

Circularity by Design for Renault Group

A New Car Door Architecture for Remanufacturing and Recycling in the 2030 Context.

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A handwritten signature in dark ink, consisting of several fluid, overlapping strokes that form a stylized, abstract shape.

Summary

The European automotive industry is one of the largest consumers of primary raw materials and every year more than six million vehicles reach their end of life in Europe. Although these vehicles are often recycled, the recovered materials are of low quality and only a fraction of recycled plastic re-enters vehicle production. Combined with the dependency on dominant material suppliers and the new EU regulation the industry is being pushed towards circularity and forced to abandon its linear model. Renault Group initiated this thesis to explore how circular strategies can be applied within its design practice. The car door was chosen as a use case. The goal of this thesis is therefore to design a circular car door concept that demonstrates the potential of remanufacturing and recycling for Renault Group and its stakeholders within the 2030 sustainable mobility context.

An analysis of the future legislative landscape and Renault Group's existing circular initiatives identified the circular capabilities the company must develop by 2030. It showed that Renault Group is building strong circular infrastructure through The Future is NEUTRAL, but that embedding circular principles into the design of new vehicles remains the least developed capability.

A product-level analysis showed that the door is not designed for the circular economy. This analysis was based on the door's functions, architecture, assembly, disassembly and component value. Together these findings revealed that the door is a subsystem whose components are difficult and time-consuming to extract, whose materials are mixed and joined irreversibly, and in which copper containing components contaminate recycling streams, which forces the recovered metals to be downcycled. These findings define the circularity gap. Renault Group's circular system is in place, but the products entering it are still designed according to linear logic. Closing this gap requires disassembly that is both fast, to make part harvesting and remanufacturing economically viable, and clean, to enable high-quality recycling.

Three concept directions were explored along the three resource cycles of the circular economy (narrowing, slowing and closing) and synthesized into a final design. A new door architecture consisting of an aluminium frame, a monomaterial PP interior panel, and a removable module in which components are clumped and surfaced. Inspired by the Centre Pompidou, the architecture exposes components rather than concealing them, making them visible, legible and accessible. The module can be liberated from the frame in a quick operation, enabling part harvesting for remanufacturing, while the removal of copper containing components improves the recycling quality of the frame.

The architecture was evaluated through validation interviews with stakeholders across the full door lifecycle and a disassembly map comparison. The concept was received as inspiring and new by the design department, technically feasible by the engineering department. Next to this it was perceived beneficial for repair by a mechanic and beneficial for end-of-life recovery by INDRA (vehicle recycler). The disassembly map comparison provided a first indication that the architecture reduces disassembly time.

This thesis demonstrates that circular value is created upstream, in decisions made during design, long before a vehicle reaches its end of life. The proposed architecture should be seen not as a finished design but as a starting point. A new approach to designing car doors and other vehicle subsystems that shows how circularity, applied from the start of the design process, can become a source of inspiration rather than a constraint.



Glossay & abbrivations

CMF – Colour, Material, Finish
CRM – Critical Raw Material
CRMA – Critical Raw Materials Act
DC (motor) – Direct Current (motor)
DPP – Digital Product Passport
ELV – End-of-Life Vehicle
EoL – End of Life
EPR – Extended Producer Responsibility
EU – European Union
PCB – Printed Circuit Board
PE – Polyethylene
PET – Polyethylene Terephthalate
PP – Polypropylene
QR (code) – Quick Response code
RFID – Radio-Frequency Identification
RQ – Research Question

Aftermarket:	The secondary market for vehicle parts and components after the original sale, including spare, reused and remanufactured parts.
Core:	A used component or product collected as input for remanufacturing.
Digital Product Passport:	A digital record linked to a product or component (e.g. via RFID/QR) that stores lifecycle data such as material composition and usage history, enabling quality assessment for reuse, remanufacturing or recycling decisions.
Design for disassembly:	Designing a product so its components can be separated easily and non-destructively at end of life.
Disassembly map:	A method that visualizes the sequence, connections and effort required to disassemble a product.
Downcycling:	Recycling in which the recovered material is of lower quality than the original.
Grade / purity:	The quality level of a recovered material.
Monomaterial:	A part made from a single material (or material family).
Part harvesting:	Retrieving components, modules, or parts from products, to use them as spare parts for servicing, maintenance, and repair. These parts might be refurbished or remanufactured.
Refurbishing:	Restoring a used product to good working condition, potentially with cosmetic improvements, without the full industrial process of remanufacturing; the result typically performs below a new product.
Remanufacturing:	Restoring a product to a condition the same as or better than a new product through an industrial process. In this report, the term is used broadly to cover value-retention processes at component level, including refurbishing.
R-strategies (9R framework):	Hierarchy of circular strategies ordered by level of circularity, from R0 Refuse to R9 Recover.
Reverse logistics:	The collection and transport of used products and cores from the point of use back to reprocessing facilities.

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01

Introduction

This chapter introduces the project. It starts with the problem statement, outlining the problems the European automotive industry currently faces and the role of the circular economy to address these problems. This leads to the design goal and the three research questions guiding this thesis. The scope of the project is then defined, followed by an introduction of the companies and stakeholders involved. Next, the methods used throughout the project are explained. The Chapter concludes with a review of the circular economy and the key frameworks used throughout this thesis.

1.1 | Problem Statement

The automotive manufacturing industry is among the largest consumers of primary raw materials such as steel, aluminium, copper, and plastics. It is responsible for 19% of demand for the EU's steel industry, 10% of overall consumption of plastics, 6% of copper, 42% aluminium and 30% of rare earth elements (European Commission,2026).

Every year, over 6 million of these produced vehicles reach their end of life in Europe (European Commission,2026). The management of these end-of-life vehicles (ELVs) has developed into a critical environmental and economic issue due to the significant volumes and hazardous nature of the waste generated (Arpino et al., 2024)(figure 1). Although the recycling rates of materials from ELVs are generally high, the scrap metals produced are of low quality (European Commission,2026) and only around 2.9% recycled plastic is used in new vehicle production (Plastics Europe, 2024).

Next to the environmental issues the automotive industry is facing further challenges: resource dependency on dominant Chinese suppliers (Britsche & Fekete, 2024), supply chain disruption due to geopolitical tension and increased competition of Chinese OEM's (KPMG, 2025).

In response to these pressures, the European Union has created new regulations, through the proposed revision of the End-of-Life Vehicle Directive and the Critical Raw Materials Act. Both push the automotive sector away from a linear model and towards circular practices. The circular economy is seen as the solution to these problems as it can reduce material waste, retain more value (Bocken et al., 2015) and builds resilience against supply disruption and ensure resource security (Böhler et al., 2025) (Baldassarre, 2024).

Renault Group has embedded circularity into its corporate strategy and is currently considered the industry leader in the circular economy (Ruet et al., 2023). Through this master thesis, Renault Group aims to explore how circular strategies can be more widely applied within its design practice.

With the growing pressure to reduce environmental impact and to improve the recovery of end-of-life vehicles, the design of the vehicle itself must also be reconsidered through the lens of the circular economy. This thesis explores how circular strategies can be applied in practice, taking the car door as a use-case. A car door is a subsystem integrating mechanical, electronic, aesthetic, and safety functions. This makes it a representative example of the challenges of rethinking a vehicle component. At the same time, its manageable scale allows it to be concretely redesigned within the duration of this thesis. This brings the project to its design goal:



Figure 1 - EoL vehicles gathered at a scrapyard

Design goal.

“Design a circular car door architecture to demonstrate the potential created by remanufacturing and recycling, for Renault and its stakeholders within the 2030 context.”

1.2 Research questions

To work towards the design goal, three research questions are formulated, each guiding one part of the project:

- **RQ 1** - What circular capabilities must Renault Group develop by 2030, based on legislation and the future policy landscape, and how do these relate to Renault's existing circular initiatives?
- **RQ 2** - To what extent is the current Renault car door designed for the circular economy, and which characteristics limit its circular performance?
- **RQ 3** - How can circular strategies be applied to the design of a car door to improve its circular impact within Renault's 2030 context?

1.3 Scope

This master thesis presents a circular car door architecture for the 2030 timeframe. The aim is not to create a door that is a 100% circular, but a concept that moves Renault Group a meaningful step further in its circular transition while remaining realistic within the company's projected capabilities for 2030.

Beyond the concept itself, the thesis is intended to inspire Renault Group's designers and engineers to rethink their current practices and to bring circularity into design decisions from the start of the lifecycle.

This thesis is part of a collaboration with Renault Group involving two parallel projects. The other project addresses circularity at the long-term system level for the 2040 timeframe. This thesis is positioned at the short-term, product level. It focuses on a realistic redesign of a door, feasible in the proposed timeframe.

Deliverables

- A new approach to designing a car door in which circular principles are clearly present.
- A graduation report presenting and substantiating the design decisions made throughout the project.

1.4 Involved companies

This graduation project is carried out in collaboration with Renault Group. The Group exists out of four separate brands: Renault, Dacia, Alpine and Mobilize. Each of these brands addresses a different segment of the market (figure 2).



Renault: “The world's best-selling French vehicle brand, Renault designs next-generation vehicles, with intuitive, useful and affordable technologies. Its two-pronged range of electric and hybrid vehicles allows everyone to move towards more sustainable electric mobility at their own pace. As part of its commitment to reducing its carbon footprint, Renault is innovating to improve safety for drivers, passengers and all other road users” (Renault Group, 2026).



Dacia: “A brand with a cool, outdoor vibe, Dacia is for customers looking for adventure, freedom and authenticity, with simple, versatile and reliable vehicles. With its iconic models delivering outstanding value-for-money, Dacia has taken up a place on the retail podium in Europe (Renault Group, 2026).



Alpine: “A brand born to race, Alpine embodies sporting excellence the French way, both on the track and on the road. Combining the know-how and heritage of its historic Dieppe plant with the engineering expertise of Alpine Racing and Alpine Cars, the brand has become the Group's sports laboratory” (Renault Group, 2026).



Mobilize: is the Group's mobility-services brand rather than a conventional carmaker. It focuses on rental, car-sharing, and related services such as financing, data and energy management, addressing mobility needs beyond individual vehicle ownership (Renault Group, 2026).



Figure 2 - Four separate brands of Renault group. Dacia, Renault, Alpine, Mobilize (left to right).

1.5 Approach & Methods

This project follows the Double Diamond design process. A framework that structures a design project into four phases: Discover, Define, Develop, and Deliver (figure 3).

Discover: This phase starts with a literature review of the circular economy. A context analysis is then carried out in two directions: a policy analysis examining circularity at the level of EU regulation, and a product analysis examining a current Renault car door through site visits, expert interviews, physical inspection and a disassembly map.

Define: The findings are converged into a set of core insights that identify the key problems preventing the current door from performing well in a circular system and translated into focused design directions.

Develop: Concepts are developed around the 9R framework of the circular economy. Three concept directions are explored, each focusing on a different circular strategy, before the strongest direction/combination is selected and developed into a final concept.

Deliver: The final concept is embodied into a door architecture and evaluated through validation interviews with stakeholders across the vehicle lifecycle

During the writing of this report, generative AI tools (such as ChatGPT/Claude) were used to assist with language, phrasing and structuring of text. The tools were used solely to support the writing process. All research, analysis and conclusions are the author's own.

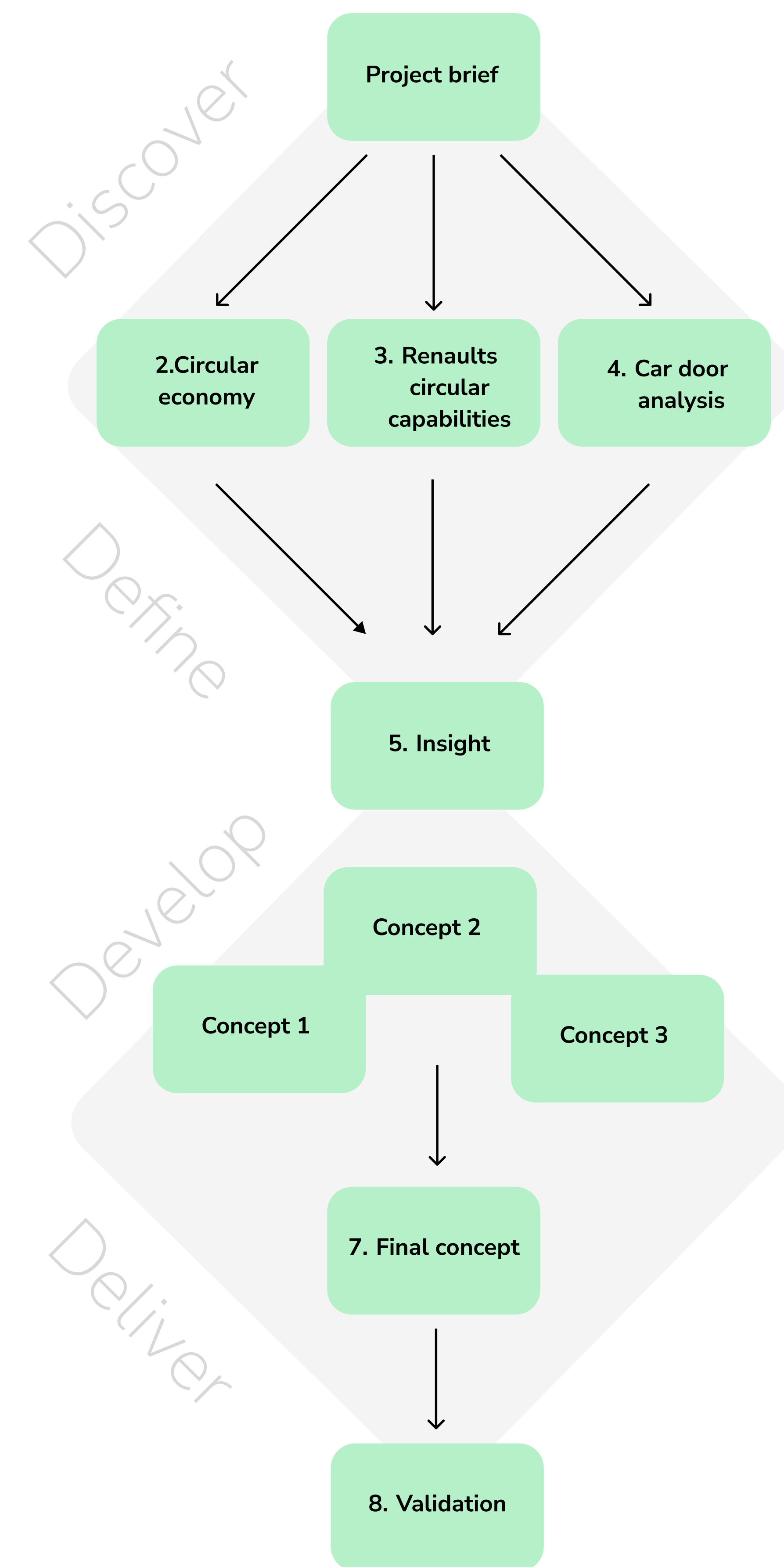


Figure 3 - Overview of the double diamond method

1.6 | The Circular Economy

This chapter introduces the circular economy and the key frameworks used to describe it. The definitions and concepts established here, the resource cycles, the value hill, and the R-strategies, form the lens through which the car door is analysed and redesigned throughout the report.

1.6.1 | Definition & Butterfly diagram

The European commission defines the circular economy as follows: “In a circular economy the value of products and materials is maintained for as long as possible; waste and resource use are minimized, and resources are kept within the economy when a product has reached the end of its life, to be used again and again to create further value” (European commission, 2015).¹

Figure 4 shows the butterfly diagram which shows the continuous flow of materials in a circular economy. There are two main cycles: the technical cycle and the biological cycle. In the technical cycle, products and materials are kept in circulation through processes such as reuse, repair, remanufacture and recycling. In the biological cycle, the nutrients from biodegradable materials are returned to the Earth to regenerate nature (Ellen MacArthur Foundation, 2021). In this report the focus will be on the technical cycle.

From a business perspective the circular economy makes sense: reuse of materials can save costs and service models can deliver new business propositions and revenues. Circular businesses allow products to stay at their highest level of value for as long as possible (Achterberg et al., 2016).

