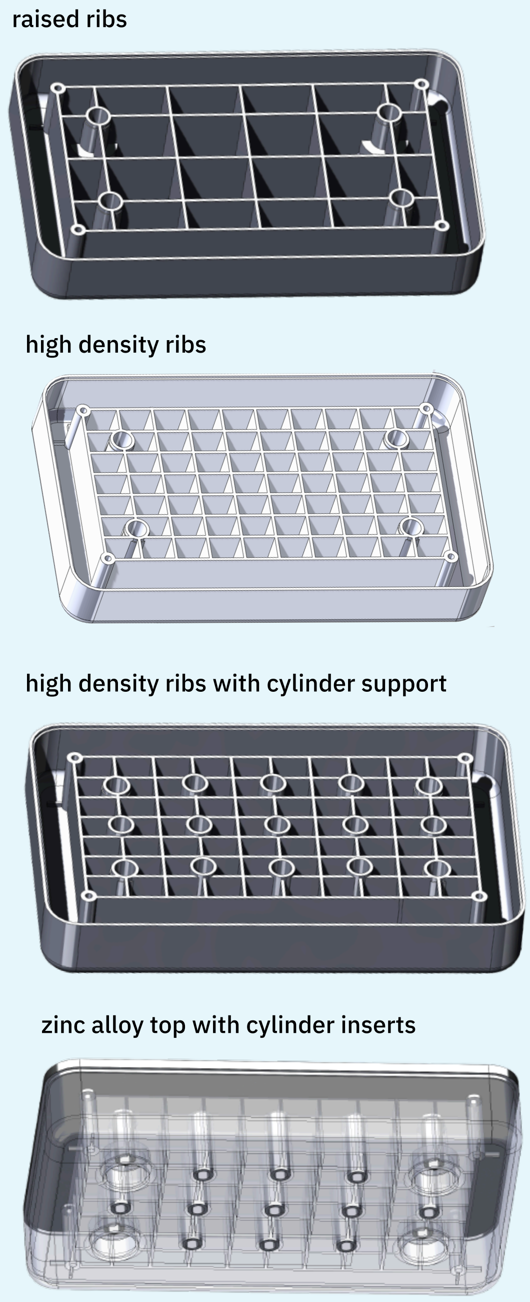


Figure 38: Inner support variation CAD models

8.2.3 FEA Simulations of the Inner Supports

Calculations to Determine the Simulation Pressure

In order to test the impact resistance of the material block and inner support variations, the worst case load was simulated in static Solidworks FEA simulations. The heaviest pressure the antenna goes under is a cow stepping on the antenna at 1000 /10 , as given by Nedap engineers who designed the original antenna.

The simple calculation to confirm the maximum pressure given was:

$$Adult\ dairy\ cow\ weight = 750\ kg$$

$$Adult\ dairy\ cow\ hoof\ size = 10\ cm^2$$

$$One\ hoof\ weight = .7 * 750 = 525\ kg$$

$$Pressure = \frac{Force}{Area} = \frac{525\ kg}{10\ cm^2} = 52.5\ kg/cm^2$$

$$Safety\ factor: 52.5 * 2 \approx \mathbf{100\ kg/cm^2}$$

The dairy cow weight came from the highest weight for the most common cows in the Netherlands, Holstein cows (Schubert et al., 2019). The dairy cow hoof size came from a study on the variations in Holstein cow hoofs and took the smallest hoof size found (Hahn et al., 1984). By adding a safety factor because of the calculation and simulation being static as compared to the reality of the impact being dynamic, the calculation confirmed the suggested pressure of 1000 kg/cm^2.

Inner Support Simulations

The FEA Solidworks simulation was a static simulation with a pressure of 1000 kgf over a 10 cm^2 area in the middle of the antenna. The area of impact for the test was put in the middle of the antenna because that is where the most empty space is without support from the stainless steel bushings or outer walls and where the PCB normally sits within the current antenna. The analysis of the simulations was mainly seeing if and where there is permanent deformation and observing the amount of displacement that happens from the cow step.

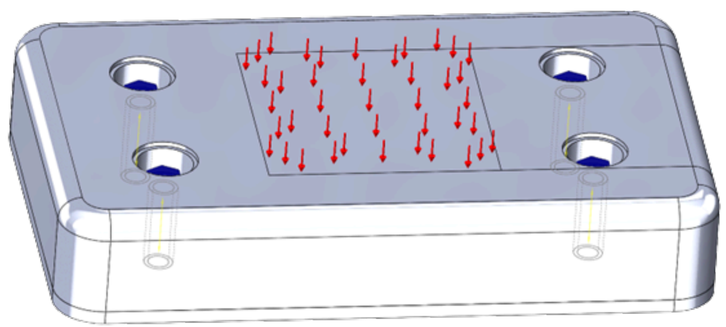
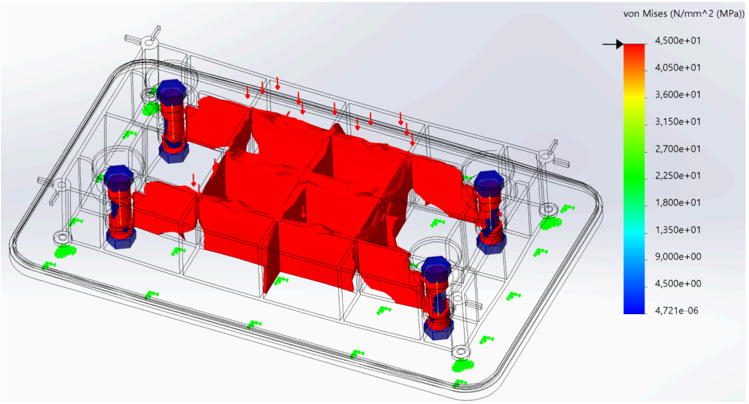


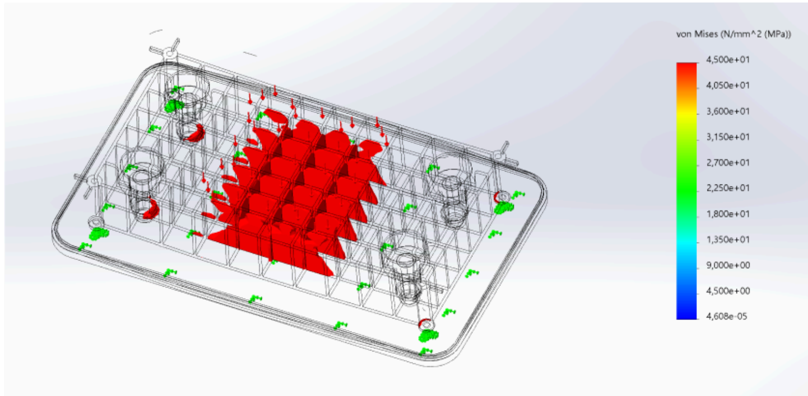
Figure 39: 1000 kgf on 10 cm^2 cow step simulation

When simulating the cow step, the permanent deformation is seen on the red zones where the resulting von Mises stress is larger than the 45 MPa yield strength of the polymer blend plastic used in the housing (Figure 40). The intention of the CAD models was to provide as much strength as possible to the antenna in order to lower the resulting stress on the plastic material's deformation from the cow step.

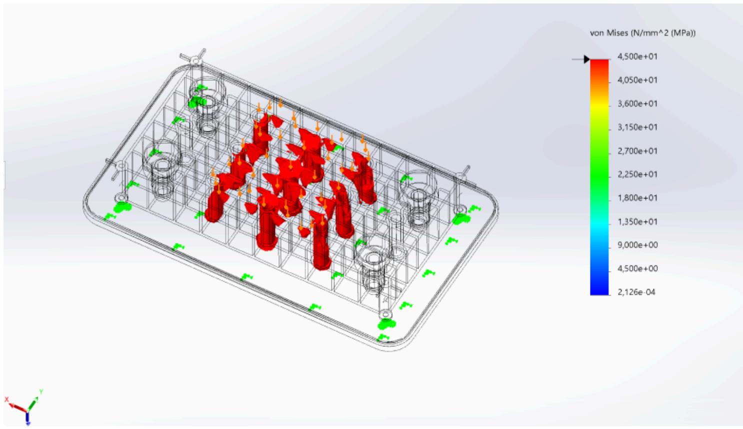
raised ribs



high density ribs



high density ribs with cylinder support



zinc alloy top with cylinder inserts

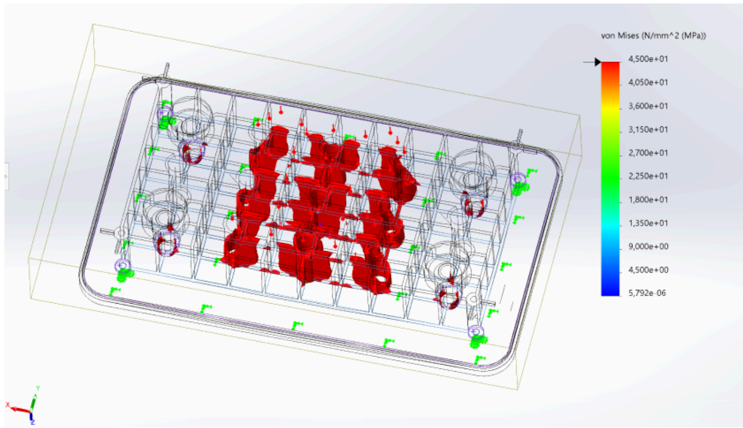


Figure 40: Inner support and stronger material FEA results with red indicating permanent deformation of housing cover plastic

The aluminum cylinder support prototype, on the bottom right of Figure 40, shows a large decrease in the red zones. The part of the red zone that is cylindrical are made of a zinc die-cast metal alloy, which has a much higher yield strength at 235 MPa. This means that the cylinders would withstand the red zones and not permanently deform. This leaves only a small part of the plastic housing deforming under the cow step.

Table X: Displacement results of the inner support cow step simulation

CAD Model	Largest Displacement (mm)
Raised Ribs	4.4
High Density Ribs	4.4
High Density Ribs with Cylinder Support	1.8
Zinc alloy top with cylinder supports	0.8

The amount of displacement of the material when the cow steps decreases dramatically when adding the zinc alloy metal supports to the high density and cylinder support ribs. That being said, the amount of plastic and metal material added by the zinc alloy cylinder prototype is large and likely infeasible cost-wise, but keeping a zinc alloy top cover and decreasing a few of the cylinders and supports could be an option for further development. Changing the cover to zinc alloy would also mean being able to remove the aluminum plate from the original design.

Material Block Simulations

In order to test the impact resistance of the materials found for the material block concept, the cow step simulations were also performed with the different materials found on Granta Edupack filling the inner space (Figure 42). Figure 43 displays the red zones that show when the inner material receives more stress than its yield strength, meaning the inner material permanently deforms. When the inner material experiences a stress past its yield strength, the displacements shown in the simulation would in reality be much larger. It should also be continually noted that the simulations should be taken as rough estimates because of their static and linear nature in compared to a real dynamic cow step.