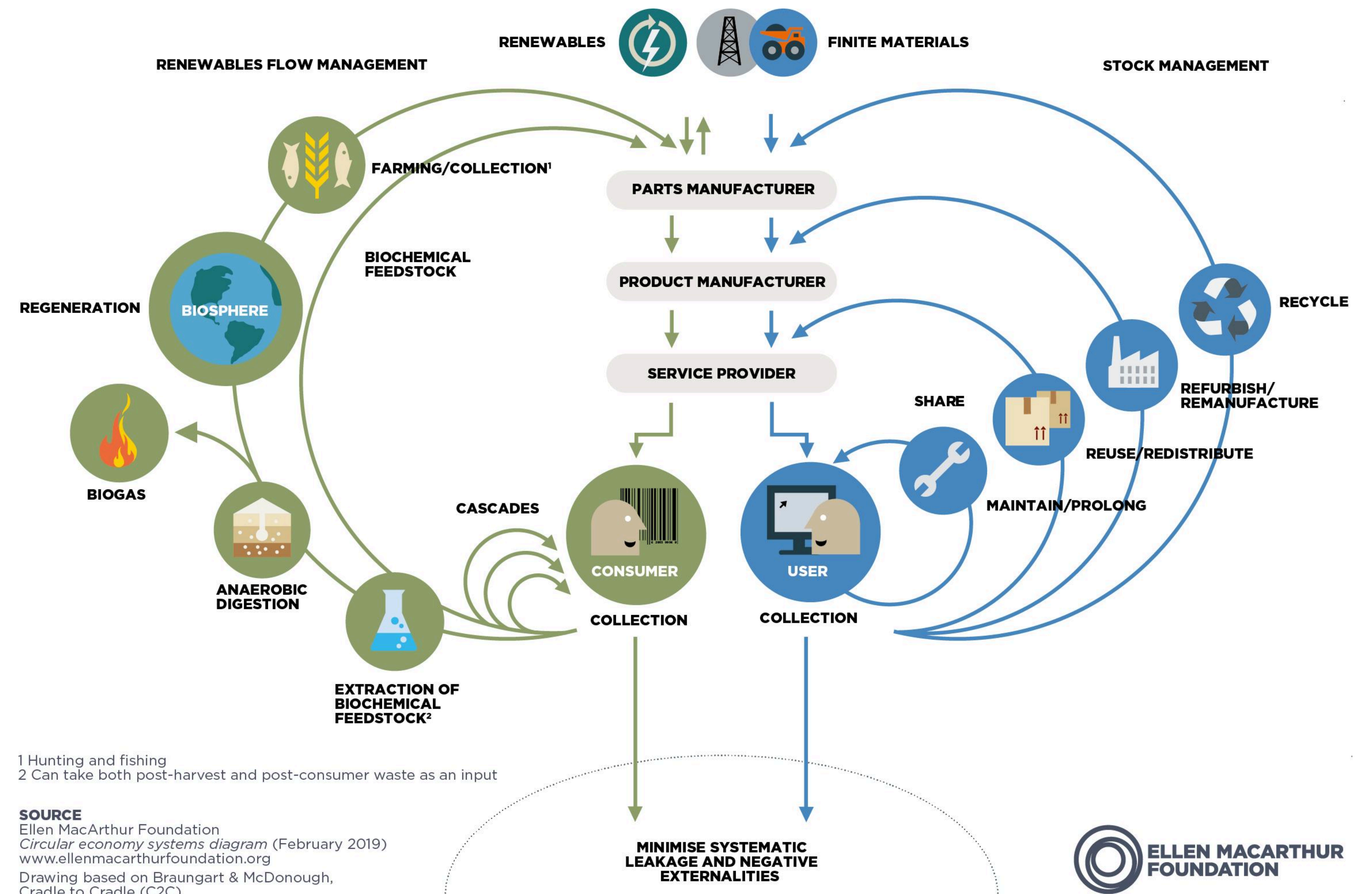


Figure 4 - The butterfly diagram (Ellen MacArthur Foundation, 2019)

1.6.2 | Value hill & 9R Framework

To understand how the circular economy can keep products at the highest level of value Achterberg et al. (2016) created the value hill (figure 5). By extracting resources, manufacturing parts, assembling them into products and distributing them to consumers, value is added at every step. Which can be seen at the left side of the hill. After the consumer uses the product, however, its value goes downhill. The old products end up in landfills or are incinerated, quickly destroying the value that was created in the manufacturing process (Achterberg et al., 2016).

Supplementary to the value hill, Potting et al. (2017) created the 9R framework (table 1). This 9R framework orders existing circular strategies by priority according to their level of circularity. In this table the different R strategies are combined with the terminology of Bocken et al. (2015). It maps the R strategies to the terminology of the resource cycles: narrowing, slowing or closing resource loops as this is used throughout this thesis.

Figure 5 shows an overview of the value hill with the 9R framework integrated. It illustrates how circular design strategies can help retain a product's value through reuse, refurbishment, repurposing, and recycling.

The value hill provides the central way of thinking about value throughout the project: value is built up through extraction, manufacturing and assembly, and the aim of a circular approach is to retain as much of that value as possible rather than letting it run downhill at end of life. The 9R framework is taken forward as the hierarchy for prioritising circular strategies. Strategies higher on the ladder retain more value and are therefore preferred, while lower strategies such as recycling are seen as a last resort. Finally, the distinction between narrowing, slowing and closing resource loops is carried through as a reminder that circularity is not a single action but a combination of strategies across the full lifecycle. Together, they form a consistent way of thinking about value and circular strategies that is applied throughout the rest of this thesis.

Note on terminology: the 9R framework distinguishes refurbishing (R5) from remanufacturing (R6). For readability, this report uses "remanufacturing" to refer to both strategies, as they follow largely the same recovery logic in this project. Where the distinction is relevant, it is made explicit.

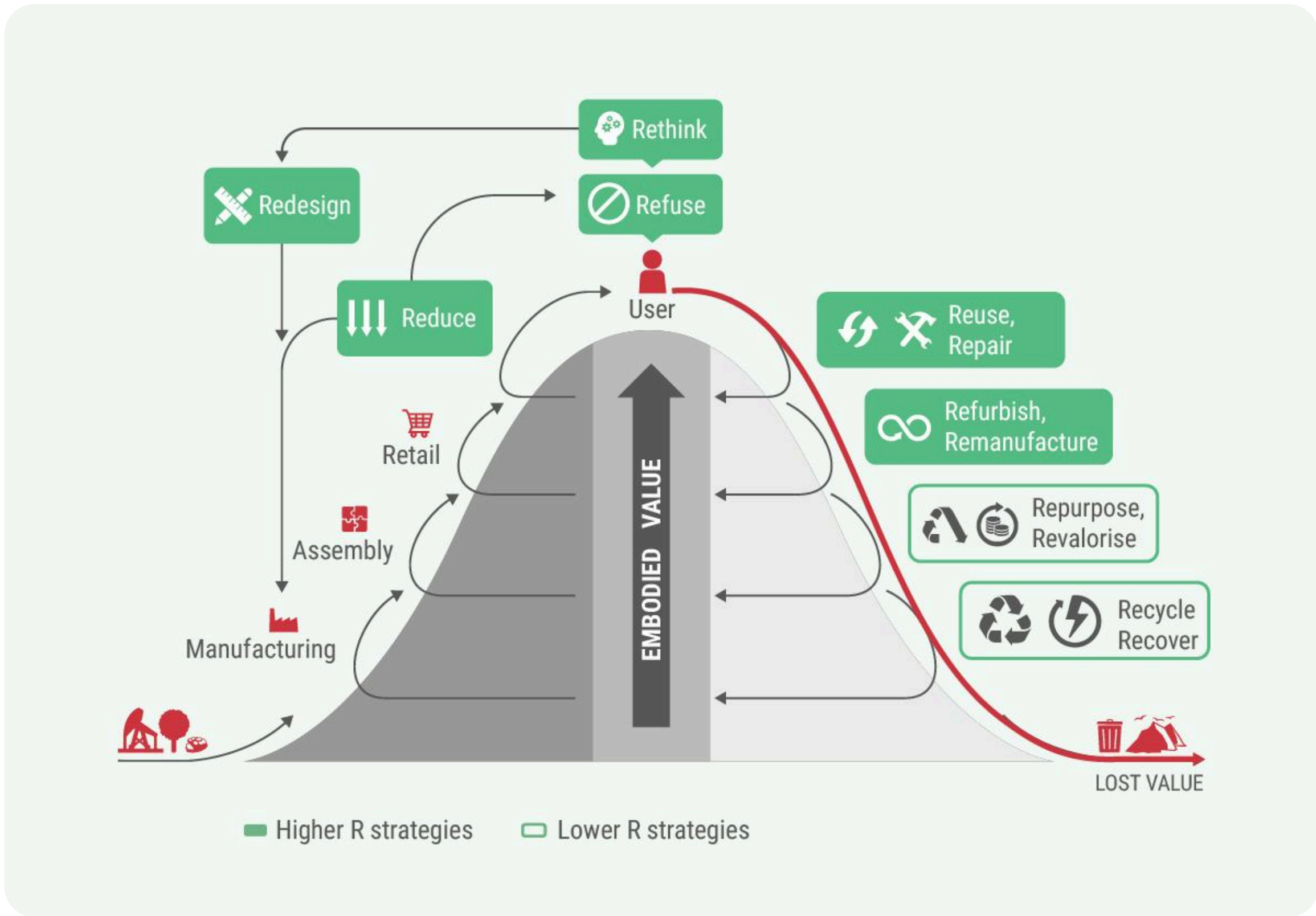


Figure 5 - Value hill integrated with R strategies

Narrow Narrow resource loops	R0	Refuse	Can we make the product redundant
	R1	Rethink	Make product use more intensive
	R2	Reduce	Consume fewer resources and materials
Slow Extend resource loops	R3	Reuse	Transfer to another consumer
	R4	Repair	Ensure easy repair and maintenance
	R5	Refurbish	Restore the used product to as new standards
	R6	Remanufacture	Recover and use parts for new products with the same function
	R7	Repurpose	Recover and use parts for new products with a different function
Close Close resource loops	R8	Recycle	Recover materials with minimum possible degradation of quality and value
	R9	Recover	Incinerate materials for energy recovery

Table 1 - the 9R Framework with definition of resource cycles. Based on Potting et al. (2017) and Bocken et al. (2015)

02.

Renault's circular capabilities by 2030

To design a circular car door concept that aligns realistically with Renault's circular capabilities in 2030, it is essential to understand the future legislative and policy landscape shaping the automotive industry, as well as the actions Renault is already taking towards circularity.

Therefore, the following research question has been formulated:

“What circular capabilities must Renault have by 2030, based on legislation, the policy landscape, and its current circular initiatives?”

To research this a literature review of EU legislation and the policy landscape is conducted, industry experts within Renault and the ‘future is neutral’ are consulted and visits to the Refactory and Indra facilities are performed.

2.1 | The ELV directive

In 2000 the European union launched the first regulations to ensure better handling of ELV's to decrease waste and pollution of the environment (European commission, 2000). This so called ELV Directive (Directive 2000/53/EC) addressed the removal and separation of hazardous substances and components, a ban on using several hazardous substances and introduced extend producer responsibility for delivering a ELV to waste treatment facility. The directive also set the first quantitative targets for vehicle recovery and recycling, both expressed as an average weight per vehicle per year. By 2006, the automotive industry had to meet a reuse & recovery target of at least 85% and a minimum recycling target of 80%. In other words, for every vehicle reaching the end of its life, on average 85% of its weight had to be either reused or recovered, while at least 80% had to be recycled. By 2015, these requirements were tightened further, with the reuse and recovery target raised to 95% of vehicle mass and the recycling target increased to 85% of vehicle mass, again measured as an average weight per vehicle per year (European Commission, 2000).

In 2023 the European Commission proposed a new end-of-life vehicles regulation that builds on the ELV directive of 2000 (European Commission, 2023). The key objective of the proposal is to tackle the lack of circularity in vehicle design and production while improving both the quality and quantity of vehicle waste flows and their treatment processes (Baldassarre et al., 2025). The proposal introduces several new measures. First, it further strengthens the reuse, recovery and recycling targets for each vehicle type although the exact figures have not yet been specified. Second, new vehicles will need to be designed in such a way that authorized treatment facilities can easily remove as many parts and components as possible. Certain specific parts will also be required to be removed prior to shredding. The proposal also sets minimum recycled content requirements for plastics of 25%. The commission is also considering introducing targets for recycled steel and aluminum and its alloys on the basis of a feasibility study which it has to conduct. This is also being considered for other materials like aluminum, magnesium, their alloys and several CRM's to decrease the dependency on imported raw materials (European council, 2025).

2.2 | The Critical Raw Material Act

Next to the ELV directive, the European commission introduced the Critical Raw Material Act in 2024 as a response to the rising risk of supply chain disruption and geopolitical dependency on raw material imports. The CRMA needs to ensure access to a secure and sustainable supply of critical raw materials, enabling Europe to meet its 2030 climate and digital objectives (European commission, 2024). In appendix A a list of the material that are deemed critical by the EU can be found.

The CRMA sets benchmarks for 2030 for different steps along the raw material value chain. The EU must supply:

- at least 10% of the EU's annual consumption for extraction
- at least 40% of the EU's annual consumption for processing
- at least 25% of the EU's annual consumption for recycling
- no more than 65% of the EU's annual consumption from a single third country

The regulation requires EU states to take measures to improve the collection of critical raw material-rich waste and ensure its recycling into secondary critical raw materials. While an overall 25% recycling benchmark has been set for strategic raw materials by 2030, material-specific targets have not yet been established. The Commission has set a requirement for permanent magnets. Targets for other material groups are to be defined through later acts (European Parliament, 2024).

A timeline of both regulations can be seen in figure 6.

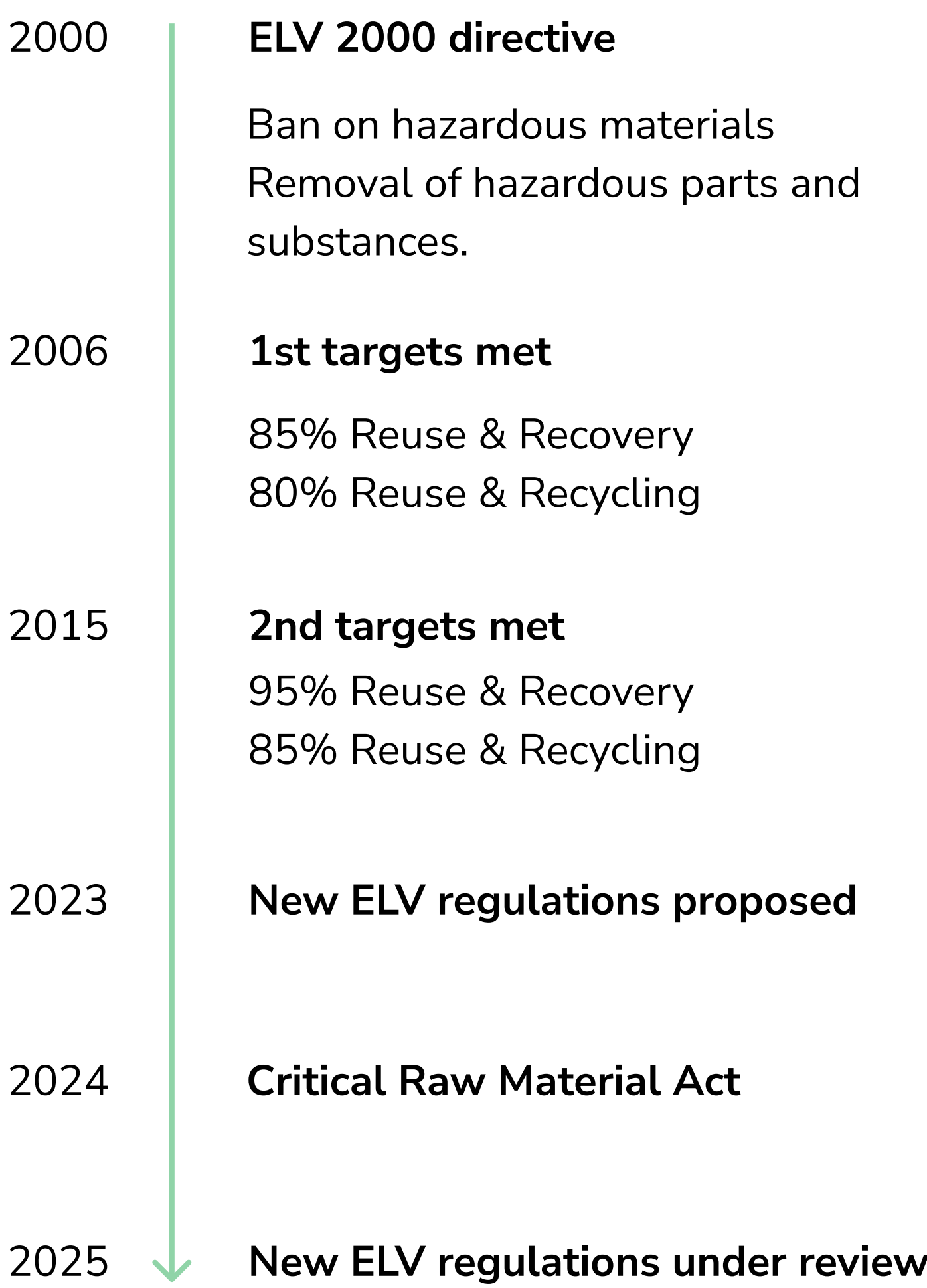


Figure 6 - Timeline of regulations

2.3 | The Future Policy Landscape

The ELV directive and CRMA are still under development. Though both policies can be used to get an insight into what the future policy landscape will look like. Based on this ELV proposal and CRMA, three trends are identified that are stated by the policy although unclear in what form it will take place.

1. Higher end-of-life recycling and recovery targets, expanding to new material groups

Based on the ELV Regulation and CRMA, it is plausible that recovery and recycling targets will tighten and that their scope will widen beyond the existing metric that uses vehicle weight. As shown by the 25% recycling benchmark for strategic raw materials by 2030. This suggests that by 2030 it could no longer be sufficient to recover a percentage of a vehicle's mass, but what material is recovered and how cleanly it is separated will increasingly become more important.

2. Mandatory recycled content requirements in vehicle production

Next to recycling targets at the end of life, as explained in the previous point, the ELV directive and CRMA also put targets on recycled material use in new vehicle production. Manufacturers will face growing mandatory requirements on what recycled material must go into a new vehicle, for now this is only the case for plastics though chapter 2.1 and 2.2 showed multiple signals that targets for more materials can be expected.

3. Stricter product and component design requirements

To achieve the previous two trends, the regulation also taps into the design of new vehicles. The requirement that vehicles need to be designed for easy removal to improve recovery and recycling shows that circular design principles like design for disassembly and material separation will become a regulatory expectation.

2.4 | Renault's circular initiatives

To determine what circular capabilities Renault must have by 2030, it is essential to understand the circular actions that Renault has already performed. The company aims to become net-zero in Europe by 2040 and globally by 2050, with a current focus on increasing recycled content, improving ELV treatment, and scaling remanufacturing activities. Renault has set a target of achieving 33% recycled material content by 2030 (Renault Group, 2024), which exceeds the current proposed minimum of 25% (see chapter 2.1).

However, Renault is investing in a broader system to make Renault a more circular automotive company and are considered an industry leader (Rue et al., 2023). Two major initiatives show this ambition: 'The Future Is NEUTRAL' and 'the Refactory'

2.4.1 The Future is NEUTRAL

The Future is NEUTRAL is a company set up by Renault and Suez, a waste processing company. The Future is NEUTRAL has the goal of creating a fully integrated circular system for the automotive industry (The Future Is Neutral, 2025). Its activities include the collection and dismantling of end-of-life vehicles, which allows parts and materials to be reused, remanufactured or recycled and then reintroduced into the automotive life cycle. The Future is Neutral exists out of several stakeholders which can be seen in figure 7. The overview of the Future is Neutral's operations can be seen in figure 8.

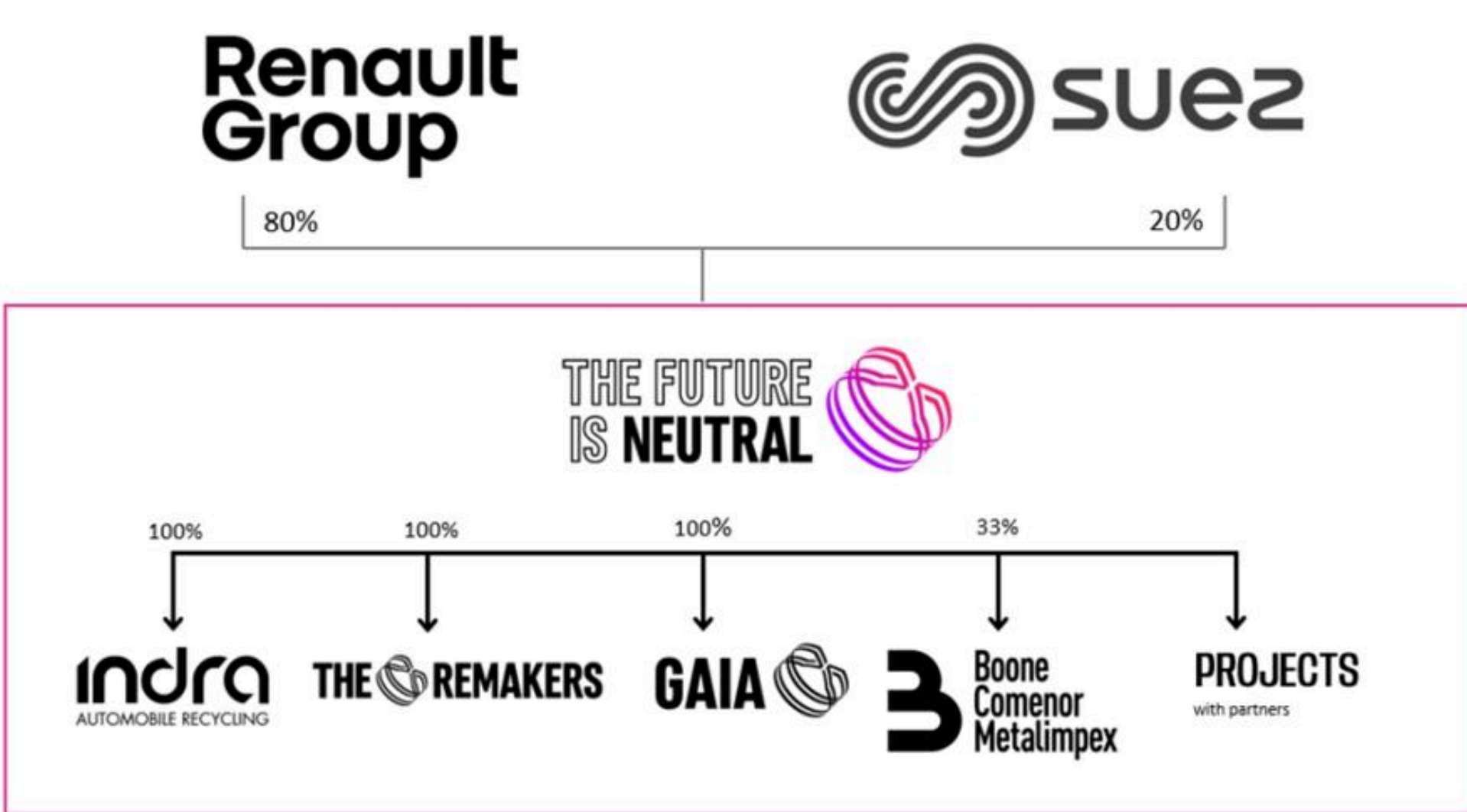


Figure 7 - Overview of stakeholders involved in the Future is Neutral (The Future is NEUTRAL, 2025)

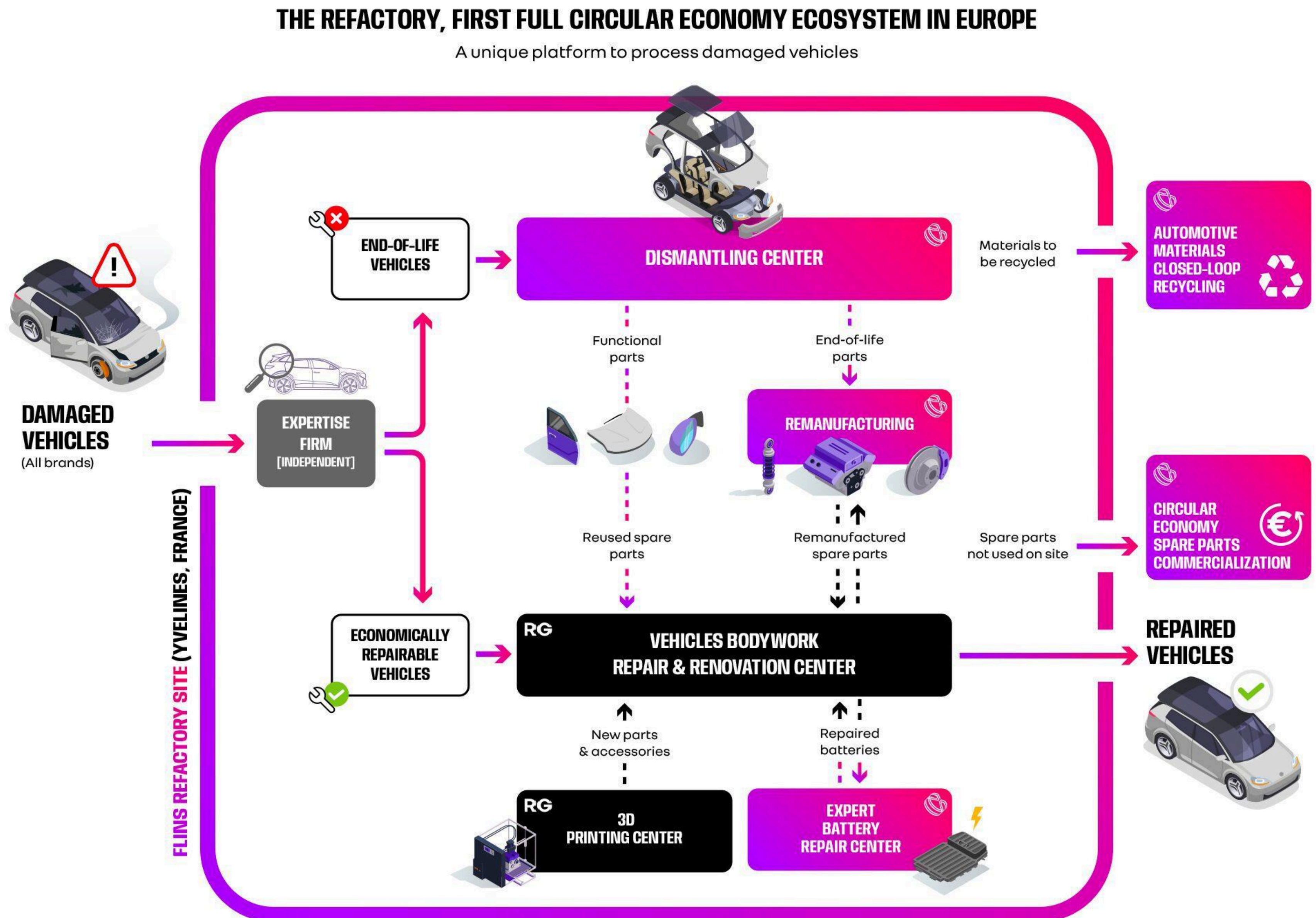


Figure 8 - System overview of the operations of the Future is Neutral (The Future is NEUTRAL, 2025)

2.4.2 The Refactory & The Remakers

The Refactory located in Flins is Europe's first circular economy plant in which ELV's are collected and dismantled. They repair vehicles and batteries to extend their lifespan, refurbish parts to ensure their reuse and recycle raw materials from EoL vehicles. (Renault Group, 2025).

When visiting the 'Refactory' and speaking with the director of the 'Remakers' it became clear that they currently are focusing on five high value components to manufacture: engines, electric motors, turbochargers, gearboxes and batteries. The focus on these components can be explained by the fact that they can achieve the highest economic gain from this and there is a stable aftermarket in place. As a result, remanufacturing is driven not only by environmental goals but also by the profitability and a strong business case. The 'Remakers' will receive a doubling of investments each year until 2030 according to the director. This indicates that the 'Remakers' could scale up their current remanufacturing practices and invest in potential new component categories.

2.4.3 Indra Recycling Facility

Indra is the French leader in vehicle recycling (Indra, 2025) that recycles damaged and ELV's for 14 different automotive brands and operates through a large network of around 300 authorized dismantling centers. INDRA's activities are the collection, dismantling, reuse, and recycling of vehicles that are no longer roadworthy due to crash damage or age of the vehicle. The main goal for Indra is to recycle these ELV's with the full compliance of the ELV directive and while doing so have a profitable operation.

After a visit and interview with Nicolas Paquet it became clear that Indra handles their vehicles in 5 different steps that are shown in figure 9. In chapter 3.4 the disassembly specified to the door and the problems that arise during this disassembly are explained in more detail.

These initiatives show why Renault Group is considered the industry leader in the circular economy. Through The Future is NEUTRAL, the Refactory and its partnership with Indra, the Group is actively building the infrastructure needed for a circular system. End-of-life vehicles are collected, dismantled, and their parts and materials are reused, remanufactured or recycled. However, the current operations also reveal a clear limitation. Remanufacturing at the Remakers remains restricted to five high-value components for which a strong business case exists, while the majority of an end-of-life vehicle is still processed through shredder-based recycling. As described by Paquet, this process results in contaminated material streams and therefore downcycled materials. The following section compares this foundation with the trends identified in chapter 2.3 to determine which circular capabilities Renault Group must still develop by 2030.



Collection

The end-of-life vehicle is collected from its owner, an insurance company, or a professional partner and transported to an authorized treatment facility of Indra. The number of vehicles coming from each "source" is determined by contracts (Paquet, 2025)

Ensuring safety for operators

Before dismantling begins the safety of the operator is ensured by setting of the airbags if needed and stabilizing the vehicle.

Depollution

Mandatory depollution is carried out. Oils and other fluids are extracted, catalytic converters and tires are removed. This step prevents environmental contamination and ensures compliance with the ELV directive.

Targeted dismantling

Targeted dismantling involves the selective removal and sorting of vehicle components based on their final destination. The most valuable parts and materials, or those for which a strong aftermarket exists, are removed. Reusable components are stored until resale, while other parts that can be recycled such as metals, plastics, wiring and bumpers etc. are separated.

Marketing of parts & (shredded) materials

Reuseable secondhand parts are sold to professionals or individuals on the national market. The parts and materials separated for recycling are shredded by Indra or by another recycling partners.

Figure 9 - Overview of Indra's operations.

2.5 | Required circular capabilities for Renault Group by 2030

Chapter 2.4 showed that Renault Group is actively building the foundation for a circular system through The Future is NEUTRAL. However, when this foundation is compared with the three regulatory trends identified in chapter 2.3, gaps become visible between what Renault Group can do today and what regulation will demand by 2030. From this comparison, three circular capabilities emerge.

2.5.1 Capability 1

Capability to recover more materials and components, and separate them more cleanly

The first trend showed that recovery and recycling targets will tighten and could expand towards material-specific requirements. Recycling an end-of-life vehicle by weight will therefore no longer be sufficient. Renault Group has the operational foundation through The Future is NEUTRAL, but Indra's current recycling operations still result in downcycled material streams (chapter 2.4). The recycling process would therefore need to evolve from recovering a percentage of vehicle mass towards recovering specific material groups at sufficient quality. The remanufacturing operations at the Remakers could likewise be scaled to a broader range of components..

2.5.2 Capability 2

Capability to secure recycled material inputs for new vehicle production

The second trend showed that mandatory recycled-content requirements are set for plastics and are likely to expand to steel, aluminium and several critical raw materials. Renault Group must therefore be able to source recycled materials at automotive-grade quality and at the scale of vehicle production. The Group has shown commitment through its target of 33% recycled material plastic content by 2030 (Renault Group, 2024), which exceeds the proposed 25% minimum for plastics, though no comparable plans for other material groups were identified in Renault's public reporting or the interviews conducted. In principle, recycled material inputs could be purchased from external suppliers.

However, closing its own material loop is strategically preferable as it reduces the import dependency the CRMA aims to address and strengthens the business case of The Future is NEUTRAL. This makes the capability directly dependent on the previous capability. The closer end-of-life recovery moves towards clean, material-specific separation, the more of that material can re-enter automotive production as recycled content.

2.5.3 Capability 3

Capability to embed circular design principles into new vehicle development

The third trend showed that circular design principles, such as design for disassembly and material separation, will become a regulatory expectation. This is the capability that the current initiatives address the least. The Future is NEUTRAL operates downstream of the design process, collecting, dismantling and recycling vehicles as they are, but it does only influence to a little extent how they are designed in the first place. The capability needed is the ability to bring circular strategies into the development process itself. The challenge is that these strategies must be weighed against established priorities such as ease of assembly and cost, which are known to conflict with circular design strategies (Shu & Flowers, 1999).

2.5.4 Interdependence of the capabilities

The three capabilities identified depend on each other. Secured recycled inputs depend on clean recovery, and clean recovery depends on what design makes possible. There are multiple routes through which Renault Group could acquire the first two capabilities. One frequently proposed route is the development of more advanced recycling and material-separation technologies (Arpino et al., 2024). However, Soo et al. (2020) point to the limits of this route and argues that although improving recycling technology is one of the most commonly suggested circular strategies, optimising recycling within current practices yields only limited improvements in overall material circularity. Instead, Soo et al. (2020) describe a strong link between how a vehicle is designed and the quality of the material that can be recovered from it. Balkenende et al. (2025) confirm this and argues that product design affects the result of the recycling process and determines to a large extent which materials can be separated from each other, which is essential for high recycling yields.

This makes embedding circular design principles the most important capability for Renault Group to develop by 2030. As long as vehicles are designed without regard for their end of life, better recycling technology can only partially compensate. Investing in circular design strategies, by contrast, can strengthen all three capabilities at once. It enables cleaner recovery, which in turn secures higher-quality recycled inputs. This answers the research question of this chapter. Renault Group must develop the ability to recover and separate more cleanly, to secure recycled material inputs, and to embed circular design principles into vehicle development. This last capability is the condition on which the other two depend.

03.

Car Door Analysis

Chapter 2 concluded that the most important capability for Renault to develop by 2030 is the ability to embed circular design principles into product development. To understand what this means in practice, this chapter analyses a Renault car door at product level. It identifies key problems and opportunities for improvement from a circular design perspective and answers RQ2:

“To what extent is the current Renault car door designed for the circular economy, and which characteristics limit its circular performance?”

The analysis focuses on the door’s functions, component architecture, as well as the process of assembly and disassembly. Data is collected through site visits, physical inspection, and creation of a disassembly map.

3.1 | Functionalities

The main function of a door is to allow people or objects to pass through an aperture, in other words facilitating ingress and egress (Macey and Wardle, 2009). Next to this, door design plays a critical role in providing practical utility and aesthetic expression. Functionally, door systems must balance accessibility, safety, and structural integrity. Aesthetically, they define a vehicle's character and market positioning (Karoliya, 2025).

Early doors were purely designed for ingress and egress of the vehicle. It wasn't until the 1960s that automotive companies started to reinforce them for increased safety. Around the late 1990 the reinforced side impact beam (figure 10) became mandatory to use in all vehicles in Europe (ACEA, 2023). Next to safety the car door saw further innovation through automation of functionalities. In 1974, Kiekert invented central locking, meaning that all doors could be locked or unlocked with the press of one button (Daidalos, z.d.). Next to automated locking, power windows became main stream in the 1980's making it possible to automatically open and close a doors window with a press of a button (Lebeuro, 2023).

Recent innovation in car door design is also about automating functionalities. The rise of electric vehicles accelerated the adoption of retractable handles. These handles sit level with the body panel and extend outward only when needed to decrease drag. The luxury segment of vehicles even offer complete automated opening and closing of doors e.g. in the Mercedes-Benz EQS. The exterior of the door has also undergone an evolution in its aesthetics. Where the door panels of the original Renault 4 (1961) and Renault 5 (1972) were largely flat and straight, with simple, uninterrupted surfaces. The exteriors of their modern successors, the Renault 4 (2025) and Renault 5 (2025)(figure 11), are more sculpted, with sharper angles, creases, and more detailed surfacing. Showing that the door plays an important role in defining the vehicle's identity.

The door has therefore grown more complex not only in function but also in form. Over time, the car door has evolved from a purely mechanical component, serving only ingress and egress, into a multifunctional subsystem. New innovations have steadily added roles to it: structural reinforcement and the side-impact beam added an improved safety function, while central locking, power windows, retractable handles introduced electrified and automated functions. As a result, the modern door brings together mechanical, structural, electronic, and aesthetic functions within a single assembly, making it currently more complex than its early predecessors. Figure 12 shows an overview of all components in a modern door and their individual function.