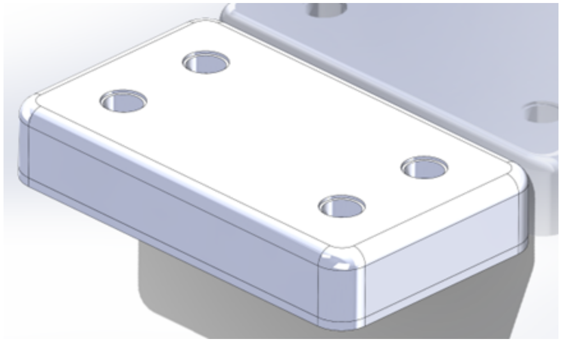


Figure 41: Example of a material block model before simulation

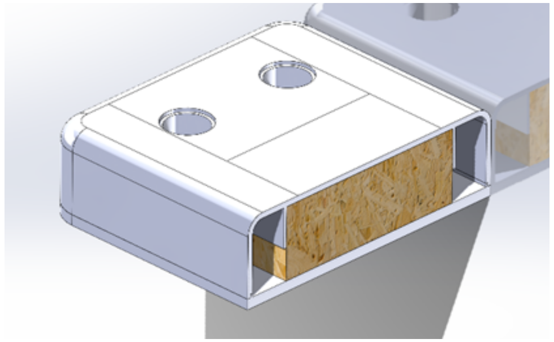


Figure 42: Example of a material block model with a sliced perspective before simulation

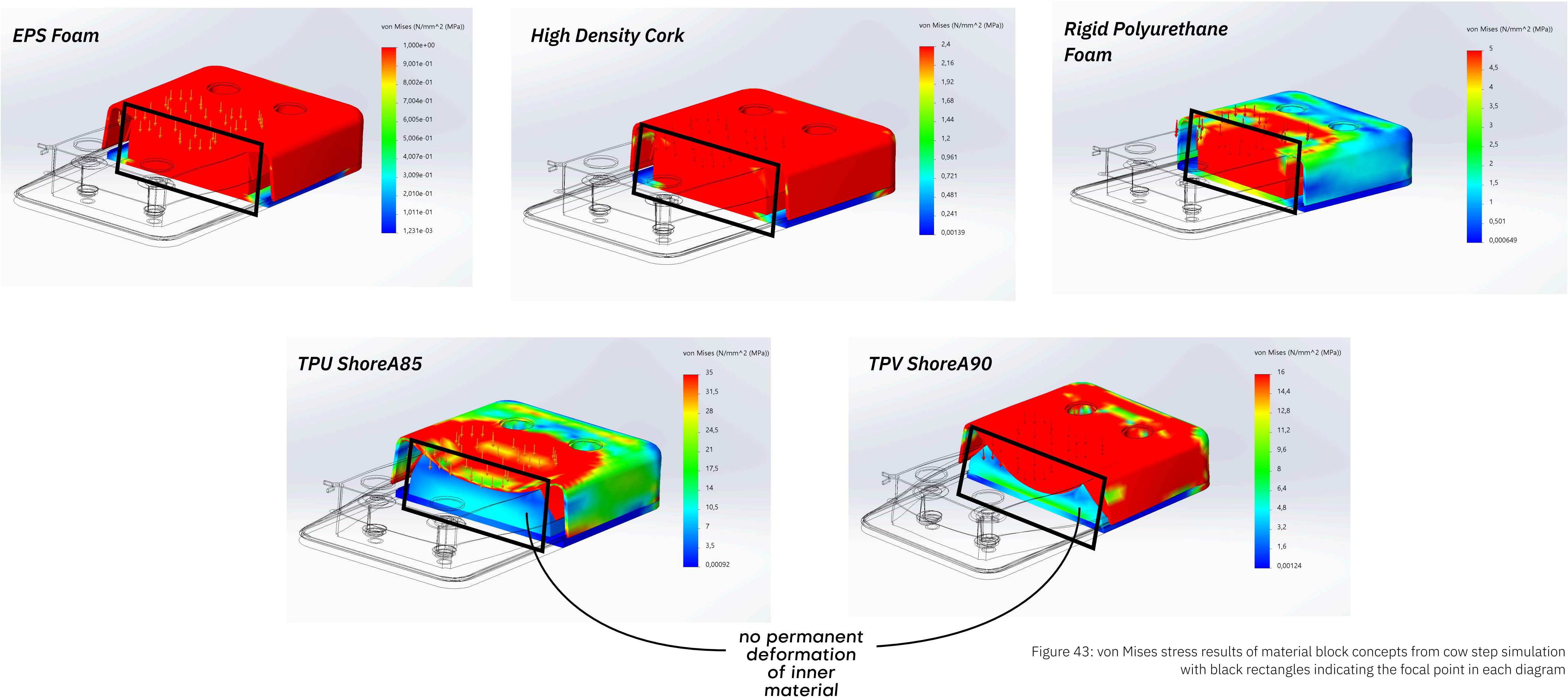


Figure 43: von Mises stress results of material block concepts from cow step simulation with black rectangles indicating the focal point in each diagram

In Figure 43, we are focusing on the inner materials' colors as pointed out by the black rectangles. The red in each visual is set to show when the resulting stress is higher than the inner material's yield strength, so red on the inner material in each picture means its permanent deformation. The thermoplastic elastomers (rubber-like materials) were the only materials to not permanently deform during their simulations of the cow step. While the displacements of the models with those materials was much higher than the other materials at the end of the simulations, the full failure and permanent deformation of the other inner materials indicates that their displacements in the simulations are severely underestimated, as confirmed by an FEA simulation expert.

Table 29 shows the displacements of the thermoplastic elastomer models also seen in Figure 45. These displacements are very large considering the depth of the model is 51mm. In order to see if the displacements accurately mean the plastic housing fractures, we need to take a look at the resulting stress on the plastic housing (Figure 44).

Table 29: Maximum displacement results of material block concepts from cow step, N/A is indicated when the resulting stress is higher than the yield strength so the displacement on the model is underestimated
*blue highlight indicates no permanent deformation

Material Assigned to Material Block	Permanent Deformation of Material Block (Yes when resulting stress > yield strength of material)	Displacement of Plastic Housing (mm)
Polyurethane foam 0.6	Yes	N/A
High Density Cork	Yes	N/A
EPS foam	Yes	N/A
TPU ShoreA85	No	19 mm
TPV ShoreA90	No	33 mm

Displacement : movement of a point or body from its original (undeformed) position
Permanent Deformation : when the resulting von Mises stress > yield strength

The simulations concluded in all of the different types of materials not upholding the antenna enough to fully withstand a cow step without deformation. The thermoplastic elastomers resisted their own permanent deformation well, but they still did not uphold the plastic housing enough to protect it from deformation.

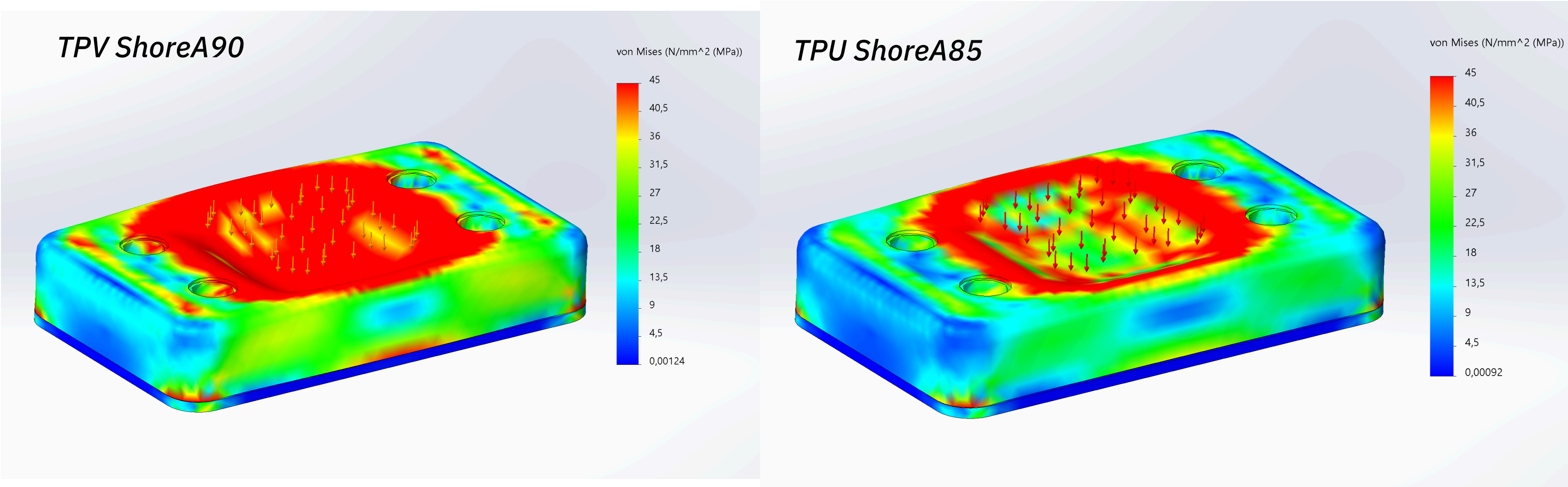


Figure 44: Permanent deformation of the plastic housing covers with thermoplastic material blocks inside, red indicating when the plastic housing deforms

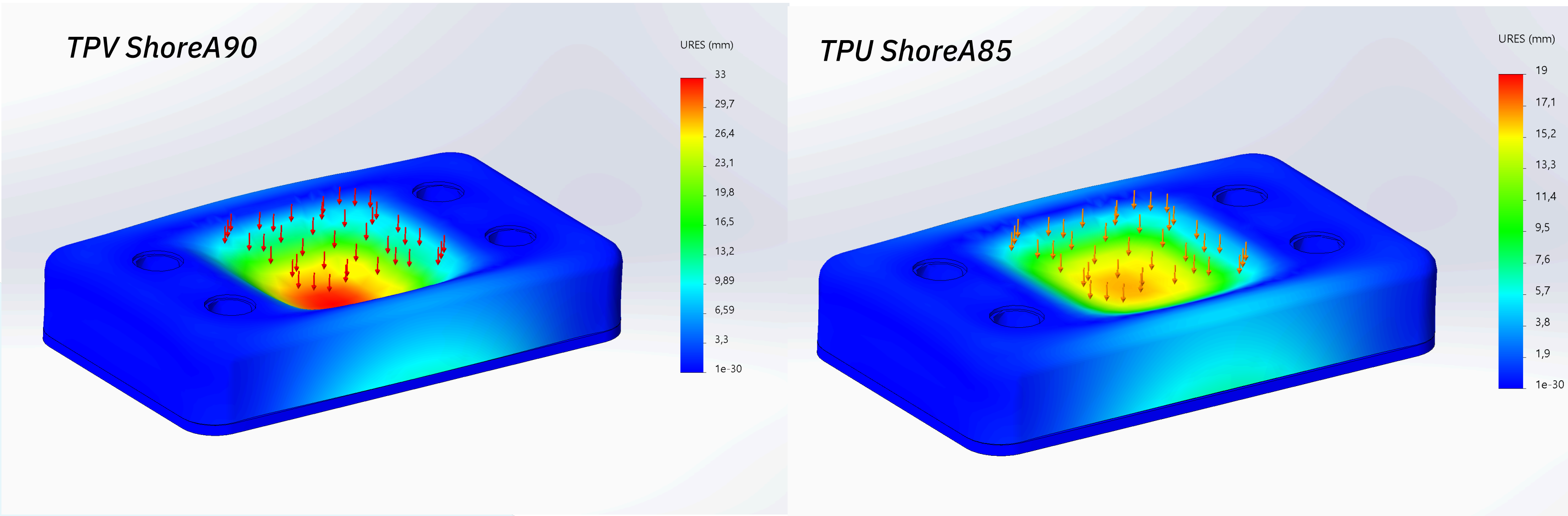


Figure 45: Displacement of the plastic housing covers with thermoplastic material blocks inside, red indicating the maximum distance the plastic housing moves

8.2.4 Adjusting Priority Part Area

Another theme seen in the brainstormed concepts is the isolation of the priority parts. Ideas involved adjusting the architecture and positioning of the electronics within the antenna (Table 30). Containing the electronics to sectioned off or smaller areas would allow for less space that needs the highest durability or a smaller amount of area needed to access for repair.