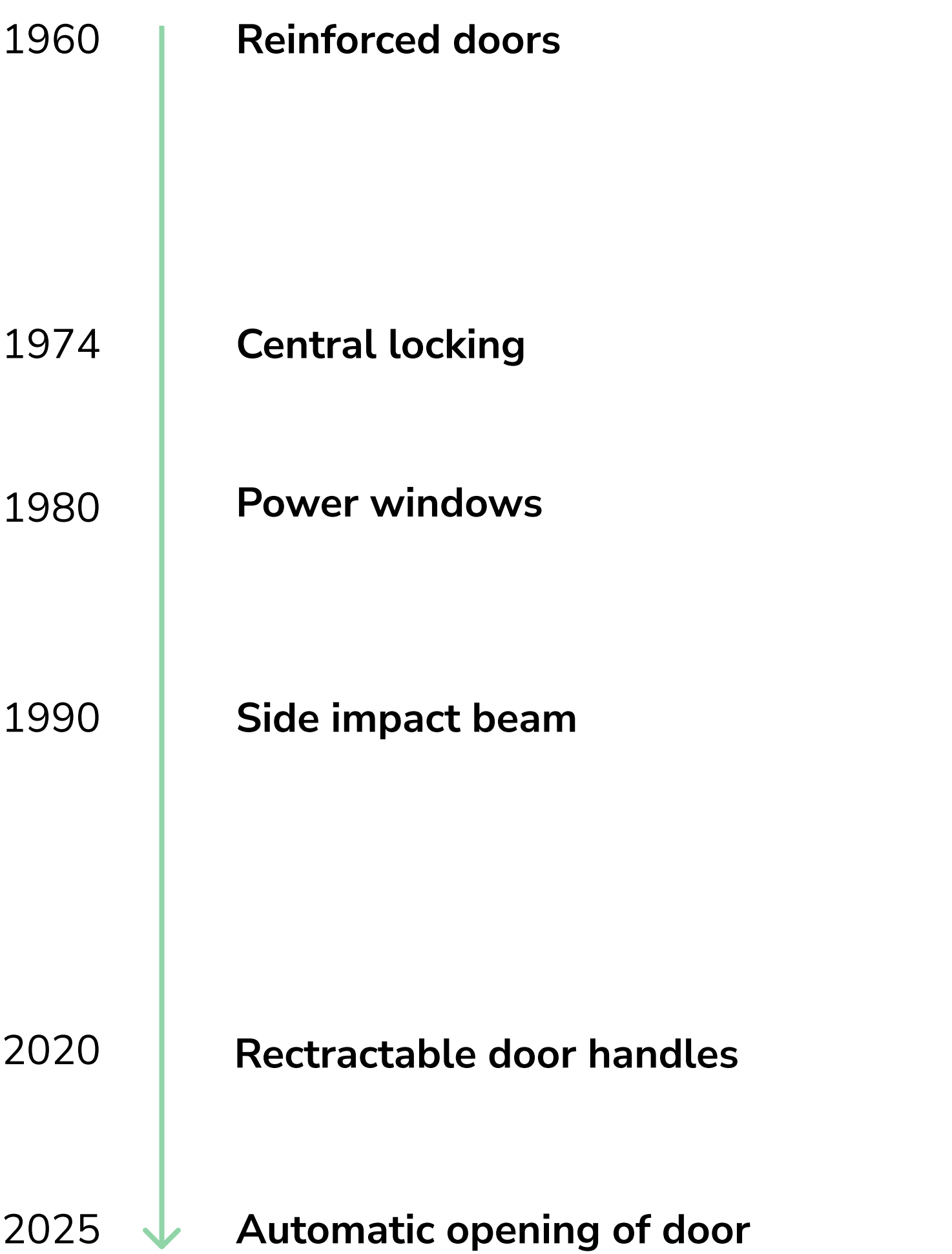


Figure 10 - Overview of the functionalities of a door

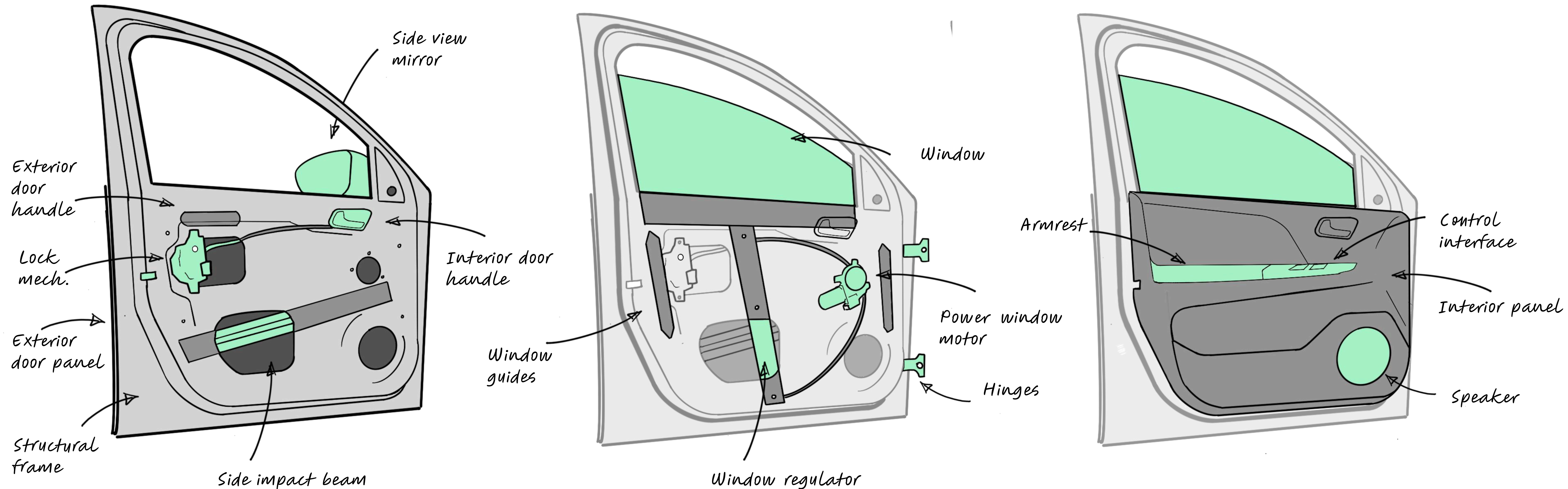


Figure 11 - Renault 4 (2025) left and Renault 4 (1972) right (Renault group, 2025)

3.2 | Door architecture

This section will explore the architecture of the door and material composition of components relevant in the scope of the project.

Figure 12 - Overview of the door's components and their function



Exterior door panel

Outside shell of the car

Side Impact beam

Acts as a shield, safeguards vehicle door from collisions

Structural frame/ Carrier

Internal frame supports placement of several components

Side view mirror

Enables driver to look at the side of the car

Exterior Door handle

Facilitates opening from outside

Interior Door handle

Facilitates opening from inside

Lock Mechanism

Locks and unlocks the door

Door Sealing and Weather-stripping

Function: Protection from rain, air and prevent leaks

Window

Allowing to occupants to look outside

Window regulator

Allowing mechanized movement to open and close window

Power window motor

Allowing rotational movement to open and close window

Wire harness

Connects electronic parts to each other or to the car battery

Window Guides

Guide window during movement

Interior Door panel

Covers the inside parts of car door (wiring, power window motor), allows placement of armrest, controls and aesthetic trim elements.

Control interface

Allows occupants to control certain features in the car e.g windows
In some cars this also contains the Door Control Module.

Speaker

Ensure audio inside the car

Armrest

Allows occupant to rest its arm, often apart of interior panel

Door hinges

Allowing movement of door and connection to chassis

3.2.1 | Components & Functions

Figure 12 shows the car door broken down into three groups of components. This distinction was chosen to show how the different components are integrated into a single assembly. The distinction reveals that the components belonging to each group are not concentrated in one place. They are distributed across the full depth of the door. The locking mechanism, for example, spans from the exterior handle on the outer panel, through the structural frame, to the interior door handle on the interior panel. This makes the door a highly integrated subsystem, in which components are scattered throughout the depth of the door.

3.2.2 Materials and CRM's

Table 2 show the material composition and cost price of each component and indicates whether CRMs are present. The presence of CRMs in these components was determined using internal documents of Renault Group and the list of strategic raw materials of the European commission found in Appendix A. The material composition and costs are based a Renault 5 door using internal documents of Renault Group. As the cost price is confidential information, symbols have been used to give an indication of differences between components.

The table shows that a large variety of materials is used within the door, and that several components contain CRMs: the wiring harness, the speaker, the control module, and the electric motors in several components. These are precisely the material groups facing the 2030 recycling benchmarks introduced by the CRMA (Chapter 2.2), which makes their recoverability from the door a directly relevant design concern.

Components	Materials	CRM present	Cost price
Structural frame	Steel	-	€€€
Side view mirror	Electronic, Steel, plastic	DC motor	€€
Window	Glass	-	€€
Lock mechanism	Electronic, steel, Plastics	DC motor	€€
Window Mechanism	Electronic, steel, Plastics	DC motor	€€
Control interface (including Controle module)	Electronic, Plastics	PCB	€€
Speaker	Electronic, Plastics, magnet	NdFeb Magnet	€
Interior panel (including armrest)	Plastics	-	€€€
Wiring harness	Copper, plastics	Copper	€€
Hinges	Steel	-	€
Sealing	Rubber	-	€€

Table 2 - Overview of components material composition, CRM and indicative cost price

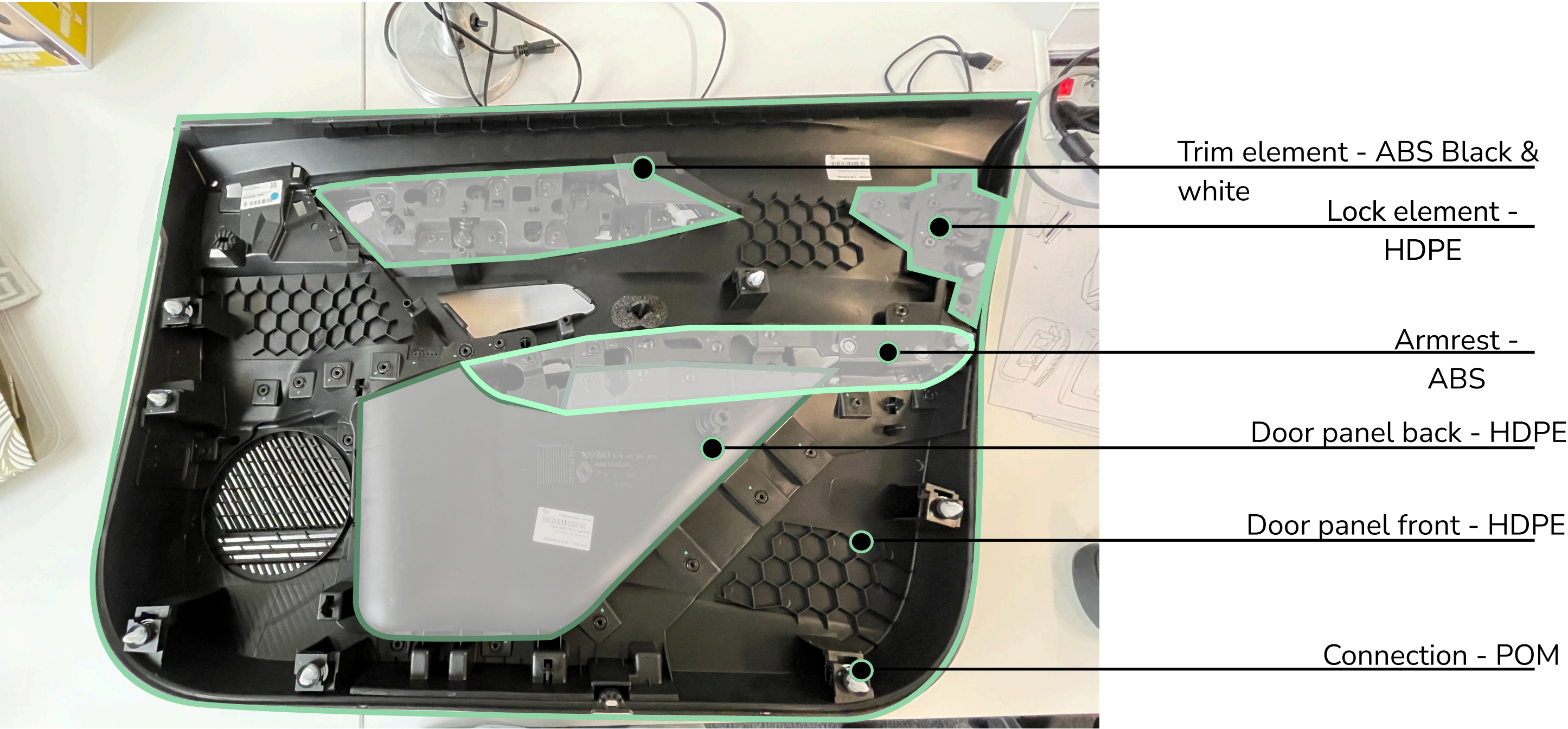


Figure 13 - Analysis of a Renault Clio (2025) interior panel.

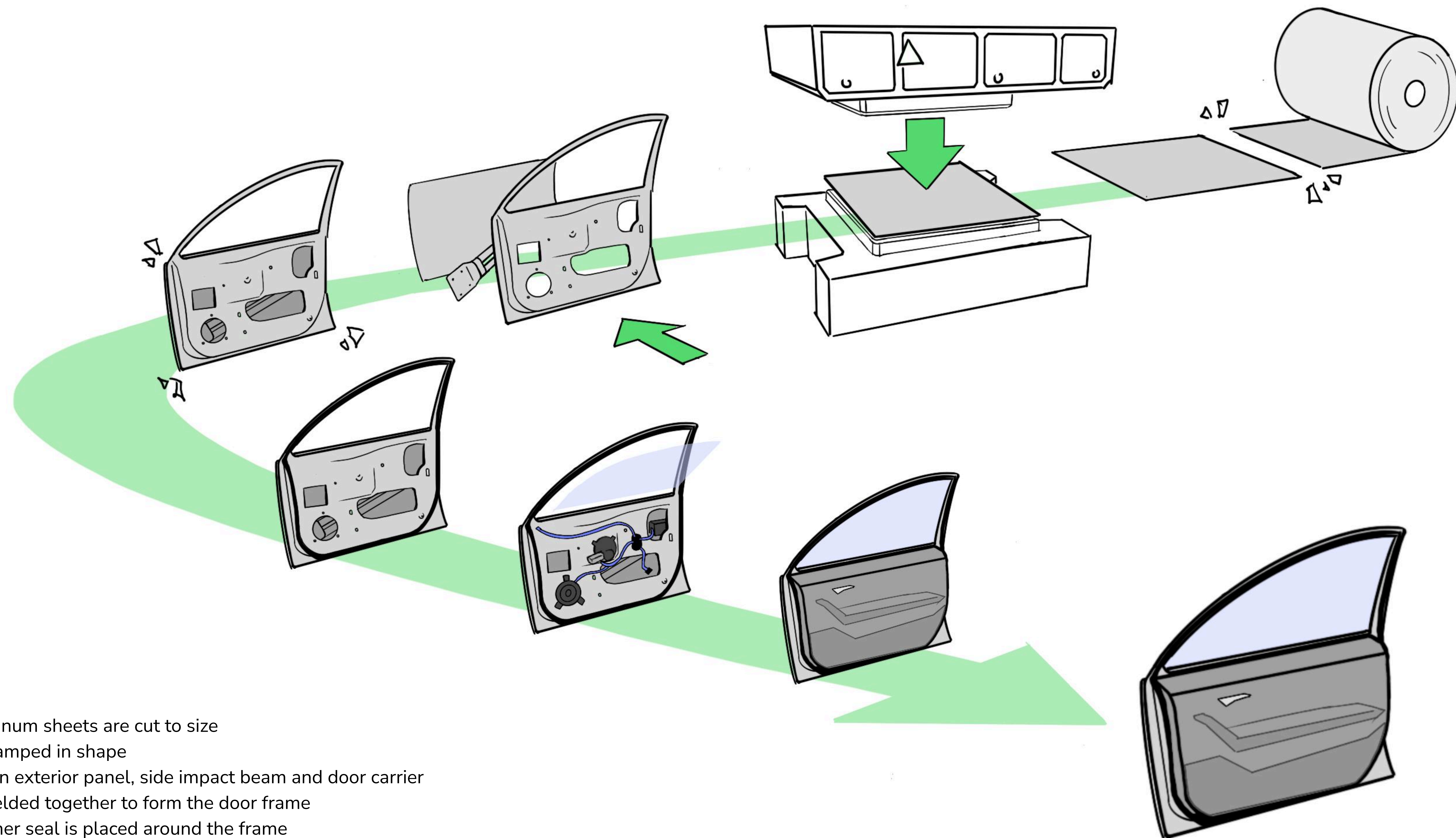
3.2.3 | Material Mixing

To show Renault's current approach to design, a interior panel of the 2025 Renault Clio was analysed. As shown in figure 13, the panel assembly is composed of five different types of plastic. This variety is the result of optimising each part for cost and for the specific functional characteristics it must provide, such as stiffness or surface finish.

The plastic parts are held together by a mix of reversible and irreversible connections. Of the 73 connections identified, 61 are irreversible (Rivets). As a result, the plastic components cannot be separated from one another at the end of life, which contaminates and complicates recycling of the interior panel. This shows that the interior panel is designed primarily from a perspective of cost and robustness, with recyclability left out of consideration.