As seen in the repairability guidelines previously discussed (Dangal et al., 2022), modularity is a common concept in circular design as it allows the easy replacement of broken parts without wasting a whole product (Berwald et al., 2021). Removing highly valuable parts before shredding in recycling can also be a motivator for designing modular parts, but this product does not contain a large quantity of valuable parts. Products that contain more hazardous materials, such as batteries, would have the additional reasoning of recycling to design for modularity.

Allowing the removal of the antenna's priority parts in one piece is relatively feasible as the priority parts (the cable, PCB, and copper wire) are all connected to each other. Moving the PCB board to the an area closer to the copper wire is very feasible and supported by the decrease in size of the PCB board available.

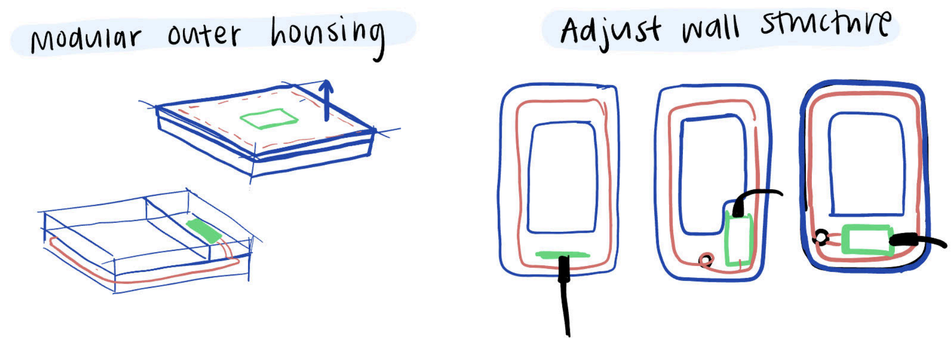


Figure 46: Brainstormed concepts for adjusting wall structure and priority part location

	Access to Priority Parts
Modular priority part section	Allows removal of priority parts by sectioning them off in their own module.
Isolating priority parts through wall structure	Addresses accessibility of priority parts principle by clustering the maintenance points (Dangal et. al., 2022).

Table 30: Requirement comparison of adjusting priority part area concepts with orange highlighting easy access to priority parts

8.2.5 Condensation Solutions

Ideas for stabilizing the temperature within the antenna without potting included a ventilation plug, something highly recommended in meetings with senior engineers, a breathing hole, desiccants, small heaters or humidity sensors, and fans.

Figure 47: Brainstorm drawings of temperature stabilization concepts

Table 31 displays the levels of durability based off of conversation with an expert reliability engineer at TU Delft and reviewing existing literature. The levels of recyclability are based on existing literature.

Heaters and fans were not added to the comparison table as they are generally too large for the size of the antenna. Additionally, they are costly and complex to implement into smaller electronic enclosures.

Technical product recyclability was not included in the requirement comparison of its dependence on how and what the concept is connected to. According to recycling experts at the e-waste recycling center, PCB coatings can be thin enough to not affect the recyclability of the copper and other valuable materials within the PCB as they are often a small percentage of the PCB's weight.

As Table 31 showcases, the solutions are generally not recyclable, but are much smaller in weight than the potting material in the current antenna. Some biodegradable desiccants such as clay are being developed (Micro-Pak, 2025) but are not currently as effective as common desiccants.

Meetings with two senior electrical engineers along with targeted literature searches led to the conclusion that ventilation plugs were the most feasible and also widely successfully used solutions for products needing condensation resistance without potting. Tencer and Moss provide the argument that diffusion plugs are the best option for antennas as the use of plastic to enclose internal antennas weakens the antenna's thermal regulation (Tencer & Moss, 2002). Additionally, there are many examples such as Laird Technologies' use of Gore-Tex plugs on antennas on top of outdoor vehicles that prove the longevity of the Gore-Tex plugs' water resistance (Gore, 2012). Diffusion plugs equalize the pressures in enclosures by releasing gases and water vapor through a microporous membrane.

Durability		Theoretical + Practical Recycl.	
	low risk		recyclable
	some risk		dependent
	high risk		unrecyclable

	Durability	Recyclability	
	Condensation Resistance	Theoretical Material Recyclability	Practical Material Recyclability
Desiccants	While some desiccants can be unreliable in quick temperature changes, molecular sieve desiccants could last up to 20 years (Tencer & Moss, 2002).	Desiccants are commonly made of chemicals like silica gel and calcium chloride, which are not mentioned as recyclable.	Desiccants are not commonly recycled and can contain environmentally harmful chemicals (Micro-Pak, 2025).
PCB coating	Conformal coatings delay moisture ingress but do not prevent it (Tencer & Moss, 2002).	Many conformal coatings are thermosets and are therefore unrecyclable (Berwald et. al., 2021).	Thermosets are unrecyclable (Berwald et. al., 2021).
Diffusion plug	Ventilation plugs efficiently minimize condensation through quick humidity equilibration (Tencer & Moss, 2002).	Gore-Tex plugs contain PTFE (Tencer & Moss, 2002), which is not a recyclable material (Berwald et. al., 2021).	PTFE is not recycled due to its degradation at the processing temperatures of common plastics (Berwald et. al., 2021).
Breathing hole	Breathing holes allow airflow and pressure regulation but can lead to too much moisture ingress without a filter.	Breathing holes do not add any unrecyclable material.	Breathing holes do not add any unrecyclable material.

Table 31: Requirement comparison of condensation solutions

8.2.6 Alternative Potting Materials

While the other categories are mainly due to the focus on removing the potting material, one of the concepts from the brainstorm is utilizing alternative potting materials that are more recyclable, more repairable, or both. This section was not as explored during brainstorming and research, but materials such as sand and silicone are of interest in further development. Sand could be tested for its impact resistance while silicone could be considered for its transparency and vision of the priority parts and potential higher liberation from priority parts as opposed to epoxy's high attachment to them during recycling. More recyclable potting materials, such as Recyclamine (Recyclamine, n.d.), are in development but are not yet commonly recycled in practice.

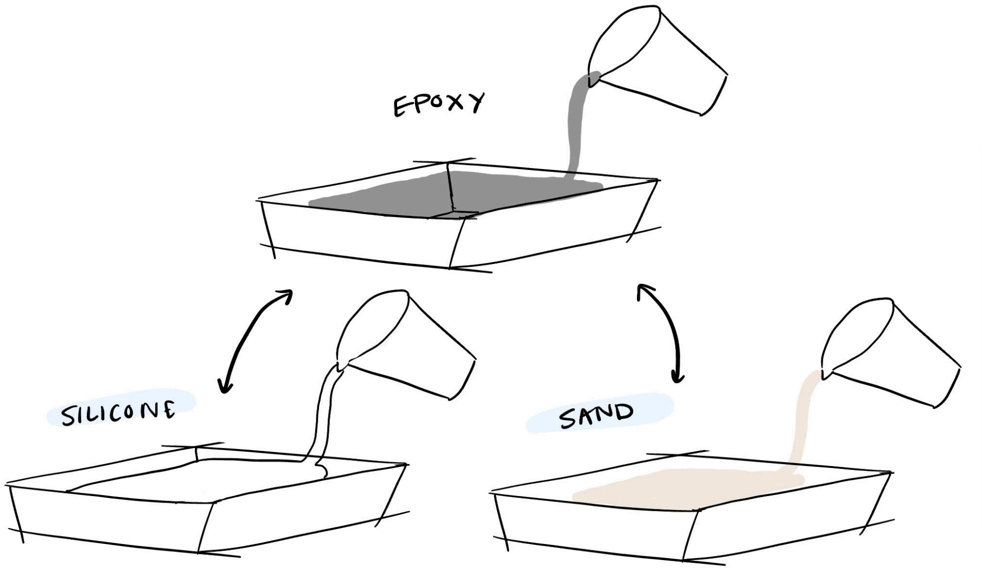


Figure 48: Alternative potting materials for future research

8.2.7 Outer Housing Materials

As the current plastic of the outer housing of the antenna is a polymer blend, which is not currently recycled in practice, other plastics were also found on Granta Edupack based on filtering for theoretical recyclability, or the “recycle” category in Granta. The recyclability of the materials were confirmed using Berwald et al.’s design for recycling guidelines (2021).

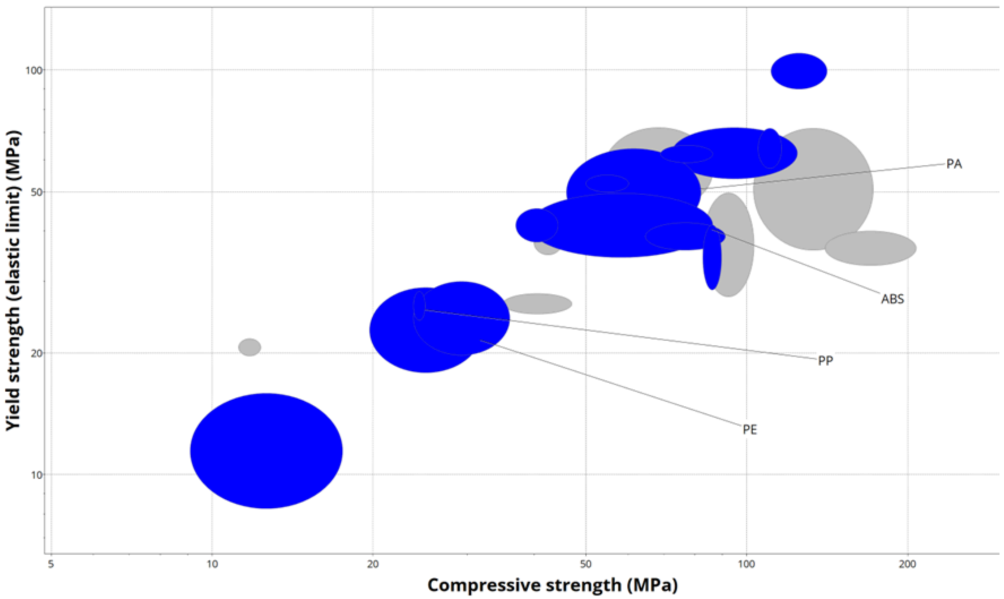


Figure 49: Plastics filtered by recyclability, yield strength, and compressive strength on Granta Edupack

	Impact Resistance		Recyclability	
	Compressive Strength (MPa)	Yield Strength (MPa)	Theoretical Recyclability	Practical Recyclability
Current polymer blend	50	45	The thermoplastics in the polymer blend are theoretically recyclable.	Polymer blends are not currently recycled.
ABS	39-86	34-49	ABS is theoretically recyclable as a thermoplastic.	ABS is commonly recycled.
PA	46-82	39-64	PA is theoretically recyclable as a thermoplastic.	PA is not commonly recycled (Mortier, 2025).
PE	20-32	18-29	PE is theoretically recyclable as a thermoplastic.	PE is commonly recycled.
PP	24-25	24-28	PP is theoretically recyclable as a thermoplastic.	PP is commonly recycled .