3.3 | Assembly

A top level overview of the assembly process of a car door can be seen in figure 14. This process is optimized for efficiency and cost optimization.



1. Steel or aluminum sheets are cut to size
2. Sheets are stamped in shape
3. Resulting in an exterior panel, side impact beam and door carrier
4. Panels are welded together to form the door frame
5. Rubber weather seal is placed around the frame
6. Various parts are individually bolted onto the frame and attached to the wiring harness
7. Interior panel is attached to the wiring harness and secured with snapfits and screws
8. Features of the door are tested

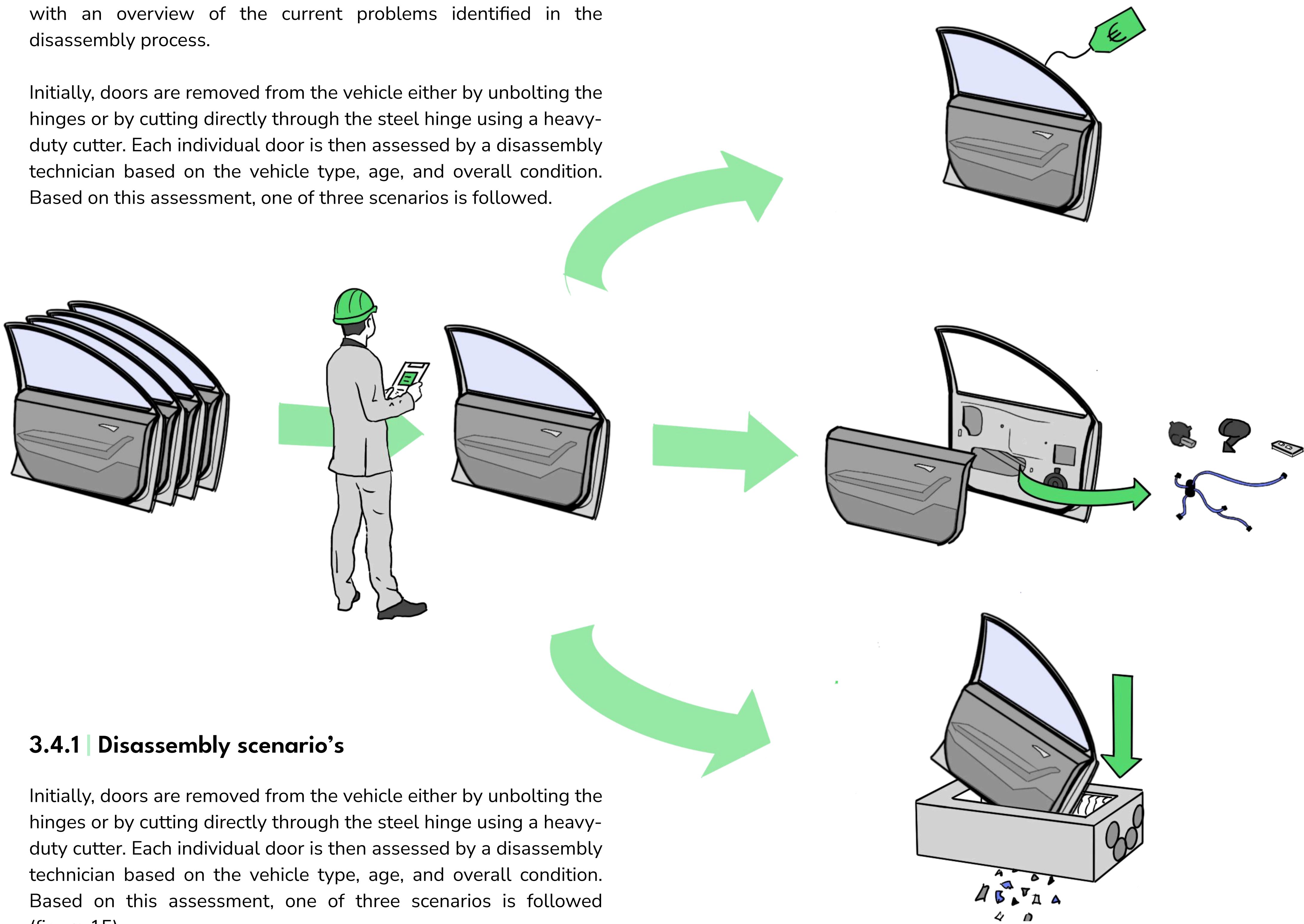
Figure 14 - Overview of a door's production process.

3.4 | Disassembly

Sections 3.1 to 3.3 described how the door is composed and how it is assembled. This section examines what happens to the door once a vehicle reaches its end of life. Based on a facility visit, it describes the steps followed in practice and the different scenarios that determine how each door is handled. This section concludes with an overview of the current problems identified in the disassembly process.

Initially, doors are removed from the vehicle either by unbolting the hinges or by cutting directly through the steel hinge using a heavy-duty cutter. Each individual door is then assessed by a disassembly technician based on the vehicle type, age, and overall condition. Based on this assessment, one of three scenarios is followed.

Figure 15 - Overview the different disassembly scenario's at Indra.



3.4.1 | Disassembly scenario's

Initially, doors are removed from the vehicle either by unbolting the hinges or by cutting directly through the steel hinge using a heavy-duty cutter. Each individual door is then assessed by a disassembly technician based on the vehicle type, age, and overall condition. Based on this assessment, one of three scenarios is followed (figure 15).

1. Full Door Resale

If the door is in good condition and sufficient aftermarket demand exists, the door is sold in its entirety as a spare part

2. Part Harvesting

When the estimated value of specific components is high enough to be worthwhile, part harvesting is performed. The components typically removed include the copper wiring harness, side-view mirror, window glass, control interface, and window mechanism including the window motor (figure 16). These parts are harvested either for their material value, such as the copper content, or because they have a strong individual aftermarket. Components that are too labor-intensive or technically complex to remove, lack sufficient aftermarket demand, or have little to no material value are left in place. The remaining door frame is then shredded to recycle the aluminum or steel content with a lower quality.

3. Full Door Shredding

When the door is deemed to have a low remaining value in its entirety. In loose parts or material, it can be chosen to shred the entire door without disassembling any parts. In this case, the door is recycled for the steel and aluminum with a lower quality as well.



3.4.2 Problems at Indra

The site visit and interview with Nicolas Paquet revealed two main problems in the current end-of-life treatment of the door. The first concerns which components are recovered. The second concerns the quality of the material that is recycled. Both are described below.

Disassembly time and the aftermarket availability determine which parts are extracted

The main factors limiting component recovery are disassembly time and the lack of an aftermarket. Components are often buried behind multiple layers of the interior panel and structure or are fastened in a complex way, meaning that accessing them requires considerable disassembly time. This is shown in more detail in chapter 3.6. This is largely because vehicles are not designed with end-of-life disassembly in mind. As a result, the time required to extract certain parts outweighs their estimated value, making it unprofitable to harvest them. This reflects findings by Tian and Chen (2016), who show that fully dismantling a vehicle is rarely the most economical option and that dismantlers must selectively recover only the components whose value justifies the disassembly effort.

Copper degrades the quality of the recycled aluminum or steel

A key problem in the current shredding process is copper contamination. As noted by Paquet, the copper wiring harness is cut out of the vehicle during disassembly. Though traces of this wiring harness and other copper containing components often remain in the frame. As copper attaches to steel during shredding, it degrades the quality of the recycled steel and aluminum (Daehn et al., 2017). This causes the material to be downcycled.

Daehn et al. (2017), Sandbag. (2025) and Paquet identify further disassembly of copper containing components before shredding as one of the solutions to this problem, next to the development of more advanced recycling techniques. This suggests that a more complete removal of the wiring harness and electric motors before shredding could improve the quality of the recycled steel and aluminum.



Figure 16 - Images of disassembled doors and the recovered components at Indra (top). Left to right: Wiring harnesses, Side view mirrors, Control interfaces and Window mechanisms.

3.5 | Component value

Chapter 3.4 showed that a component is only removed when its value is high enough, and its disassembly time low enough, to make recovery worthwhile. What that value actually is, however, remains unclear. This section therefore assesses the value held in the door's components along two dimensions: what they are worth as functional parts on the aftermarket, and what they are worth as shredded material.

3.5.1 | Component value

A value assessment is performed to understand which components within the door hold either economic value as a functional part or hold material value as a recycled material. To answer this, each component identified in chapter 3.1 is assessed against two dimensions. Its reuse market value (the value a part has as a functional part on spare part aftermarket) and it's material value (the value recoverable if the components were shredded and the material sold as commodity). The comparison can be seen in table 3.

Reuse values show the indicative price ranges of a Renault Clio from 2010- 2014 on European spare part platforms showing the highest and lowest price observed at the time of writing. These values have been verified by a mechanic. Estimation of material values are calculated using weights from a database of Renault of a R5 door and the EU commodity prices for the relevant material. It should be noted that the material values presented are favorable estimates: where a price range was available, the highest was used, aluminum prices were used in preference to steel, Next to this no material losses during the shredding and recycling process were taken into account as the full weight of the components were used. This comparison excludes operation costs for both recycling and disassembly of components.

Part	Material	Reuse value low	High	Weight	Price/kg	Material value
Door frame	Alu	66,00 €	150,00 €	15,381	1,15 €	17,69 €
Side view mirror	Glass, Plastic	20,00 €	203,00 €	1,637	0,42 €	0,69 €
Lock	Mixed electronics	35,00 €	132,00 €	0,386	1,15 €	0,44 €
Window	Glass	23,00 €	55,00 €	3,116		unknown
Window mechanism & Motor	Mixed electronics	55,00 €	98,00 €	0,636	1,15 €	0,73 €
Window sealing	Rubber	4,00 €	13,00 €	1,08		unknown
Wiring harness	Copper	23,00 €	70,00 €	0,453	7,20 €	3,26 €
Interior panel	Mixed plastics (PP)	15,00 €	125,00 €	2,75	0,42 €	1,16 €
Control interface	Plastics (PP)	12,00 €	76,00 €	0,067	0,42 €	0,03 €
Speaker	Mixed electronics	3,00 €	10,00 €	0,147	0,42 €	0,06 €
Interior door handle	Plastics (PP)	6,00 €	38,00 €	0,093	0,42 €	0,04 €
Hinges	Steel	7,00 €	34,00 €	0,022	0,15 €	0,00 €
		269,00 €	1.004,00 €			24,10 €

Table 3 - Value assesment of component's reuse value vs material value.

3.5.2 | Results

Table 3 shows a big contrast between the total reuse value and material value that can be achieved. The total reuse value of the door ranges from €269 in a pessimistic scenario to €1,004 in an optimistic scenario against a total material value of approximately €24. This means that shredding the door for its material value, destroys between 91% and 97% of its potential value at it's end of life. This shows the principle of the value hill discussed in chapter 1.6 in full effect. The value assessment shows that a large amount of value is held in the door's components. Section 3.4, however, showed that this value is rarely captured, because the decision to extract a component is determined not by its value alone but also by the disassembly time. Whether the components value can be recovered therefore depends on how easily and fast the components can be harvested. The following section examines this.

3.6 | Assessment of current car doors

To assess how easy components can be harvested from a car door two car doors were disassembled completely (figure 18 and 19). The hotspot mapping tool developed by Flipsen et al. (2020) and a disassembly map based on the methodology of De Fazio et al. (2021) were used. Ideally, three doors would be analyzed for comparison (De Fazio et al, 2021). However, due to time constraints during the visit to Indra, only two doors could be disassembled.

3.6.1 | Hotspot Parts

To identify the target components for the disassembly map, the hotspot mapping tool proposed by Flipsen et al. (2020) was used. This tool identifies target components by means of hotspot indicators. The following indicators can be applied:

- Economic indicator,
- Environmental indicator,
- Failure indicator/ Priority status It indicates the components with the highest failure rate or functional importance

In table 4 an overview of which part has which indicator can be seen. The economic indicators have been determined by the hotspot mapping tool and the findings of chapter 3.5. The environmental indicators have been determined by the hotspot mapping tool. The components relevant for the priority indicator have been selected based on failure rate and functional importance, following the approach recommended by Flipsen et al. (2020)

3.6.2 | Disassembly Map Structure

A summary of the structure can be seen in figure 17.

Building blocks

The disassembly map consists of two main elements: parts and activities. Parts are represented by circles containing a part number (1), which corresponds to the part name listed in the parts list. The part list is located in a legend. Disassembly activities are represented by rectangular boxes that indicate the type of connection being loosened and the tools that are used. The color of each box represents the level of force required to perform the activity (2).

Linear and parallel disassembly

The disassembly map uses two types of sequences: Linear and parallel. In a linear sequence, you must remove parts in a specific order (3). For example, you have to remove part A before you can remove part B. In a parallel sequence, you can remove two parts in any order you like (4). This is also known as the OR relationship (Steffner, 2021)

And/OR sequence

Parallel sequences can also require you to remove two parts that are side by side in order to reach a part underneath them. This is called an 'and'-relationship. Unlike the previous 'or'-logic, here you absolutely must remove both parts, you cannot skip either one. However, just like before, you can still remove them in any order you choose just like the OR relationship. As shown in example (7), an 'or'-relationship indicates two accessible parts, A & B, which need to be removed to fulfil a following 'and'-relationship to remove part C (Steffner, 2021).



Components	Economic indicator	Environmental indicator	Priority part
Structure	Target	Target	
Wiring harness	Target	Target	Target
Window Motor			Target
Control interface			Target
Side view mirror			Target
Locking mechanism			Target

Table 4 - Overview of target components.

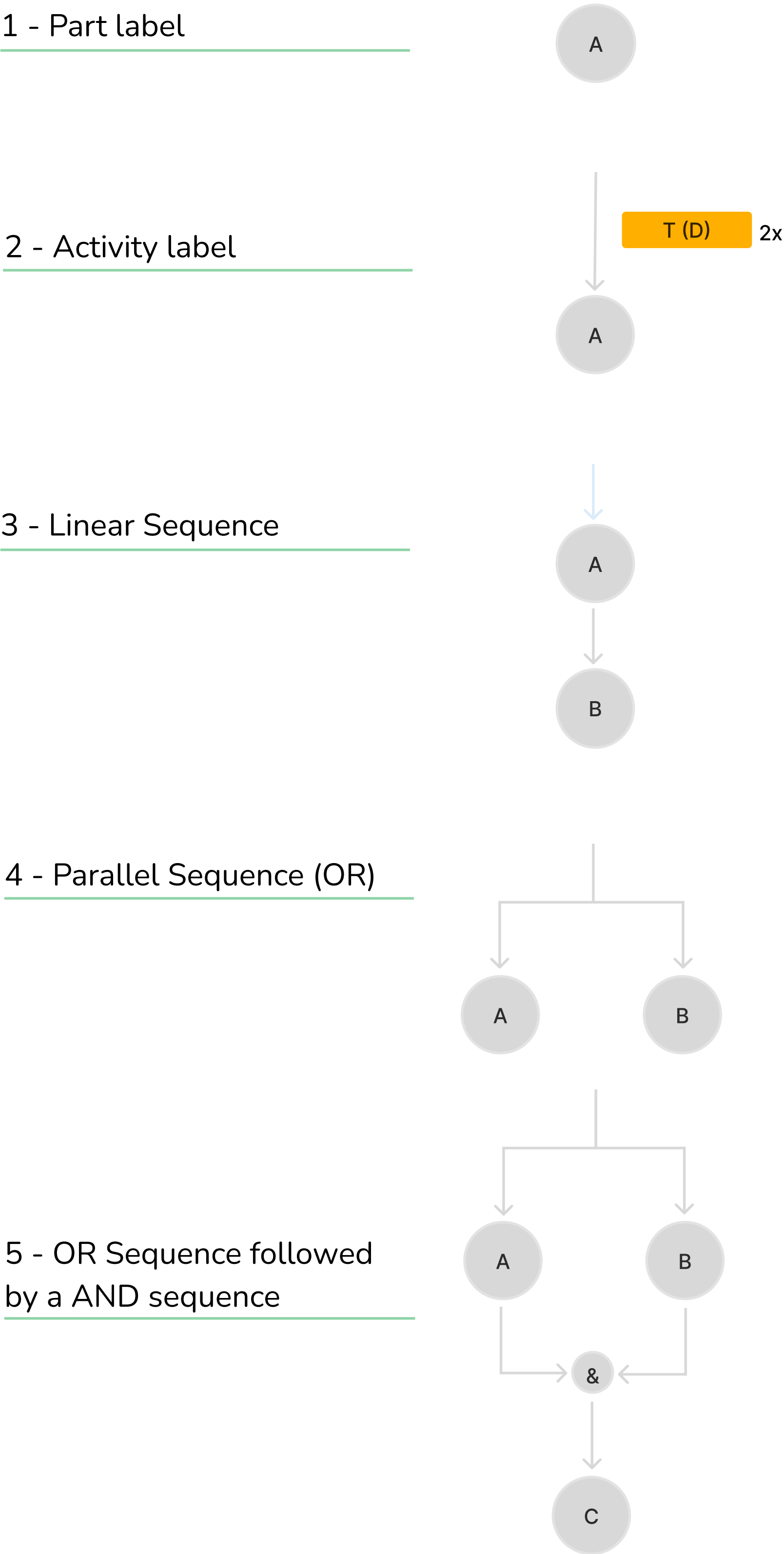


Figure 17 - Overview disassembly map structure based on (Vermaat 2020)

3.6.3 | Penalties

According to De Fazio et al (2021) and Flipsen et al (2020) 6 different penalties can be given to each step that complicates disassembly. The penalties are shown in the disassembly map by either an icon located next to the disassembly step or by color of the activity box (only for ‘force intensity’). An overview of the penalties can be seen in table 5.

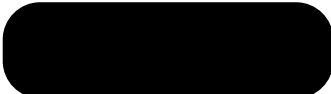
	Force intensive: the action requires considerable force and the use of both hands or moving the entire arm (over 20N)
	Time intensive: the action requires more than 1 minute to complete
	Product Manipulation: Manipulation of moderate weight of product or moving around it
	Low visibility: Hidden connector, difficult to reach with tool or to identify
	Non reuseable connector: Connector is not reusable after a first disassembly

Table 5 - Overview of penalties icons and explanation.

Door A



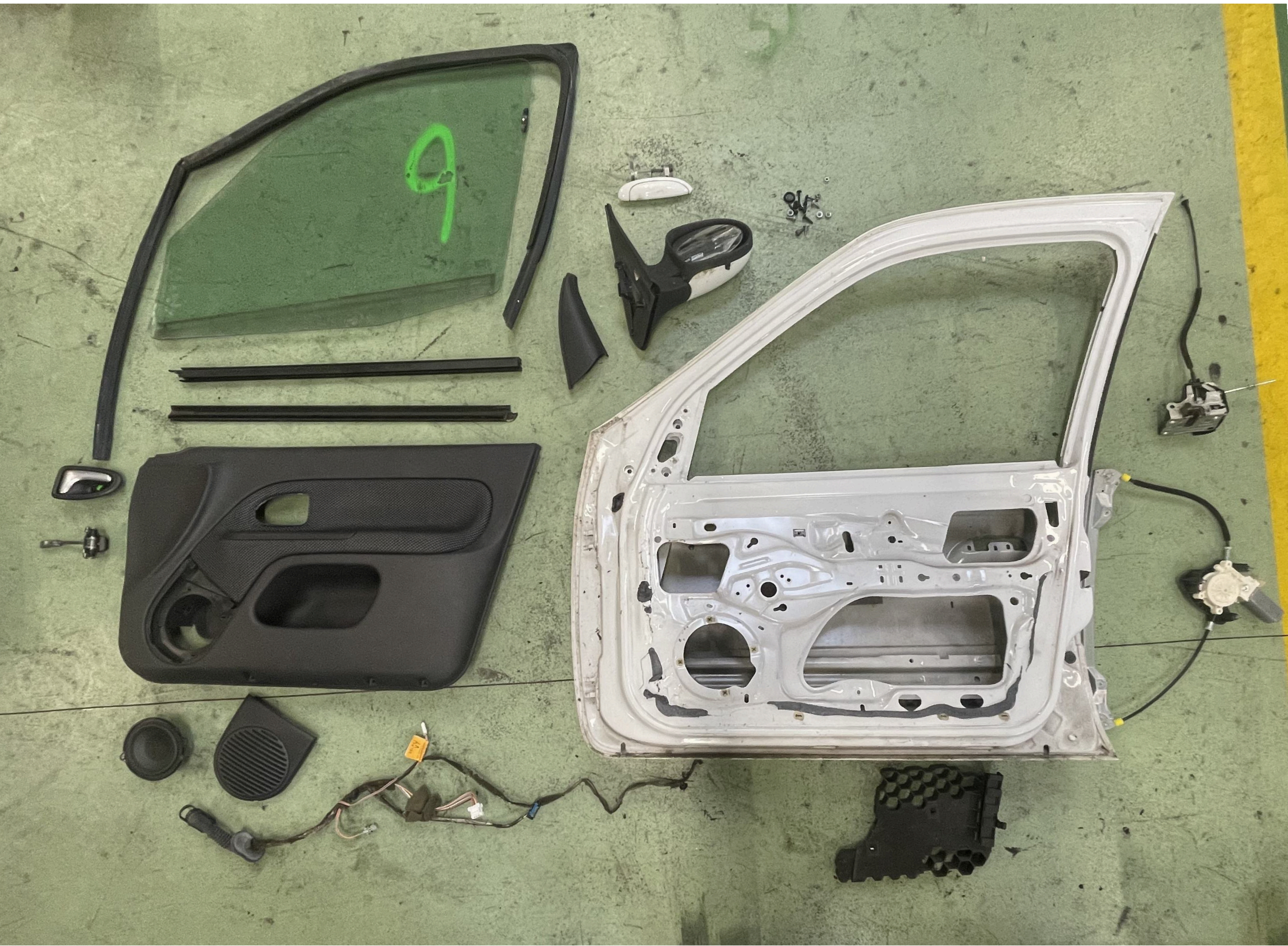
Figure 18 - Image of Door A, Renault Clio (2004)

Door B



Figure 19 - Image of Door B, Renault Espace (2005)

Door A



Components

- 1. Hinge support
- 2. Side view mirror cap
- 3. Screw cap side view mirror
- 4. Speaker cap
- 5. Interior handle
- 6. Side view mirror
- 7. Speaker
- 8. Interior panel
- 9. Wiring harness
- 10. Windowmechanism
- 11. Lock
- 12. Exterior handle
- 13. Horizontal window sealing strips
- 14. Electronic window control
- 15. Window guider
- 16. Window Sealing
- 17. Window
- 18. Structure

Motion type

= Hand motion

= Single motion tool

= Multiple motion tool

Type of tool

(H) = Hand

(Sc) = Screwdriver

(Sp) = Spudger

(D) = Drill

Force intensity

Low

Medium

High

Penalties

= Product manipulation

= Low visibility

= Uncommon tool

= non reusable connector

Connectors

S. F. = Snap fit

F. F. = Friction fit

C. Plug = Cable Plug

Push B = Push button

Torx = Torx screw

Adh. = Adhesive

Target components

= Failure indicator

= Environmental indicator

= Economic indicator

Figure 20 - Door A disassembled and legend of disassembly map

Door A

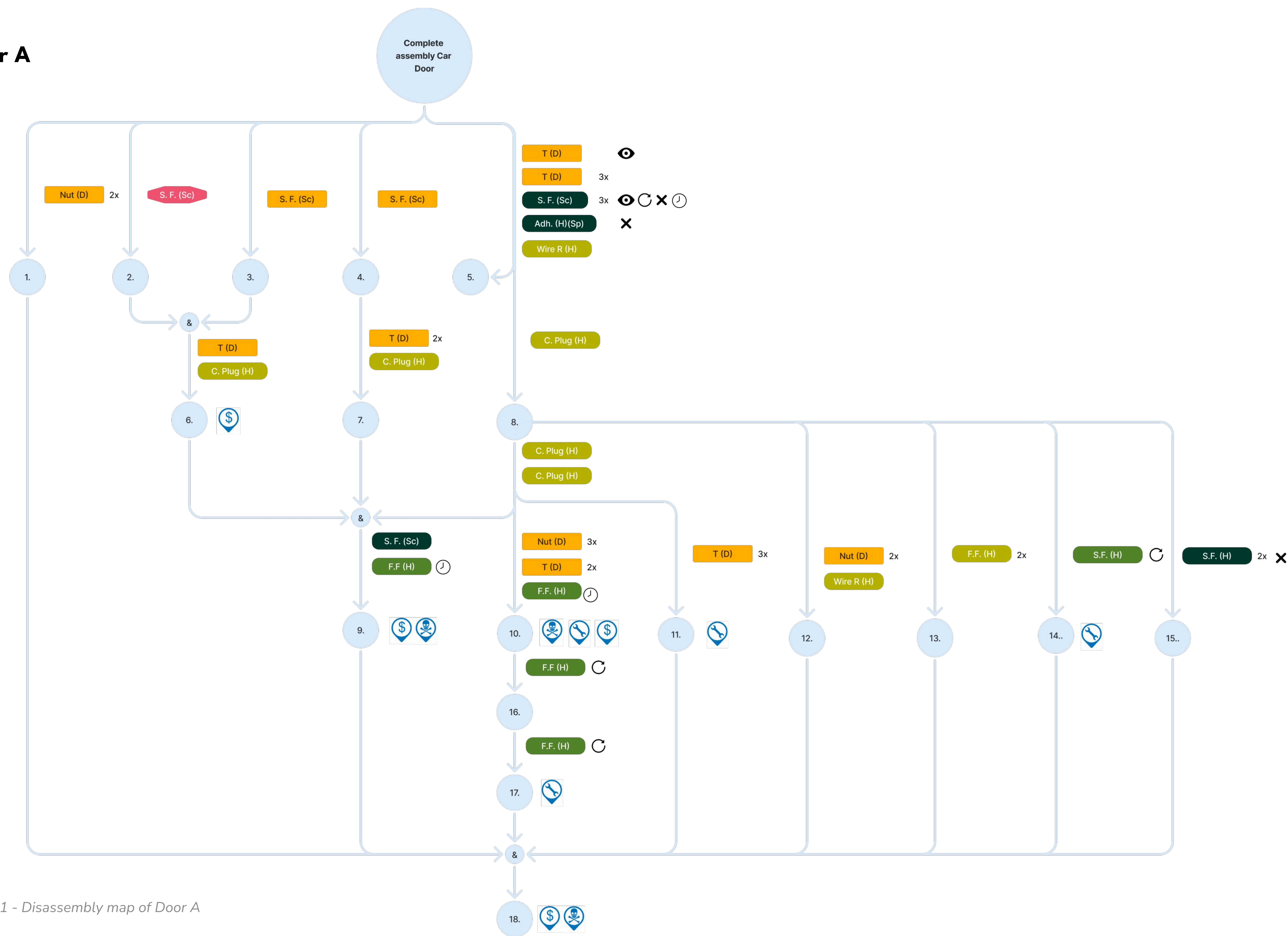


Figure 21 - Disassembly map of Door A

Door B



Components

- 1. Hinge support
- 2. Side view mirror cap
- 3. Screw cap side view mirror
- 4. Speaker cap
- 5. Interior handle
- 6. Side view mirror
- 7. Speaker
- 8. Interior panel
- 9. Wiring harness
- 10. Windowmechanism
- 11. Lock
- 12. Exterior handle
- 13. Horizontal window sealing strips
- 14. Electronic window control
- 15. Window guider
- 16. Window Sealing
- 17. Window
- 18. Structure

Motion type

= Hand motion

= Single motion tool

= Multiple motion tool

Type of tool

(H) = Hand

(Sc) = Screwdriver

(Sp) = Spudger

(D) = Drill

Force intensity

Low	Medium	High

Penalties

= Product manipulation

= Low visibility

= Uncommon tool

= non reusable connector

Connectors

S. F. = Snap fit

F. F. = Friction fit

C. Plug = Cable Plug

Push B = Push button

Torx = Torx screw

Adh. = Adhesive

Target components

= Failure indicator

= Environmental indicator

= Economic indicator

Figure 22 - Door B disassembled and legend of disassembly map

Door B

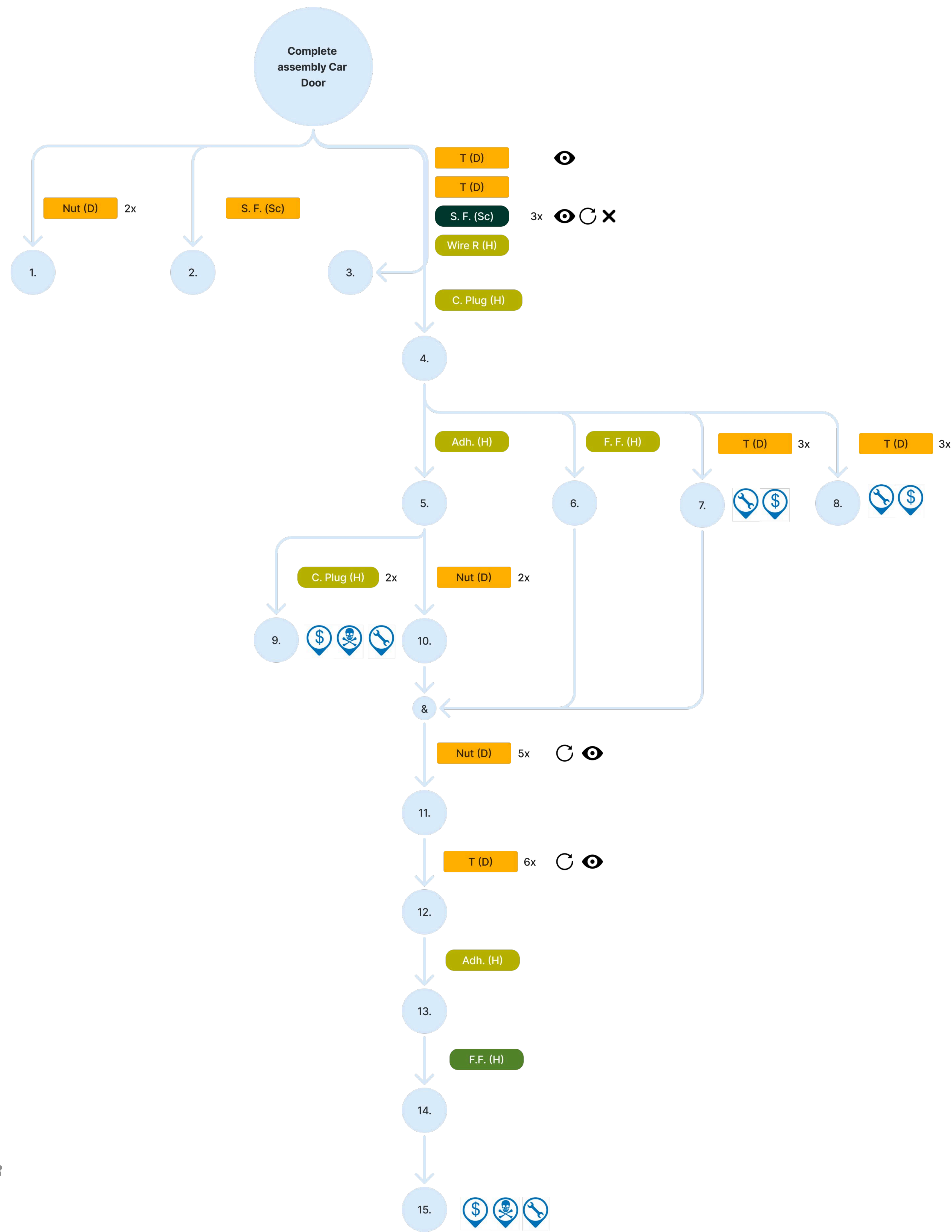


Figure 23 - Disassembly map of Door B

3.6.4 | Results

Figures 20 to 23 show the disassembly map created for door A and B. In this section the results will be explained.

The interior panel obstructs access to components

For both doors, the interior panel proved to be one of the most challenging components to disassemble (figures 24 & 25). Both Door A and Door B required multiple different activities to complete its removal (four activities for Door A and five for Door B) and both incurred multiple penalties. The activities included unfastening screws, releasing snap-fit connections, detaching adhesive bonds, disconnecting a cable attached to interior door handle and disconnecting a cable plug. Several penalties were given during this process and were consistent for both doors. Some screws were hidden behind caps or were difficult to see at the edge of the interior panel, resulting in a low visibility penalty. The release of the snap-fit connections required large force and repeated product manipulations, resulting in a force intensive penalty and a product manipulation penalty. The force exerted on the panel resulted in broken snap-fits in both doors, for which a non-reusable connector penalty was assigned. This step was observed to be the most time-consuming activity across the entire disassembly process of both doors, resulting in a time intensive penalty.

Target components are deep in disassembly tree

In both doors, almost all target components with an economic, environmental, or priority indicator are located deep in the disassembly tree, meaning a significant number of steps must be completed before they can be reached. In both doors, most components were fastened using screws or bolts, though five different sizes were used across the assembly, requiring frequent tool changes during disassembly (figure 26). The window mechanism received a product manipulation penalty in both doors, as its size and weight made it difficult to handle during removal. A clear structural difference can be seen between the two doors. Door A shows a parallel sequence, while door B follows a more linear one. This distinction is relevant as a parallel structure allows access to multiple components simultaneously. This reduces the total number of linear steps required to reach the target components. Door A is in that regard more favorable. Though, in both doors all components are individually bolted or screwed to the frame, meaning each part must be unfastened separately, which limits the speed and efficiency of the disassembly process massively.



Figure 24 - Process of removing the interior panel Door A



Figure 25 - Process of removing the interior panel Door B

Cable plugs complicate removal of the wiring harness

When removing the wiring harness, several cables were difficult to detach in both doors. This likely explains why Indra cuts the wiring harness loose from the plug (chapter 3.4) rather than disconnecting it properly, as this saves time during the disassembly process.

Limited access to parts within the structure.

Several components are mounted inside the frame, which has only narrow openings (figure 27). This results in poor accessibility and low visibility. Removing parts like the locking mechanism and window mechanism was therefor time-intensive and required repeated product manipulations.

Clean frame requires significant action.

To achieve a completely clean steel/aluminum door frame, 28 activities were performed for Door A and 16 for door B. In the case of Door B, the lock, exterior door handle, and frame could not be fully separated without risking destructive disassembly, and due to time constraints these components were left as a remaining subassembly. This indicates that even with considerable effort, a fully clean frame cannot always be achieved.



Figure 26 - Different bolts and screw used for Door A



Figure 27 - Narrow opening marked in blue.

3.7 | Conclusion

The analysis of the car door across its architecture, assembly, industrial disassembly, complete disassembly and component value show that the door is currently not designed for the circular economy.

The door is not designed for disassembly.

The door is a complex subsystem in which components are scattered throughout the doors depth. As the disassembly map shows, almost all target components sit deep in the disassembly tree, requiring a significant number of sequential steps before they can be reached. Once accessible, components are fastened individually sometimes with different connectors requiring tool changes and therefore increasing the disassembly time. With the interior panel being one of the largest obstacles.

This complexity is the result of a design process oriented entirely toward ease of assembly and cost optimization, with no consideration for disassembly and what happens at the end of life.

Disassembly time and aftermarket availability reinforce each other negatively.