Table 32: Plastics filtered by recyclability, yield strength, and compressive strength on Granta Edupack

While there are many recyclable options for replacing the unrecyclable polymer blend, ABS is currently the most recycled out of all of the options (Andreas Bill et al., 2019) and would therefore be the safest choice for ensuring the housing’s recyclability.

9.4 Product Architecture Redesign

In order to explore the tensions that arise when putting the concepts from each part of the architecture together, a possible redesign is presented in this section. Figure 50 displays which concepts were chosen from each product architecture category.

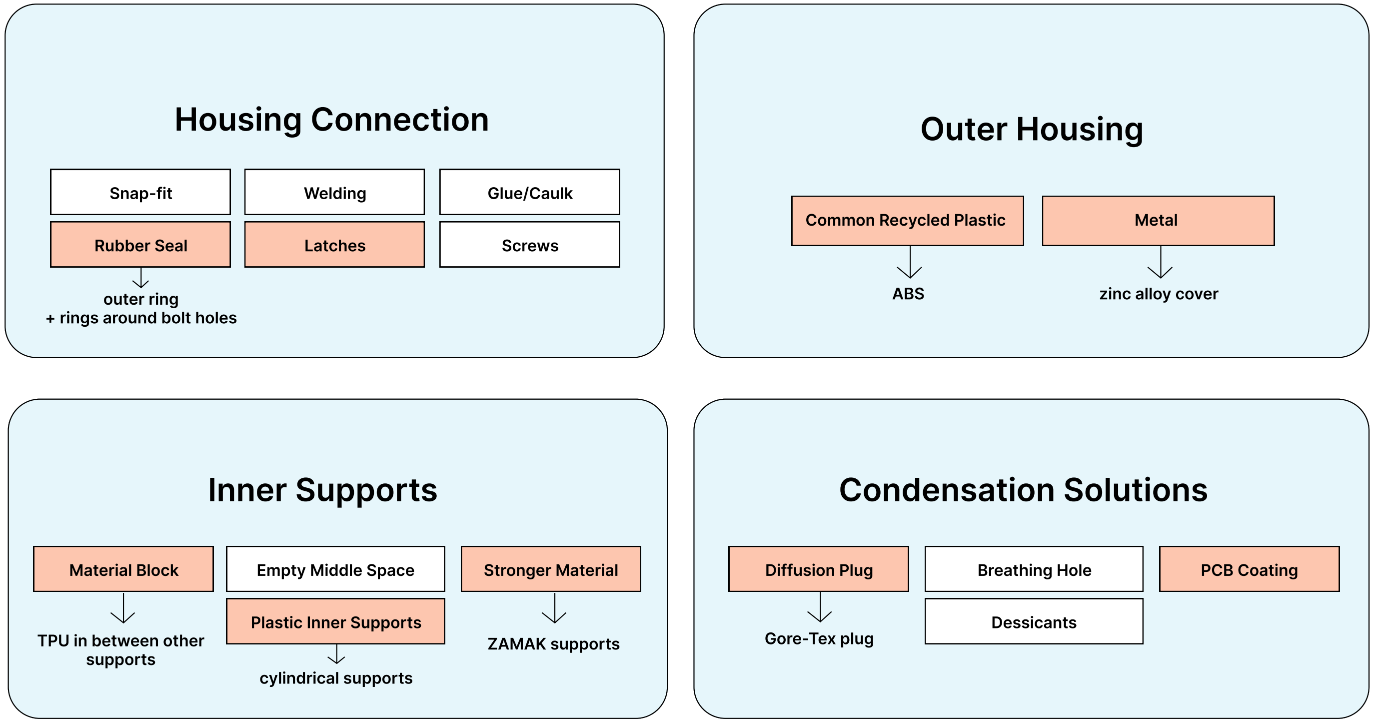


Figure 50: Choices from each product architecture area for case study redesign

9.4.1 Housing Connection

A latch design with a rubber seal was chosen for the redesign because of their allowance of quick disassembly and ability to provide a high IP rating together. Though rubber seals are often made of practically or theoretically unrecyclable materials, they allow for the disassembly and repair of the product compared to welding and glue or caulk. Their performance of fulfilling the redesign requirements is seen in Table 32.

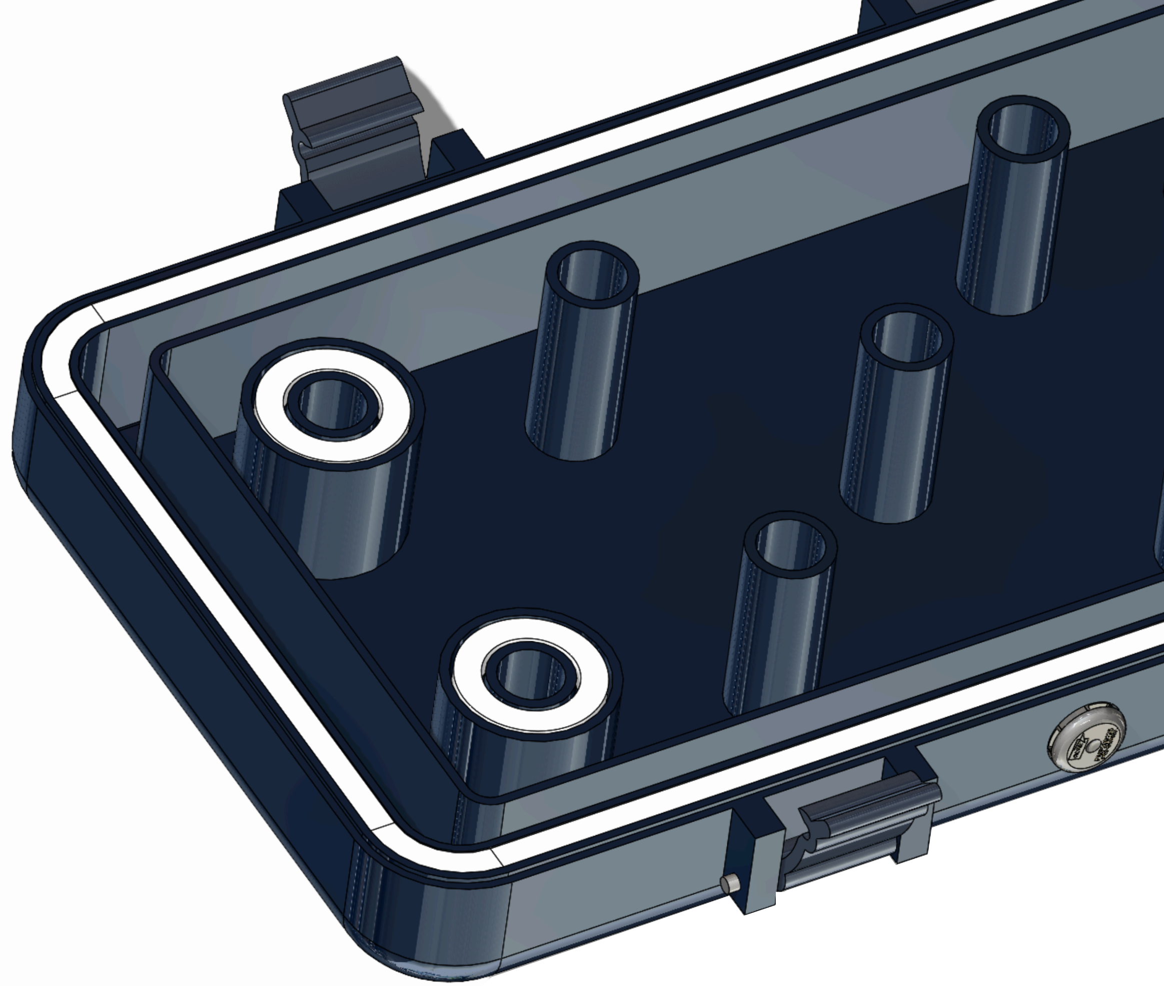


Table 32: Choices from each product architecture area for case study redesign

	Durability	**Repairability**	**Recyclability**		
	Water and Dustproof	Access to Priority Parts	Theoretical Material Recyclability	Practical Material Recyclability	Technical Product Recyclability
Latches	Rubber seal paired with a compression connection provides IP65+ waterproofing.	Impermanent connection allows for quick access	ABS is a thermoplastic and recyclable. The zinc alloy is recyclable according to recyclers.	ABS and the alloy are generally recycled and recovered according to a recycling worker.	Plastic-metal connections can lead to pollution or material loss of metals (Versloot, 2024). Same-material connections are more easily recycled.
Rubber seal		Impermanent connection allows for quicker access	TPV is a thermoplastic. Thermoplastics can be recycled (Berwald et. al., 2021).	Thermoplastic elastomers are not generally recycled.	Elastomers are likely to be filtered out (Berward et. al, 2021)

Durability
- low risk
- some risk
- high risk

Repairability
- easy access
- unpredictable access
- no access

Theoretical + Practical Recycl.
- recyclable
- dependent
- unrecyclable

Technical Recycl.
- high liberation
- unpredictable
- low liberation

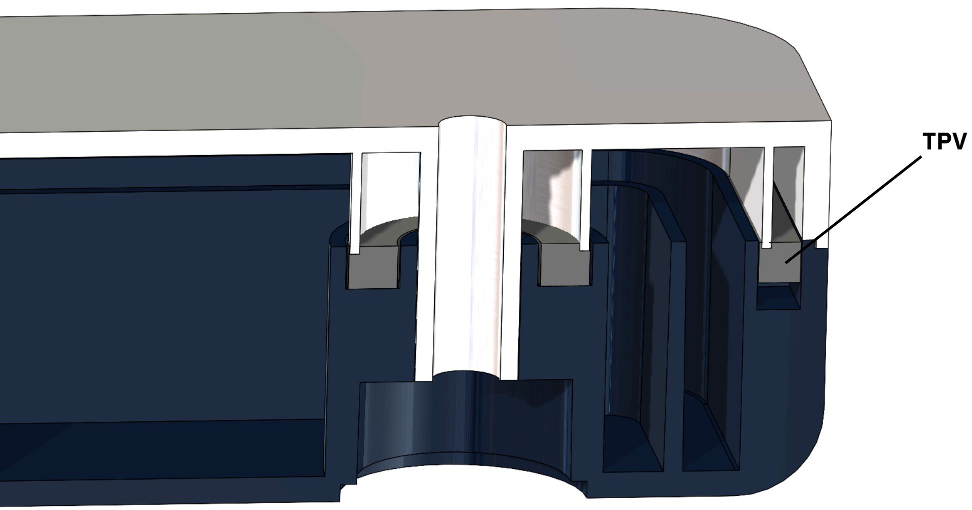
Rubber Seal Locations

When deciding between latches and screws, the rubber seal location was a factor in the choice. Figure 51 indicates the two areas where seals are needed to protect from water ingress, around (or circling) the bolt holes and the outer rim of the antenna. If screws were used to compress the rubber seal for high water protection, the space around the screws would also need to be sealed by rubber. This would entail a more complication rubber gasket.