At Indra the decision whether to extract a component is decided by two factors: the time required to remove it and the availability of an aftermarket. Because the door is difficult to disassemble, extraction is slow and therefore costly. As a result, only parts or materials with a sufficiently high and reliable aftermarket value are removed or recycled.

Right now, these two factors reinforce each other negatively, parts are not extracted because no aftermarket exists, and no aftermarket develops because parts are not extracted. This suggests that if disassembly time could be reduced, it may become more worthwhile to extract a greater number of parts. This could strengthen aftermarkets and increase the amount of parts that are reused and can improve recycling quality as components that contaminate the recycling stream can be extracted as well.

Recycling destroys economic value.

The component value assessment shows that the reuse value of the door's components is considerably higher than their material value. Although this comparison relies on several assumptions and should be read as indicative rather than exact. Though the difference is large enough to show a clear pattern: shredding the door for its materials recovers only a fraction of the value built into it through design, engineering, and manufacturing. This confirms the principle of the value hill. Recycling is the least favourable of the circular strategies, because it discards the functional and economic value still held in the components.

04.

Core insights & Concepts

This chapter bridges the analysis phase and the design phase of the project. It first presents the core insights, which bring together the findings of Chapters 2 and 3 into the central problem this is called the circularity gap. These insights are then translated into three concept directions, each focusing on a different circular strategy. Together, they form the foundation for the final concept and to answer RQ3:

“How can circular strategies be applied to the design of a car door to improve its circular impact within Renault's 2030 context?”

4.1 | Core Insights - The Circularity Gap

The analysis phase approached the project from two directions. Chapter 2 examined circularity at the level of policy and corporate strategy. It identified three capabilities Renault Group must develop by 2030 to meet upcoming regulations and showed that Renault Group is already an industry leader in pursuing a circular system. Through The Future is Neutral, Renault Group is actively building the infrastructure, logistics, and partnerships needed for a circular system.

Chapter 3 examined circularity at the product level and reached a contrasting conclusion. The car door is not designed for the circular system Renault Group is building. Components are difficult and labour-intensive to disassemble. Next to this poor material separation causes recycling operations to result in downcycled material. While the ambition to become more circular is present, the products feeding the circular system are far from optimised for it.

This is the circularity gap. Renault Group's ambition and circular infrastructure are in place, but the products entering that system are not built to take advantage of it. This does not only limit Renault Group's circular impact but also limits exploring and strengthening business model opportunities through The Future is Neutral. Closing the gap requires intervention at the product level: the door must be redesigned. To achieve a higher circular impact, Renault Group should both enable higher R-strategies and improve its current recycling strategy. The condition on which both depend is disassembly that is fast and clean.

Fast.

Chapter 3.4 showed that at Indra the decision to extract a component is an economic one. A part is only harvested when its expected resale or material value exceeds the cost of the time required to remove it. Because target components in the current door sit deep in the disassembly tree and are individually mounted, this calculation fails for most parts. Which results in the fact that functional target components are shredded along with the frame. In this case disassembly time therefor determines which R-strategies are economically viable at all. This is also supported by literature as reducing disassembly time and its related costs directly increases the economic feasibility of reuse, repair and remanufacturing. (Vanegas et al. 2018).

Clean.

Cleanliness concerns the quality of what disassembly yields, which in turn determines the quality of the recycling that follows. In the case of the door it can operate on two levels: the purity or grade of the recovered material fractions and the integrity of the recovered components.

At the material level, materials must be separated into homogeneous fractions to achieve high recovery yields and avoid downcycling (Faludi et al., 2025). In the current door this separation fails. Copper from the wiring harness and electric motors remains in the door during shredding, contaminating the steel and aluminium streams and forcing the recovered metal to be downcycled (Daehn et al., 2017, Chapter 3.4). Disassembly is the one of the means to achieve this separation. By removing contaminating components before shredding, disassembly can substantially increase both the yield and the purity of recycling streams (Vanegas et al., 2018). Clean disassembly, in this sense, means disassembly that is complete enough to deliver homogeneous material fractions.

At the component level, clean means non-destructive. Dismantling can be categorised as destructive or non-destructive, depending on whether parts are damaged or retain their completeness during separation (Tian & Chen, 2016). Since remanufacturing requires returning components to a like-new condition, a component that is damaged during disassembly loses the very value that reuse and remanufacturing are meant to retain. A window motor that is recovered quickly but broken in the process has been removed, not recovered.

In the current door, these two requirements are in direct trade-off. Speed is bought through destructive or partial disassembly, while clean disassembly costs time that the recovered value rarely justifies. The analysis in Chapter 3 shows this trade-off in practice. Indra cuts the wiring harness loose rather than disconnecting its plugs and components that are too time-consuming to reach are simply left in place. Fast but not clean. Conversely, the complete disassembly performed in Chapter 3.6 required 28 activities to obtain a clean frame for Door A, while for Door B a clean frame could not be achieved at all without destructive action. Clean, but far too slow to be viable at industrial scale. This conflict is also seen in literature as Design strategies aimed at end-of-life recovery have been found to conflict both with one another and with established priorities such as design for assembly (Shu & Flowers, 1999).

The aim of this project is therefore to find a solution for this conflict. To design a door that enables disassembly which is both fast, opening up higher R-strategies through viable component recovery. And clean, enabling higher-purity recycling by separating contaminating materials before shredding.

These insights are translated into three concept directions. Each direction addresses a different resource cycle and responds to the insight in a different way: Concept A narrows resource flows, reducing what must be disassembled in the first place; Concept B slows resource flows by making component recovery fast enough to be viable; and Concept C closes resource flows by making material separation clean enough to prevent downcycling.

4.2 | Concept directions

As explained in Chapter 1.6 the circular economy can be described through three resource cycles: narrowing resource flows, slowing resource, and closing resource flows (Bocken et al., 2016). A truly circular product cannot rely on a single one of these principles, it requires advances across all three, considering the full lifecycle from production to end-of-life. Bocken and Geradts (2022) make a similar point at the level of strategy, arguing that circular strategies realise their full potential only when combined.

Rather than attempting to address all three strategies at once, this project first develops three separate concept directions. Each deliberately focusing on one strategy while still using the insights of chapter 4.1 (figure 28). Concept A explores narrowing: reducing material and component use at the start of the lifecycle and lowering how much must be disassembled in the first place. Concept B explores slowing: it targets fast disassembly, extending the life of components by making their recovery quick enough to be viable for reuse and remanufacturing. Concept C explores closing: it targets clean recycling, improving the purity of recycled material streams by separating contaminating components before shredding.

This separation is a choice, not a claim that any one concept is circular on its own. Isolating each strategy makes the design implications of each strategy visible and gives Renault Group a clear, holistic overview of the circular strategies available for the car door. The three concepts share a common design element: each introduces a module in which certain components are grouped. How this module is configured and how it contributes to circularity differs in each.

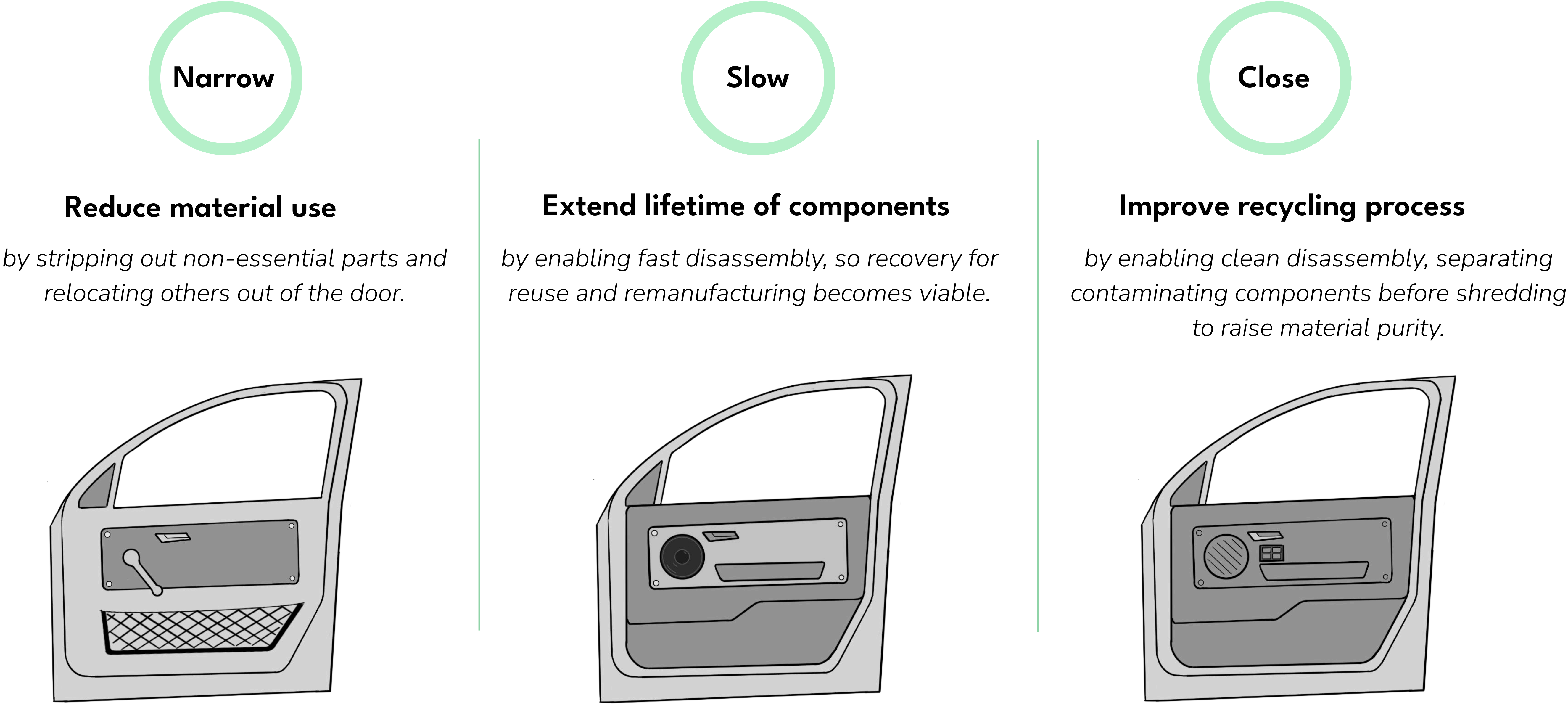


Figure 28 - Overview of concept directions

4.3 | Strategy A - Reduce

Goal:

Redesign the door to use the minimum of materials and components. Non-essential functions are removed or relocated. Components with CRM's are removed as much as possible. The structural frame is exposed where possible, eliminating the need for a full interior panel. Circular impact is at the beginning of the lifecycle, narrowing resource loops.

Removed / Relocated

- Speaker - to center console
- Armrest - to seat
- Interior panel - partly removed

Components in module

- Window crank
- Interior door handle

Key benefits

- Large CO₂ reduction through lower material use and manufacturing energy
- Lower manufacturing costs

Barriers

- Potential increase in road noise
- Limited consumer acceptance

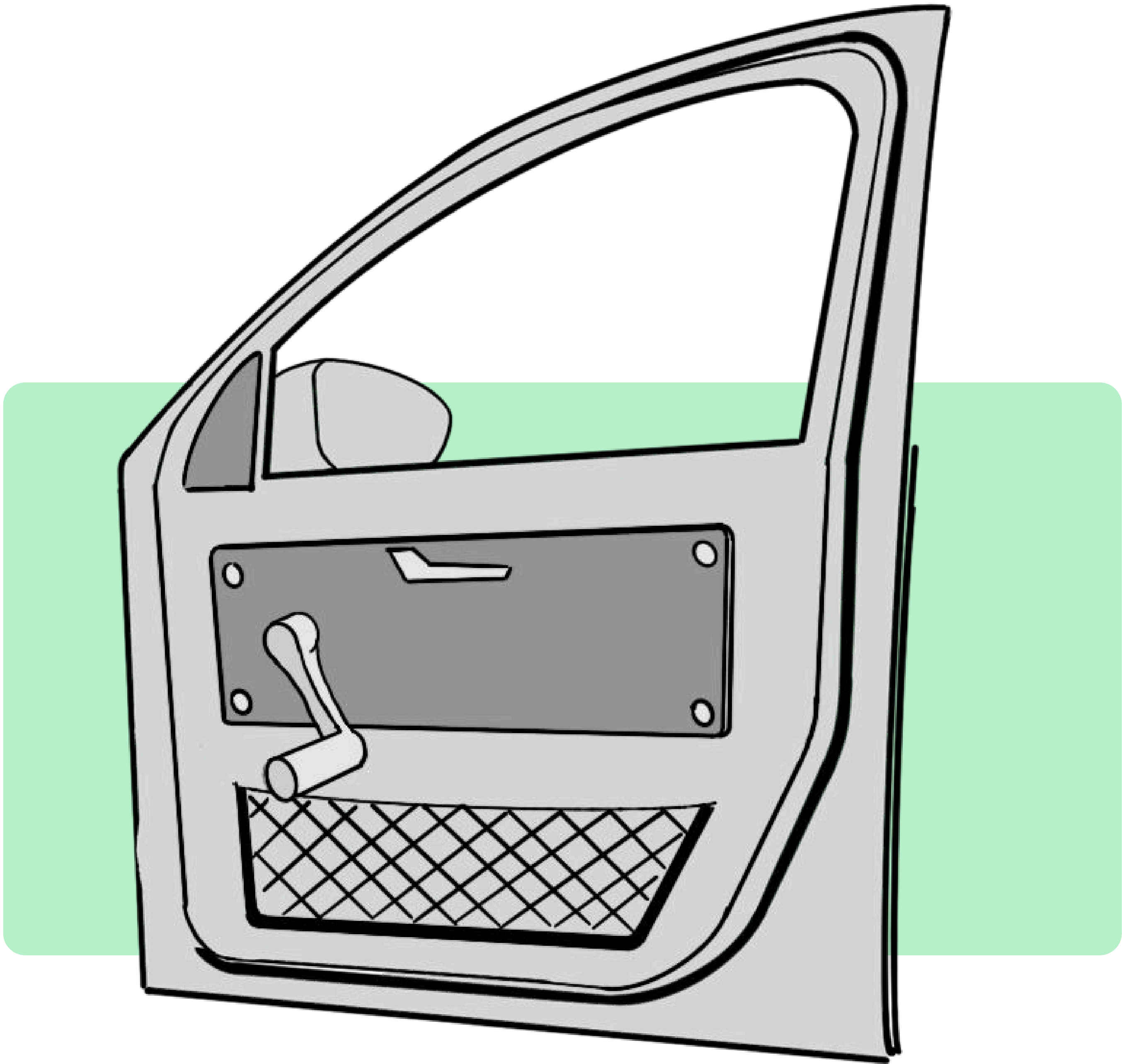
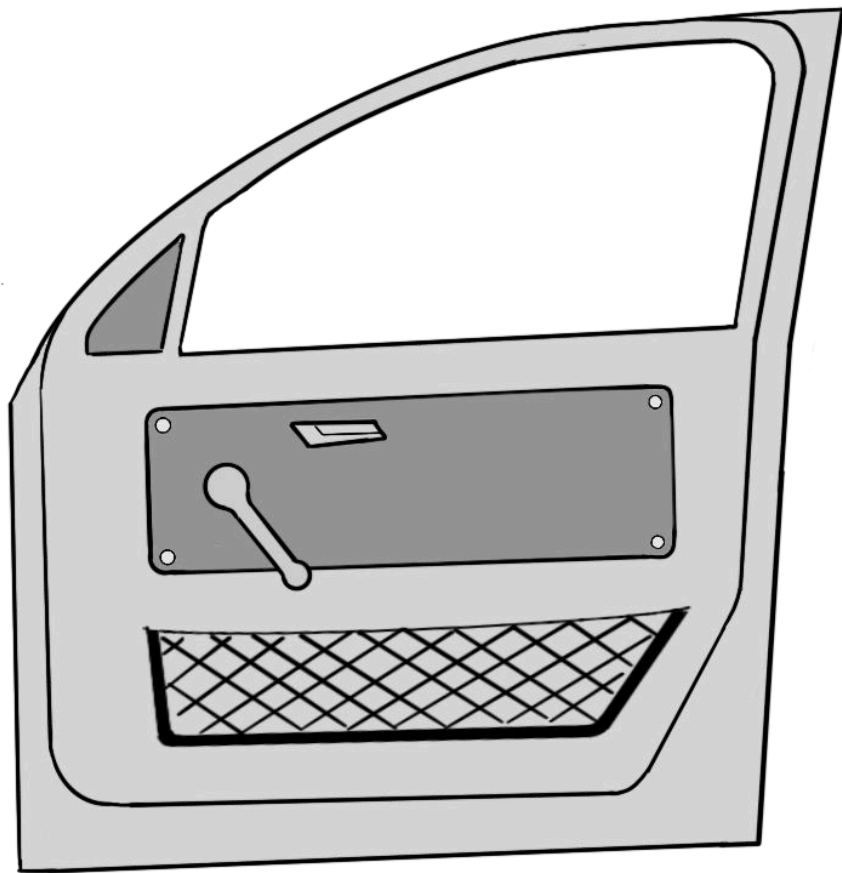


Figure 29 - Summary of Concept A - Reduce

4.3.1 | Design strategy

The Reduce concept (figure 29) applies two strategies from the 9R framework: R0 Refuse and R2 Reduce. R0 is applied by refusing components that introduce CRM's into the door assembly replacing them with simpler alternatives or relocating them out of the door entirely. R2 is applied by reducing the material use of the components that remain. Together, these design decisions result in a door that consumes fewer natural resources and less energy in production which could drive manufacturing costs down. Next to this it generates less complex waste at the door's end-of-life.

4.3.2 | Removed and relocated components

Three components are removed or relocated in this concept based on their function or their material composition.