After deciding on the latches, the dilemma of choosing the location of the rubber seals arose. Two concepts for the rubber seal were generated: an outer and inner ring or an outer ring with circular rings more closely protecting the bolt holes (Figure 51, 52). The second concept was chosen as the first concept leads to a larger amount rubber needed for the design.

Seal Material Selection

A TPV rubber was chosen for the final design because of its thermoplastic characteristic and therefore high likelihood of being filtered out during recycling. TPV was also used in a design for recycling case study by PolyCE because of its high waterproofing performance and thermoplastic characteristic (Feenstra et al., 2021).



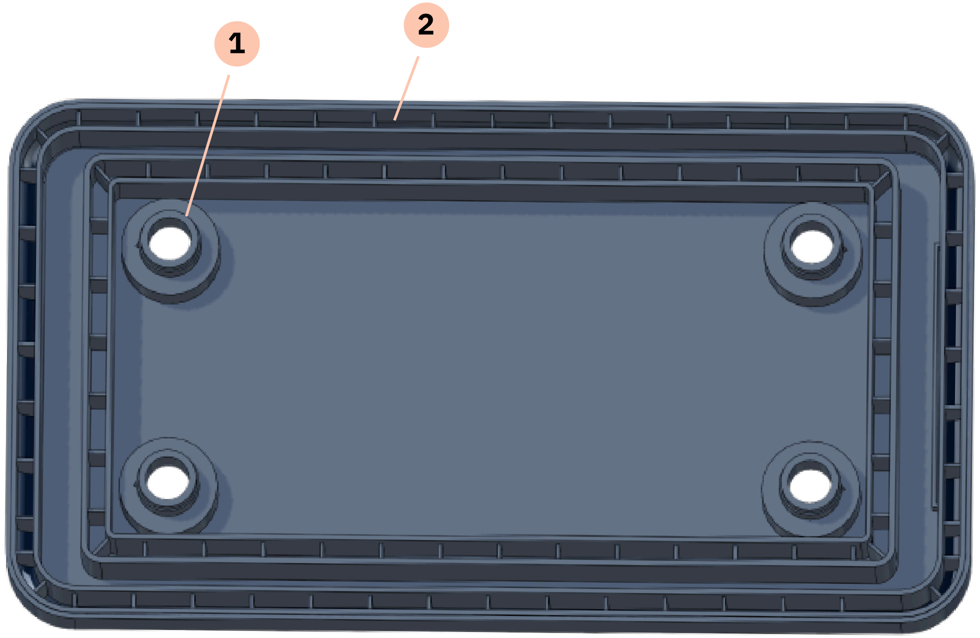


Figure 51: Outer and inner rubber seal locations with indicators of the two places that could cause water ingress

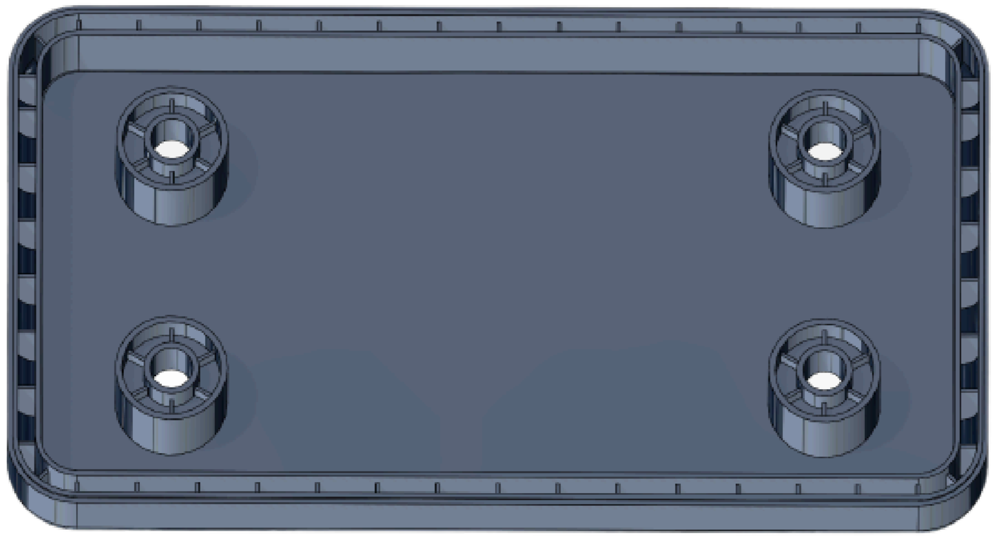
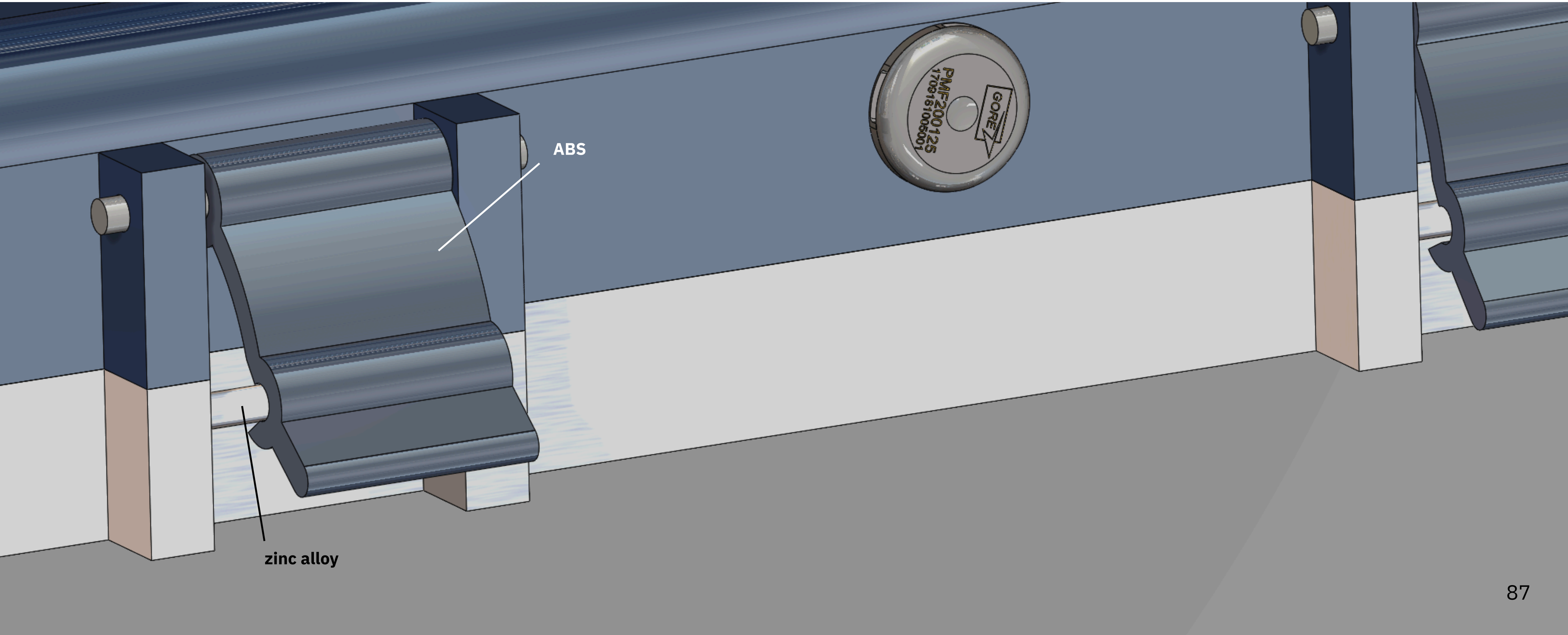


Figure 52: The second option for seal placement with circular seals around the bolt holes

Latch Design and Material Selection

Two latches instead of one were added on either side of the antenna for added reliability. The latches and their pins are made of the same ABS plastic as the housing in order for the latch to be flexible enough to snap onto the latch catch (Figure 53). The latch catch, or the notch that receives the latch, was decided to be the same metal as the metal cover for easy manufacturing.

Figure 53: Types of materials decided for the latch design



9.4.2 Inner Support Design

The large focus area of the inner supports was choosing durable (impact resistant) yet separatable materials for repair and recycling. To strengthen the empty space inside the antenna that was formerly filled by EPS foam and epoxy, a TPU material block along with plastic and zinc alloy cylinder supports were chosen (Figure 54, 55). A blend of each of the inner support concepts was created because of the impact failure from the plastic supports and material blocks separately. Additionally, the antenna was shortened length-wise (while the wall the copper wire glides along stays the same dimensions for the antenna's functionality). This allows for just enough space for the PCB and copper wire and creates a smaller, vulnerable priority part area.

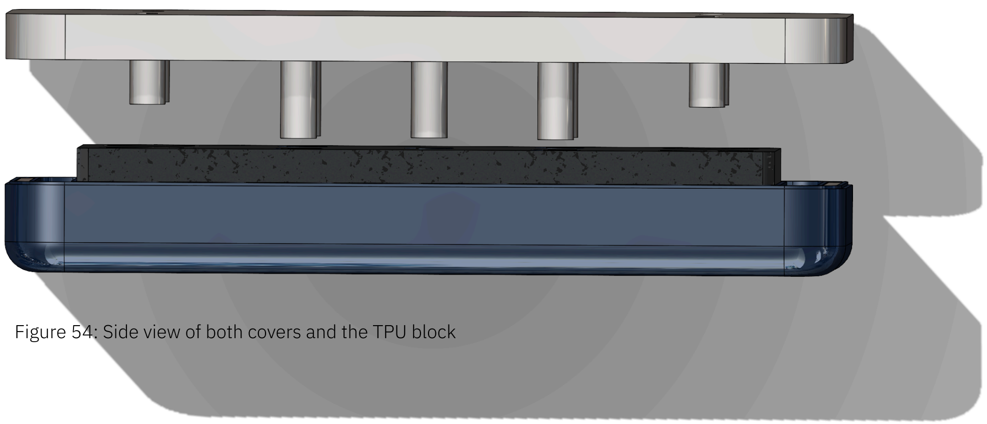


Figure 54: Side view of both covers and the TPU block

While a plastic-metal (different material) connection is not ideal for recycling, they are impermanently connected through the latch design which allows for much easier liberation as compared to being bonded together with epoxy.

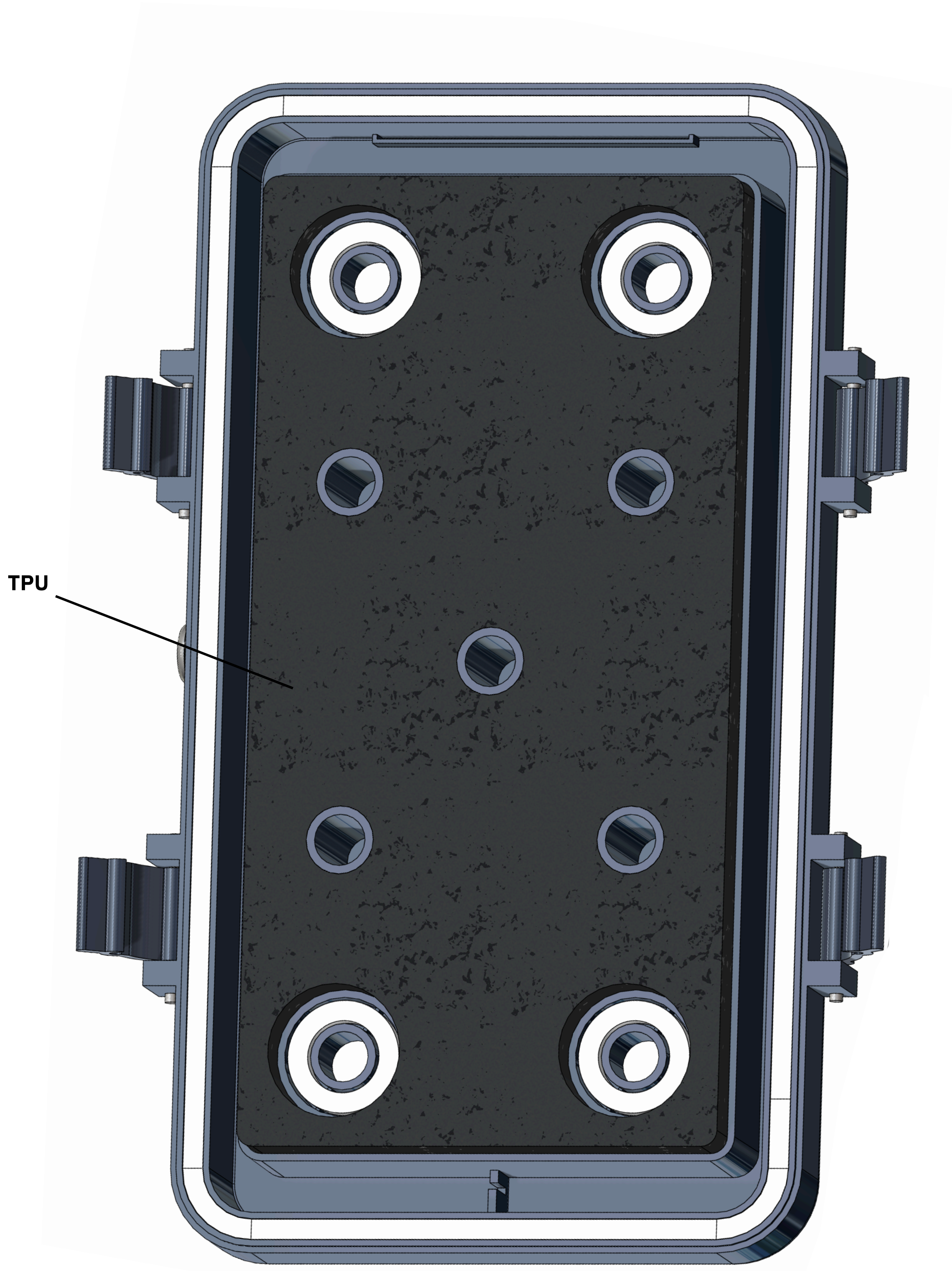


Figure 55: Final design of bottom cover's inner supports with a material block and plastic cylinder supports

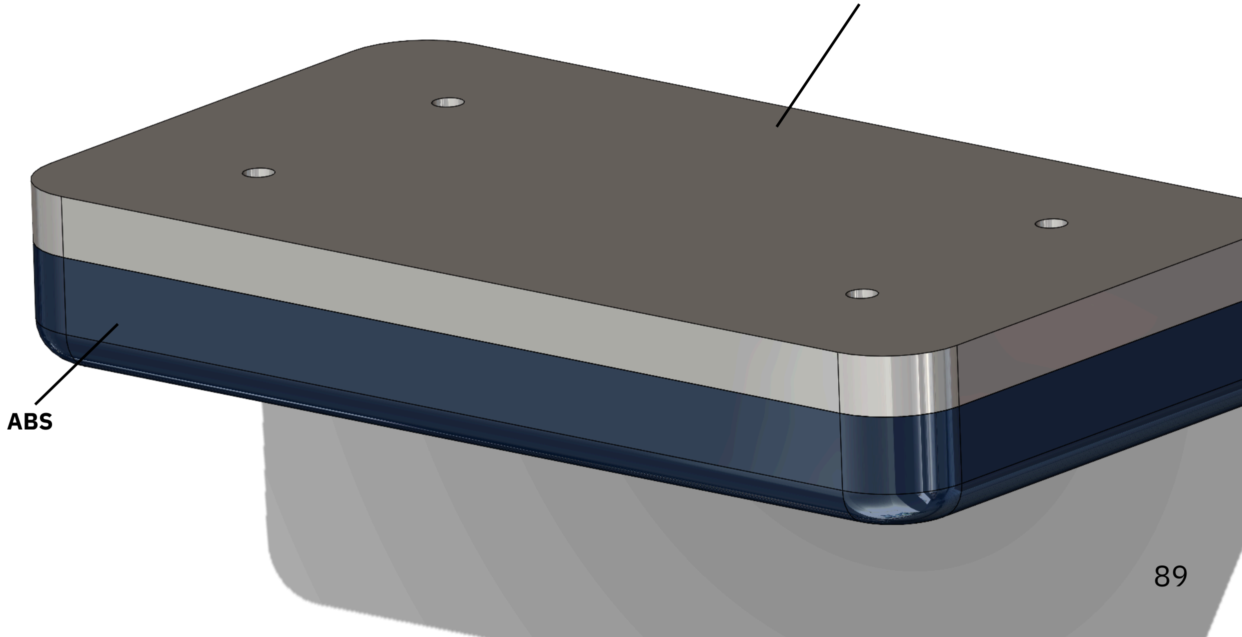
9.4.3 Outer Housing Material

When choosing an outer housing material, the tradeoffs mainly lie in choosing strong yet recyclable materials.

ABS was chosen as one of the housing material's because of it being the most commonly recycled plastic and its similar material properties compared to the original polymer blend. A metal also became part of the outer housing after seeing the added inner support of having metal cylinders in the impact simulations (Figure 56).

When selecting a metal, a zinc alloy, was chosen due to its high manufacturability as its die-castable, its high strength properties, and its recyclability. This zinc alloy is generally over 95% zinc with very small amount of copper and magnesium. The alloy would likely end up in the non-ferrous fraction, as its not magnetic, and the copper would be recovered along with the zinc by metal smelters according to the metal wheel from Van Schaik et al. (2012) and a conversation with a recycling center worker.

Figure 56: Material selection of housing cover materials



9.4.4 Condensation Solution

A Gore-Tex plug was added for condensation resistance, as it was the favored condensation solution concept among engineers met with and in literature as previously discussed (Figure 57). The diffusion plug contains unrecyclable PTFE but weighs a few grams, very little in comparison to the over 1000 grams of unrecyclable potting material in the current design. Additionally, a conformal coating on the PCB is recommended to be added as most are thin enough to maintain the recyclability of the copper in the PCB.

Diffusion Plug Placement

A meeting with a reliability engineer informed the placement of the diffusion plug. Diffusion plugs are best placed on the ground-facing face of products if there is open air below. This antenna has two versions, one with a cable entering from the back and one from the side, meaning the antenna can be installed either upright or upside down. With the risk of water ingress being too high if the antenna is installed upside down (with a Goretex plug facing upward), the Gore-Tex plug was placed on the longer side of the antenna. Another option could be placing arrows or other indicators of which orientation to install the antenna on.

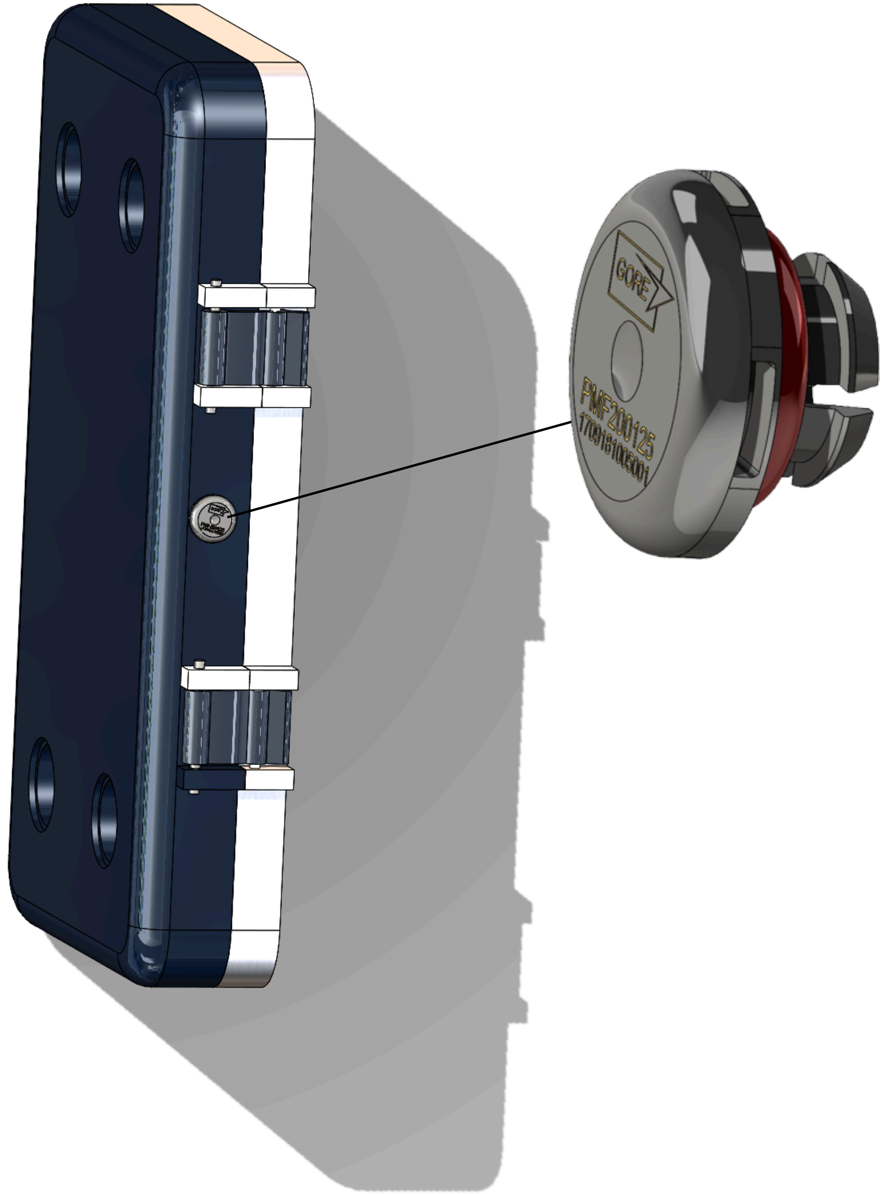


Figure 57: Gore-Tex plug location and close up in the model

9.4.5 Priority Part Stabilization

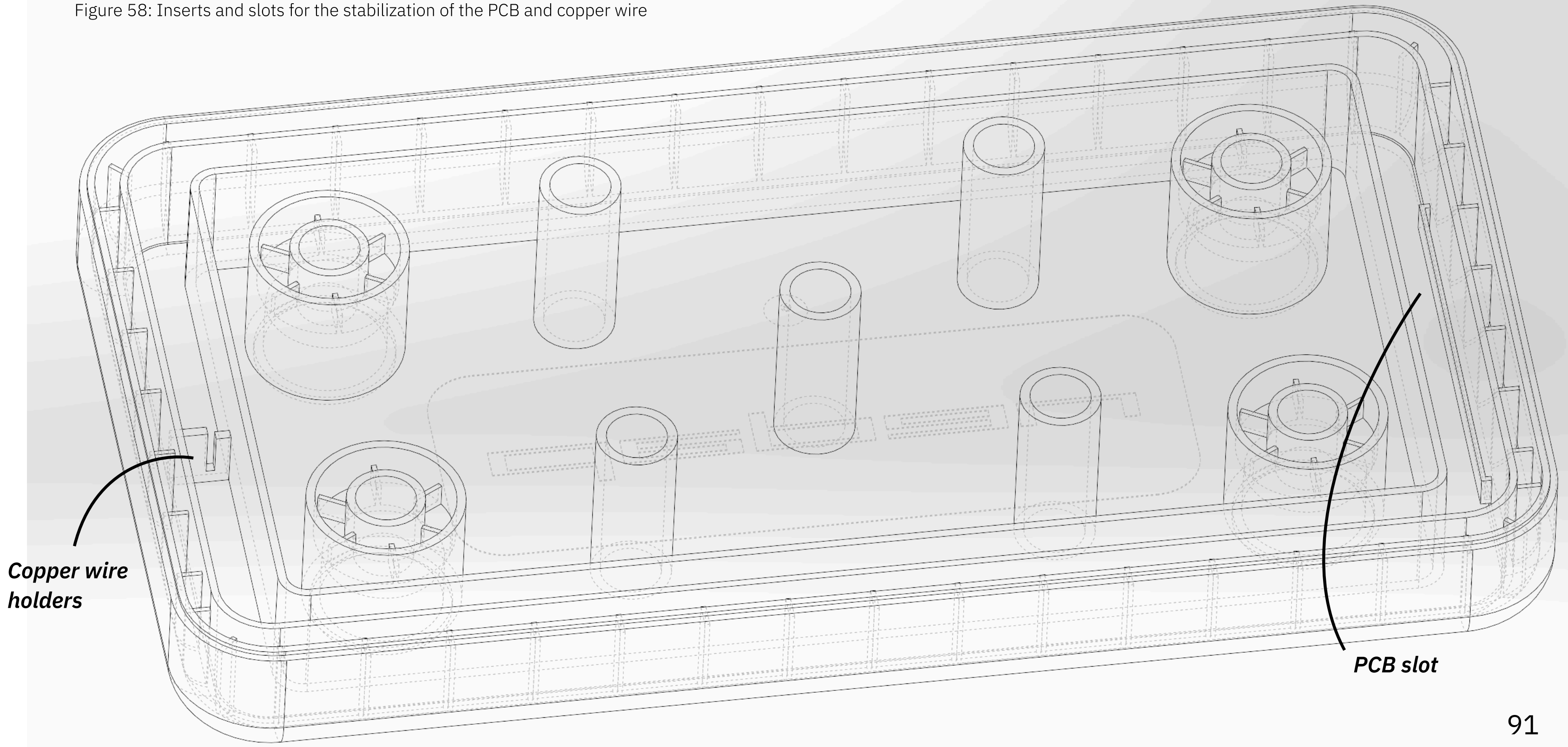
Component Protection

When deciding where to place the priority parts, there was a question between keeping the PCB in the middle of the model compared to on the side of the model for best impact protection. Ultimately, the PCB was placed on the side of the model in order to have extra support from the double plastic walls used to create the rubber seals and for immediate access after opening the antenna.

Maintaining Functionality Requirements

A key aspect in choosing how to stabilize the components is maintaining the functionality requirements of keeping the copper wire the same dimensions and maintaining the connections between the components. In this design, the PCB is stabilized by a friction fit slot that allows the PCB to be inserted close to the copper wire to maintain their connections. The copper wire is supported by ribs with space inserts to ensure its correct dimensions (Figure 58).

Figure 58: Inserts and slots for the stabilization of the PCB and copper wire



9.4.6 Evaluation of the Redesign

In this section we will visualize and discuss the performance of this prototype in relation to the redesign requirements.

Durability	Repairability	Theoretical + Practical Recycl.	Technical Recycl.
low risk	easy access	recyclable	high liberation
some risk	unpredictable access	dependent	unpredictable
high risk	no access	unrecyclable	low liberation

Concept		Durability			Repairability	Recyclability		
Category	Selection	Water and Dust proof	Condensation Resistance	Impact Resistance	Access to Priority Parts	Theoretical Material Recyclability	Practical Material Recyclability	Technical Product Recyclability
Housing Connection	TPV rubber seal	Rubber seal paired with a compression connection provides IP65+ waterproofing.		Slightly dampens impact	Easy disassembly access	Thermoplastics can be recycled.	Thermoplastic elastomers are not generally recycled.	Thermoplastic elastomers are likely to be separated out (Berwald et. al., 2021).
	Latch design				Access to the priority parts within a few seconds.	ABS is a thermoplastic and recyclable. The metal is a recyclable zinc alloy.	ABS and the zinc alloy are generally recycled and recovered according to a recycling worker.	Plastic-metal connections can lead to pollution or material loss of metals (Versloot, 2024). Same-material connections are more easily recycled.
Inner supports	TPU material block			Does not uphold housing by itself but distributes the load well.	The material block allows for easy disassembly.	Thermoplastics can be recycled (Andreas Bill et al., 2019)	Thermoplastic elastomers are not generally recycled (Berwald et. al., 2021).	Thermoplastic elastomers are likely to be separated out (Berwald et. al., 2021).
	Zinc alloy top with cylindrical supports			The metal cylinders provide high impact resistance.		The zinc alloy is recyclable according to recyclers.	Zinc alloys are generally recycled and recovered according to a recycling worker.	The zinc alloy is non-ferrous and is expected to separate as easily as the non-ferrous metals in the shredding experiment did.
Condensation Solutions	Diffusion Plug		Ventilation plugs efficiently minimize condensation through quick humidity equilibration (Tencer & Moss, 2002).			Gore-Tex plugs contain PTFE (Tencer & Moss, 2002), which is not a recyclable material (Berwald et. al., 2021).	PTFE is not recycled due to its degradation at the processing temperatures of common plastics (Berwald et. al., 2021).	The snap-fit or screw-in fit of Gore-Tex plugs may not liberate well from the plastic.
	PCB Coating		Conformal coatings delay moisture ingress but do not prevent it (Tencer & Moss, 2002).			Many conformal coatings are thermosets and are therefore unrecyclable (Berwald et. al., 2021).	Thermosets are unrecyclable (Berwald et. al., 2021).	PCB coatings are thin enough to not affect the recyclability of the PCB.
Outer Housing	ABS Housing	ABS is water resistant.		Provides similar strength properties as the original polymer blend but does not uphold the antenna against the worst case by itself.		ABS is a recyclable thermoplastic.	ABS is a commonly recycled plastic.	Plastic-metal connections can lead to pollution or material loss of metals (Versloot, 2024). Same-material connections are more easily recycled.

Table 33: Evaluation table of the performance of the model in terms of the requirements

Repairability

As seen by Figure 59, the repairability of the antenna largely improves with the redesign. The polyurethane epoxy disabled reaching any of the priority parts in the original design while the redesign allows for access to all priority parts and other components of the antenna. This means that even though the antenna may be less impact resistant, any broken part would be replaceable, which could extend the life of the redesign.

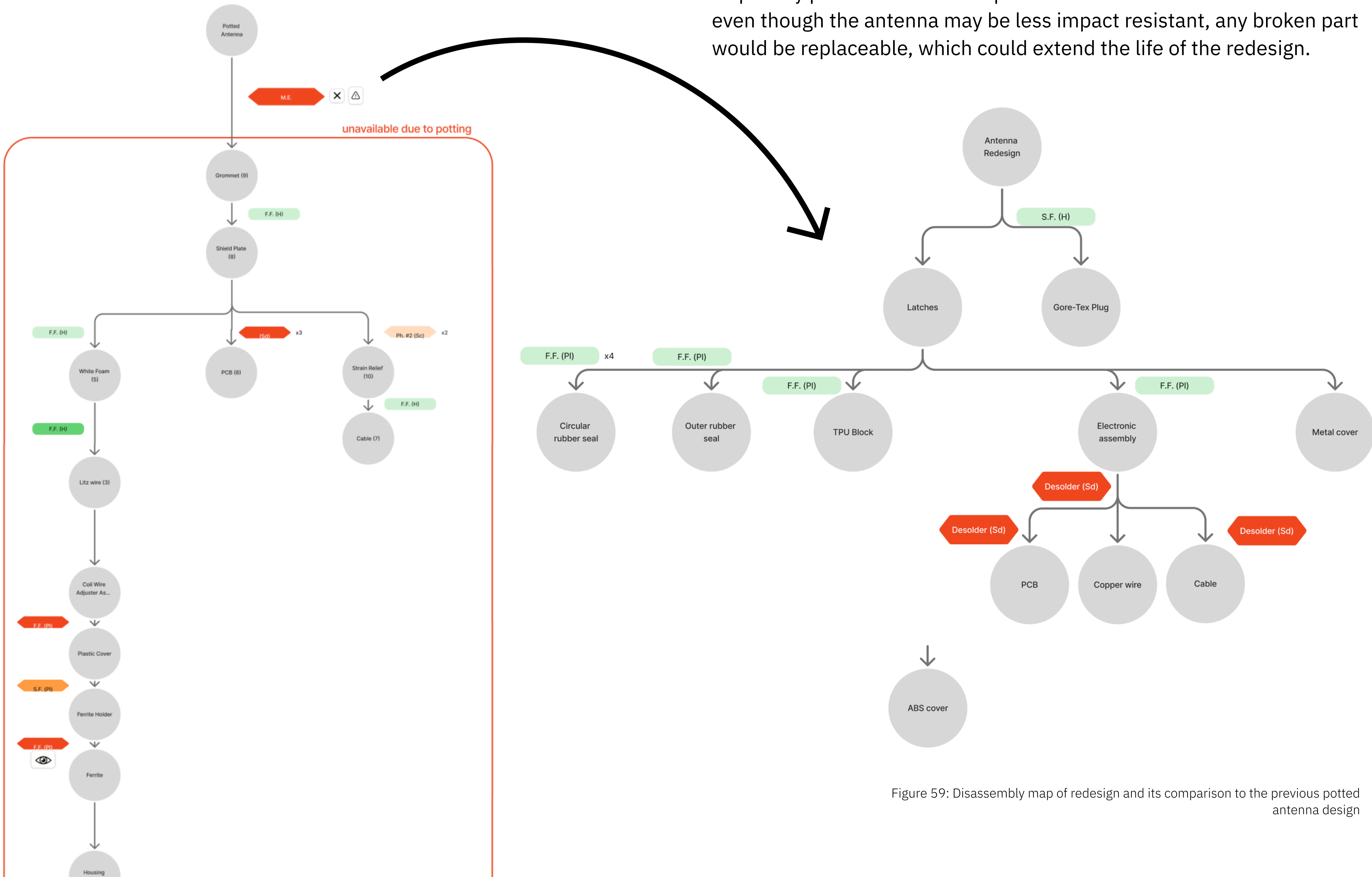


Figure 59: Disassembly map of redesign and its comparison to the previous potted antenna design

Durability

The redesign is expected to be less impact resistant than the original antenna because of the result of an evaluation simulation where the redesign was unable to fully support the plastic housing under 1000 kg/10 cm^2 without permanently deforming. During the evaluation simulation, the plastic permanently deformed 7mm but the TPU and metal cylinders withstood the impact. It is important to note that the 100 kg/cm^2 pressure is an extreme worst case and happens much less often than a cow horn or face hitting the antenna, which would be a much lower pressure on the antenna. Real-life tests should confirm the more common pressures and their effect on the antenna.

Fortunately, the redesign fulfills the other more common environmental durability requirements, as the compressed rubber seal and diffusion plug are solutions that are highly proven in industry.

Recyclability

While the the diffusion plug and the PCB coating unrecyclable, these components are expected to be less than 3 grams total. The TPU and TPV materials in the redesign are likely to be separated out of the other material streams and are 979 grams as opposed to the 1070 grams of polyurethane potting that left the valuable materials almost completely unrecycled and likely incinerated. The TPV and TPU, in comparison to the epoxy, in theory allow for the priority parts and all other materials in the antenna to be recycled as they do not bond to the materials like epoxy. The ABS and zinc alloy materials allow for a theoretically recyclable outer housing as opposed to the unrecyclable polymer blend used in the original.

Feasibility

With a few tweaks, the manufacturing of the redesign is expected to be feasible. With an injection moldable plastic cover, die-castable metal cover, and mold and machinable TPU, the materials are standard enough to have manufacturing solutions.

The cost of materials in the redesign is expected to be higher than the original design due to the metal cover and TPU materials being used as replacements to the cheaper EPS foam and epoxy. By removing the potting material, aluminum plate, and stainless steel bushings, the antenna’s total materials are about 2.5 euros cheaper, but the addition of the metal and TPU lead to a 9 euro increase in the initial material cost before the added cost of new manufacturing additions.

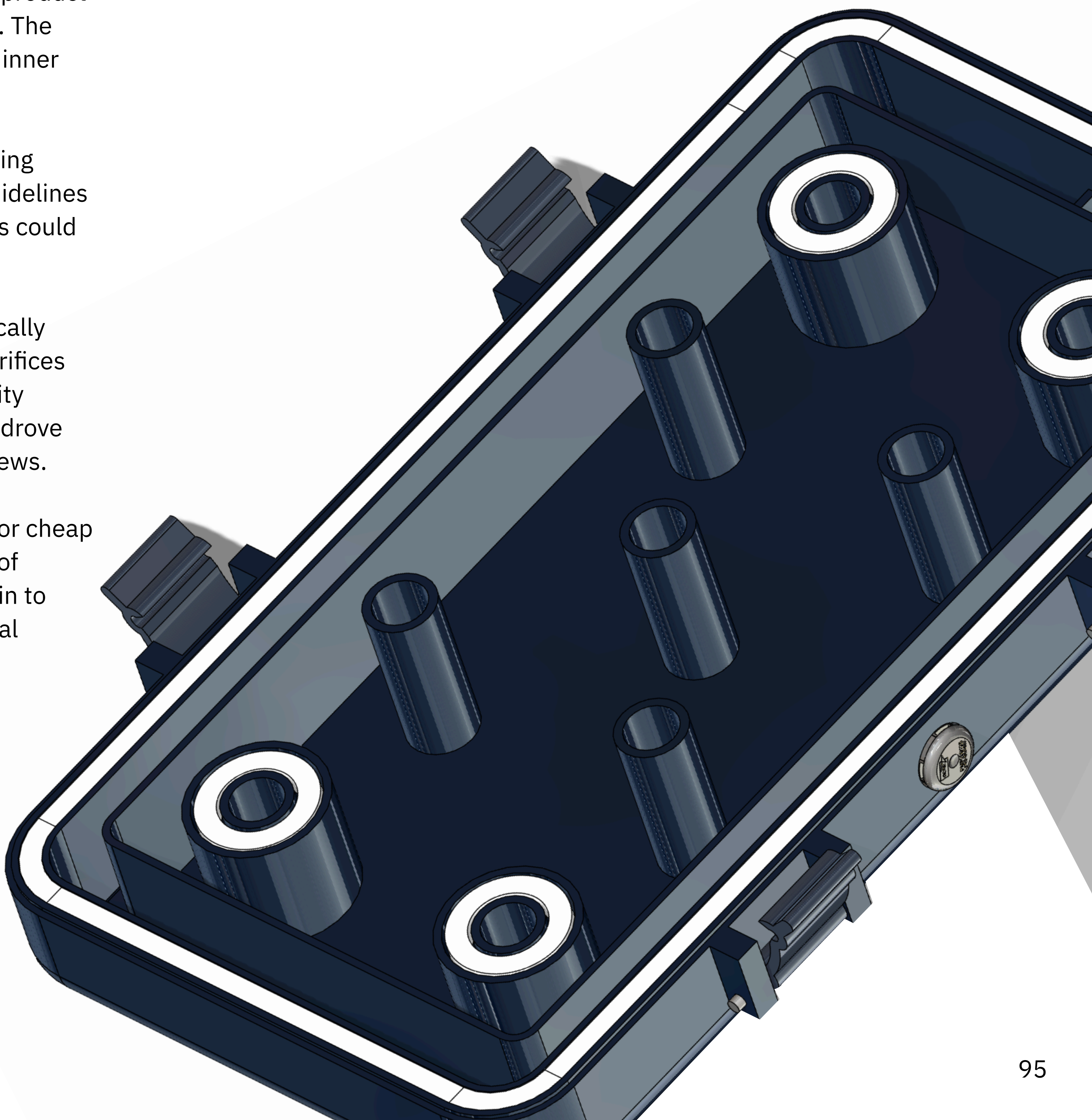
9.4.6 Conclusion

The physical redesign began with identifying the aspects of the product architecture that fulfilled different requirements of the antenna. The categories were the outer housing, the housing connection, the inner supports and the condensation solutions.

A large part of the redesign entailed material selection. Comparing materials by their properties, fulfillment of existing literature guidelines and impact resistance informed final choices on which materials could fulfill the properties that the potting material currently fulfills.

Choosing certain concepts over others, such as choosing practically unrecyclable rubber seals and a Gore-Tex plug, led to small sacrifices on recyclability for the sake of fulfilling repairability and durability requirements. Additionally, fulfilling functionality requirements drove design decisions such as choosing a latch design over using screws.

While the final design is not expected to be as impact resistant or cheap as the original design, it showcases the process and possibility of finding more recyclable and repairable materials that can conjoin to replace materials like epoxy causing the loss of valuable material recovery across the electronics industry.



Chapter 9: Discussion and Conclusion

Research and Analysis

As the life and design of the product is largely influenced by the harsh environmental conditions it sits within, the project began with barn visits and interviews with users and stakeholders of the product. This qualitative research largely informed the requirements of maintaining the high durability of the product, the main competitive advantage of products standing in harsh environments.

The contextual research also revealed the different end-of-life's of the product and how much influence the farmer has on the recovery of the product's materials. As the farmer has the final say on where the product ends up at the end of its life due to the ownership model of the product, the focus for the user requirements became guiding, motivating, and informing farmers toward sustainable disposal choices. As only a few barns from the Netherlands and the USA were visited, interviewed, or surveyed, more quantitative and representative research could be done for a global product like this.

Further research and analysis of the product revealed the complete unrepairability of the antenna and the loss of 95% of the most valuable materials within the antenna, the copper and copper-containing PCB, during recycling. This was largely due to the potting of the antenna and revealed how crucial it is for material recovery to utilize solutions other than epoxy or other (bonding) material connections to fulfill durability requirements.

Existing guidelines and conversations with recyclers also revealed the theoretical unrecyclability of a large volume of the antenna, including the housing cover's polymer blend and the potting material. The process of finding out the recyclability of the different materials in the antenna revealed the lack of consistency in recycling practices, as each recycling center has different processes, which can even be dependent on the day. This is problematic for designers wanting concrete guidelines for circular design, especially for globally sold products, and emphasizes the need for publicized recycling data and regulation. Additionally, the complete lack of collection data available for this product highlights the need for more specific e-waste collection data, as business to business products seem to be less regulated for sustainability currently. This being said, there are currently some well-proven generally recycled plastics, like ABS, but other material types were more difficult to determine the recyclability of, even locally.

Designing for Repair, Recycling, and Durability

The methods used for analyzing the repairability and recyclability of the product, such as the hotspot map, disassembly map, existing guidelines, and shredding test, all resulted in the main, non-conflicting finding that the potting material put the valuable materials at large risk of not being accessible or separatable for repair or recycling.

The durability analysis created a large tension with the repair and recycling methods when revealing that the potting material fulfilled many of the durability requirements, like condensation resistance, water and dustproof, and impact resistance, all as one material. This also presented a challenge for maintaining the design simplicity of the product while still fulfilling the durability requirements. Additionally, it was difficult to test the exact durability of the product and redesign options without real in-context testing and more time. Testing the redesigns through a the worst-case impact simulation may have led to an overly extreme impact resistance criteria.

While the methods were helpful in pinpointing the value, access, and local recyclability of the materials and connections in the product, this project showcases that designing for durability or a specific temporal lifetime of a product requires real-life, physical, in-context testing. Additionally, more methods and case studies on designing for the circularity of long-lifetime, technologically mature products like this antenna should be developed. Quantitative methods, perhaps including Life-cycle Assessment data, for designers could also aid in determining the best design combinations for the least negative impact on the climate.

The Redesign and Overall Outcome

The redesign showcased the dilemmas that arise when seeking to combine the best solutions for repair, recycling, and durability. Oftentimes, the functional requirements must be prioritized over the circular guidelines and lead to sacrifices in the product's circularity. The final prototype in this project still contained some theoretically or practically unrecyclable material, but the big difference was that the chosen materials and connections had much less risk of negatively affecting the recovery and repair of the valuable materials in the product.

Another takeaway from this project is the large impact that choosing theoretically and practically recyclable materials, especially for the high volume materials, has on the end of life of a product. Making the switch to a well-confirmed recyclable material when it has little impact on the final performance of the product, such as switching from a polymer blend to a practically recycled plastic, is an easy way of improving the circularity of a product.

While there were some durability requirements left by the potting material that were easily fulfilled by simple, industry-proven solutions like rubber seals and diffusion plugs, the impact resistance proved harder to find simple, more sustainable solutions. This could also be motivation for researchers to develop recyclable yet robust materials.

Chapter 10: Recommendations

Physical Redesign

There are a few aspects of the physical redesign that were unaddressed in this project's limited prototyping time. Applying an entry point for the cable, likely through the connection of the plastic and metal cover with a seal around it, is needed. There was also not enough time in this project for iterating on the stabilization of the priority parts, manufacturing, or cost.

A large next step for this project would be physical testing of the prototype and other redesigns, especially for testing the performance of the prototype in comparison to the durability requirements. Also, ensuring the validity of the durability requirements through barn testing should also be conducted, as the impact resistance criteria used in this project is expected to be extremely over-specified.

Additionally, it should be noted that while this product did not have a large quantity of valuable or hazardous materials, other products at the company, for example with batteries, would profit even more from a circular redesign. For products with a long-lifetime like this antenna, discussing with recyclers what materials are not currently practically recycled but are expected to in the future would be a valuable strategy.

Product Journey Redesign

As the product journey redesigns were initial ideas, they are also in need of further testing and discussions among stakeholders for their feasibility and expected impact. Additionally, holding more general sustainability meetings or conversations among stakeholders could be very impactful, as the products produced by Nedap are part of a larger web of stakeholders who have more direct contact with the farmers that own the agricultural products like this antenna.

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