The armrest is removed from the door and relocated to the seat. The soft foam and fabric of the armrest are more in line with the materials already present in the seat than with the steel and aluminum structure of the door, making the seat a more natural place for this component.

The speaker is relocated to the center console, this is done for two reasons. First, by removing the speaker from the door it limits the amount of REE's in the door assembly as the speaker contains magnets. Second, by relocating the speaker the total length of the copper wiring harness can be reduced.

The interior trim panel is partially removed and replaced by a much smaller surface panel, big enough to house the interior door handle and window crank and to conceal the internal frame structure. This single design decision has two circular benefits. First, it reduces the polypropylene content of the door assembly. Second, it improves the disassembly of the interior panel which was identified as the single most time-intensive activity during disassembly in chapter 3.6. The reduced panel is fastened with clearly visible, standardized bolts, replacing the snap-fit connections. This reduction of the interior panel could lead to an increase in road noise as the structural frame is now part of the interior.

4.3.3 | Components in module

Two components remain in the module: the window mechanism and the door handle.

Hand Crank

For the window mechanism, three options were considered. Retaining the electric window motor would introduce an electric motor containing CRM's, and additional copper wiring into the assembly. A vent mechanism would eliminate these elements but as this mechanism tilts the window open partially it is less desired. A manual hand crank is therefore chosen, as it allows the window to be fully opened without introducing any electronic components or CRM's into the door.

Door handle

The door handle facilitates one of the core functions of the door, opening and closing. And therefore it cannot be removed. Though it is reduced to simple strap which requires minimal material.

4.4 | Strategy B - Reuse & Remanufacturing

Goal:

Redesign the door to recover and use or remanufacture components to extend the lifetime of these components. Several components are clumped into a single module and can be removed in a simple operation at its EoL. This module can then be reused entirely or components can individually be disassembled and reused or remanufactured in other doors. The circular impact is at the middle of the lifecycle as components are kept at their highest value for as long as possible.

Components in module

- Interior door handle
- Speaker
- Window motor
- Armrest
- Control interface

Key benefits

- Reduces disassembly time and costs
- Creates opportunities for value retention through reuse and remanufacturing

Barriers

- Extra investments in reuse and manufacturing operations
- Potential increase in manufacturing costs
- Aftermarket development

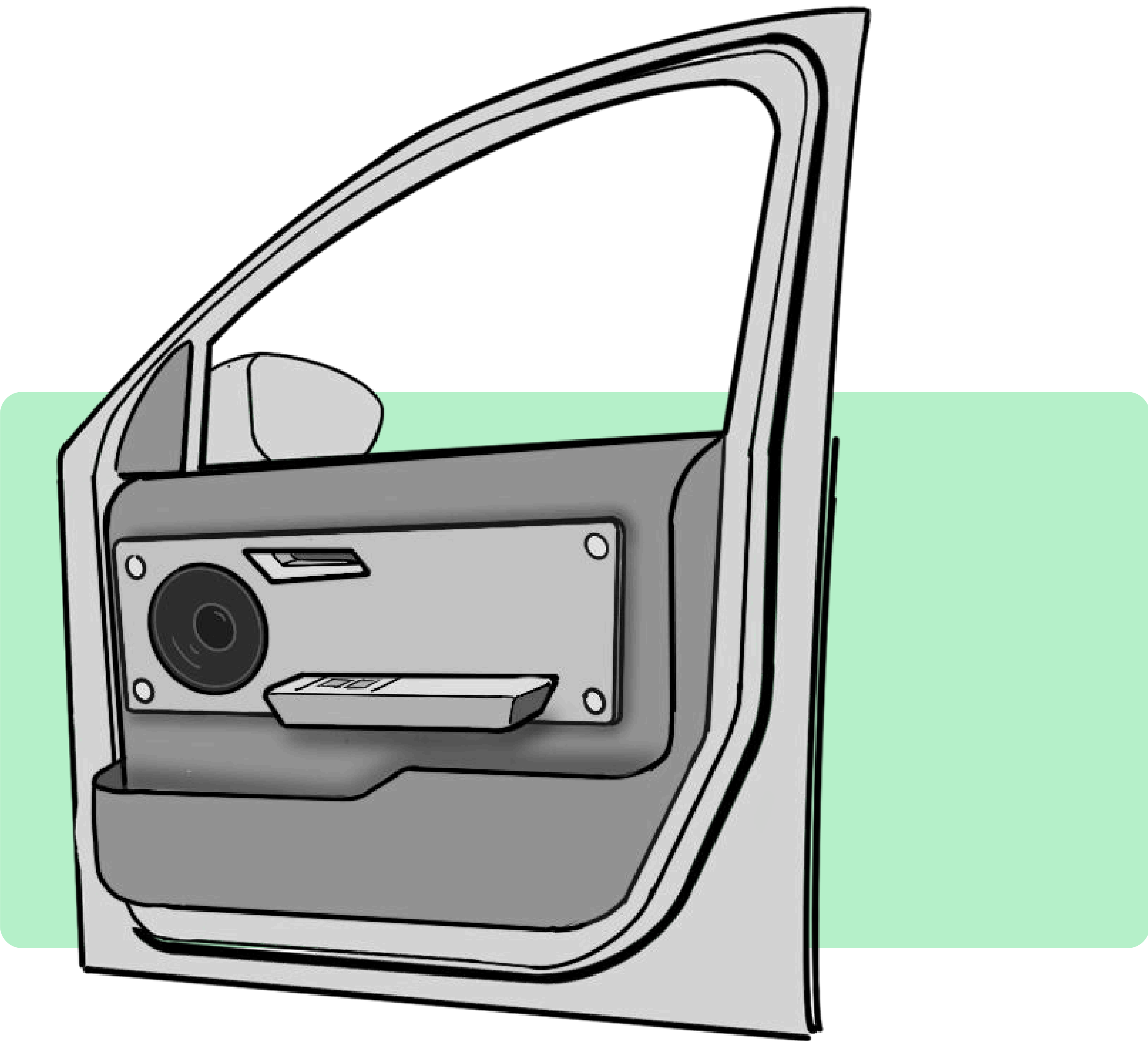
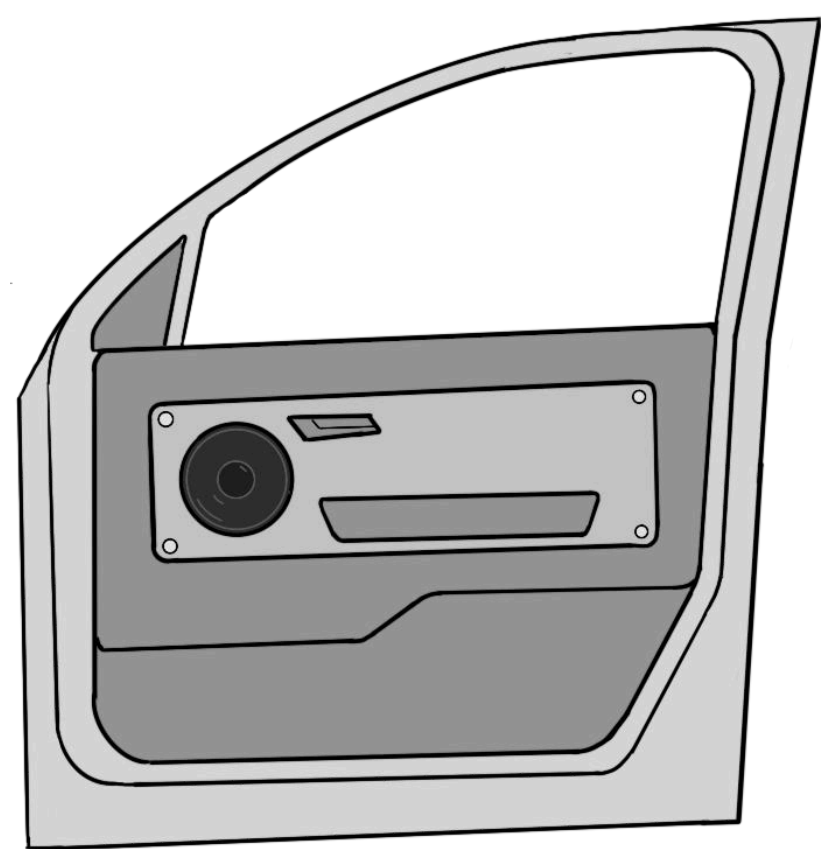
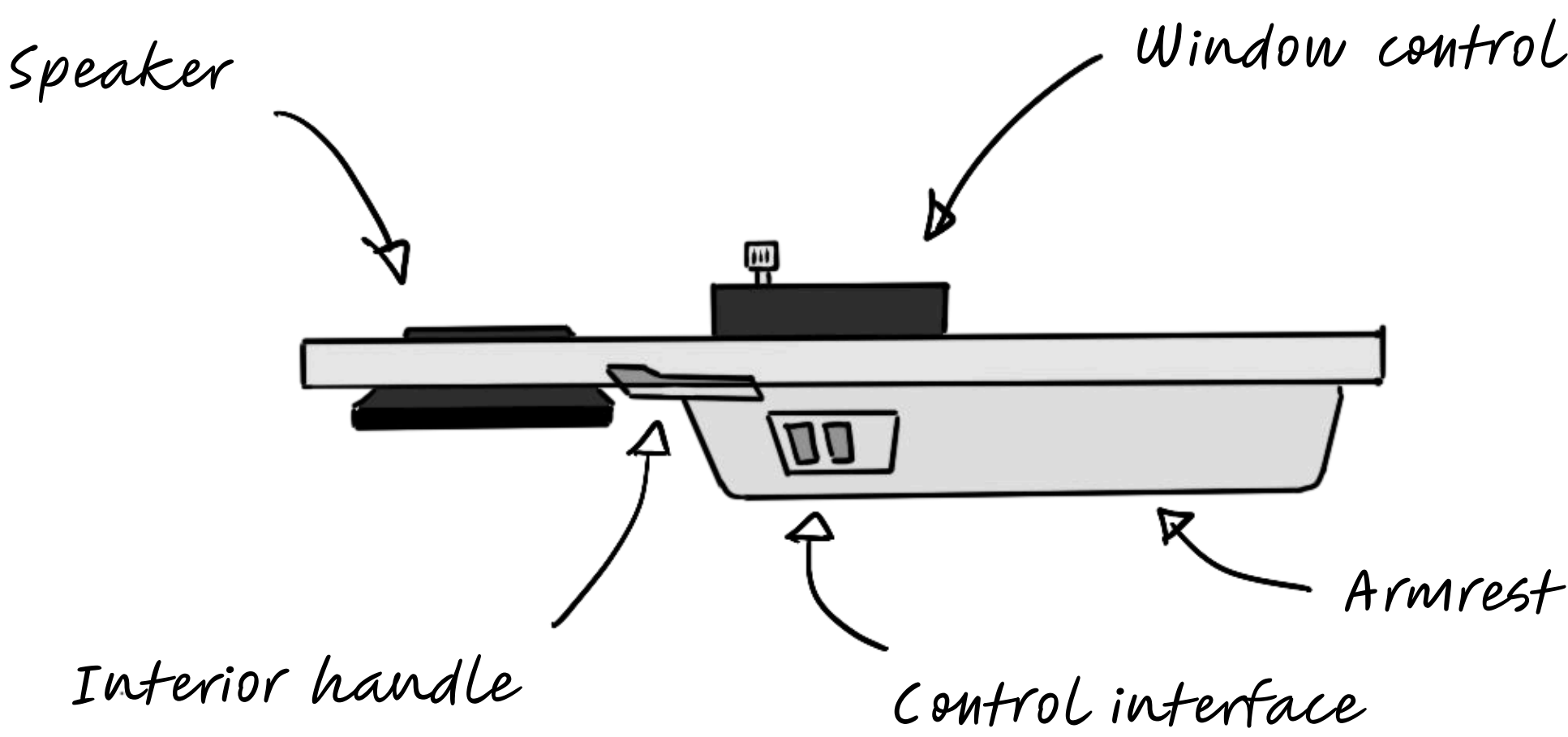


Figure 30 - Summary of Concept B - Reuse & Remanufacture

4.4.1 | Design strategy

This concept focusses on extending the lifecycle of components by applying R-strategies at the mid-life stage of the lifecycle (figure 30). By clumping several components into a single module that can be easily removed from the door assembly, the time and therefore cost required for disassembly drops. As stated in Chapter 3.4, the disassembly time is the biggest barrier for component recovery at Indra. The reduced disassembly time creates opportunities across multiple R-strategies: R3 Reuse, allowing the module or its components to be reused directly in another vehicle. R4 Repair, as easier access to the module also benefits repair. R6 Remanufacture, allowing individual components to be restored and returned to the aftermarket.

4.4.2 | Components in module

The choice of which components should fit in this module was determined by criteria: position, size and value.

The position of the components determines if it is feasible to combine certain components into one module. Therefore an overview was created mapping the positions of components in current doors (figure 31). Ranges were used to combine the different positions of different doors.

Components that are seen as too large like the storage compartment and the window mechanism or components that are primarily on the outside of the door, like the exterior door handle and side view mirror are excluded from this comparison as this would make the module complex and less effective. Components with negligible value like window guides and hinges are also excluded.

The lock mechanism is excluded from the module while it does contain value. For safety reasons the lock mechanism needs to be encapsulated by a sturdy frame. Therefore including the locking mechanism in the module would introduce new criteria complicating the module.



Figure 31 - Visual model of location of components

4.5 | Strategy C - Recycling

Goal:

Redesign the door to create cleaner recycling streams by limiting material contamination. By creating distinct material layers so that at EoL each layer can be shredded separately preventing copper from degrading the aluminium or steel stream. Higher quality recycled material could be used again as automotive-grade material, which can be fed back in the Renault supply chain. The circular benefit happens at the end of the lifecycle and tries to close the material loop.

Components in module

- Speaker
- Window motor
- Control interface
- Wiring harness
- Lock mechanism

Key benefits

- Cleaner recycling streams which can be sold for money
- Opportunity to close material loop

Barriers

- Increase in plastic costs due to monomaterial
-

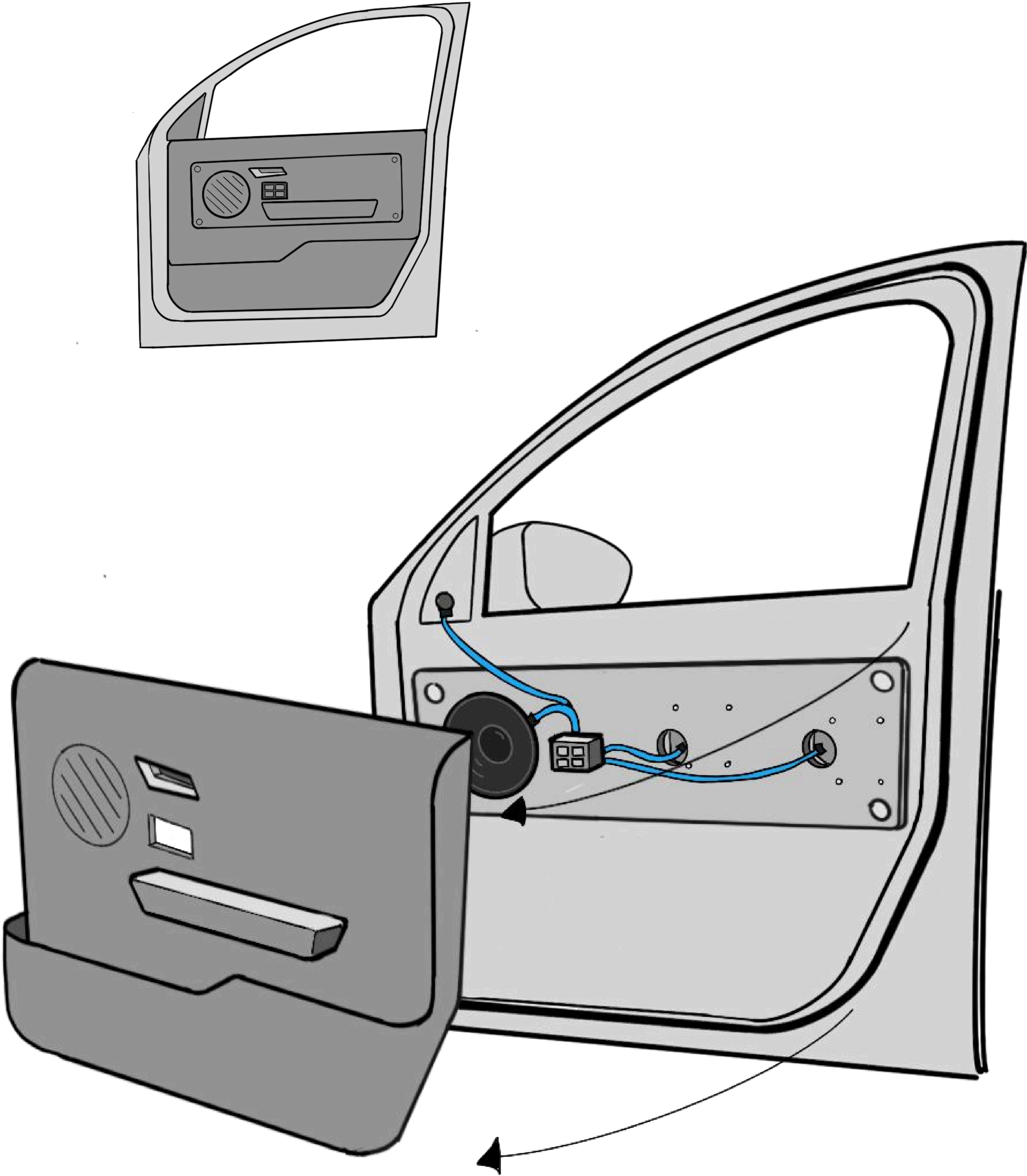
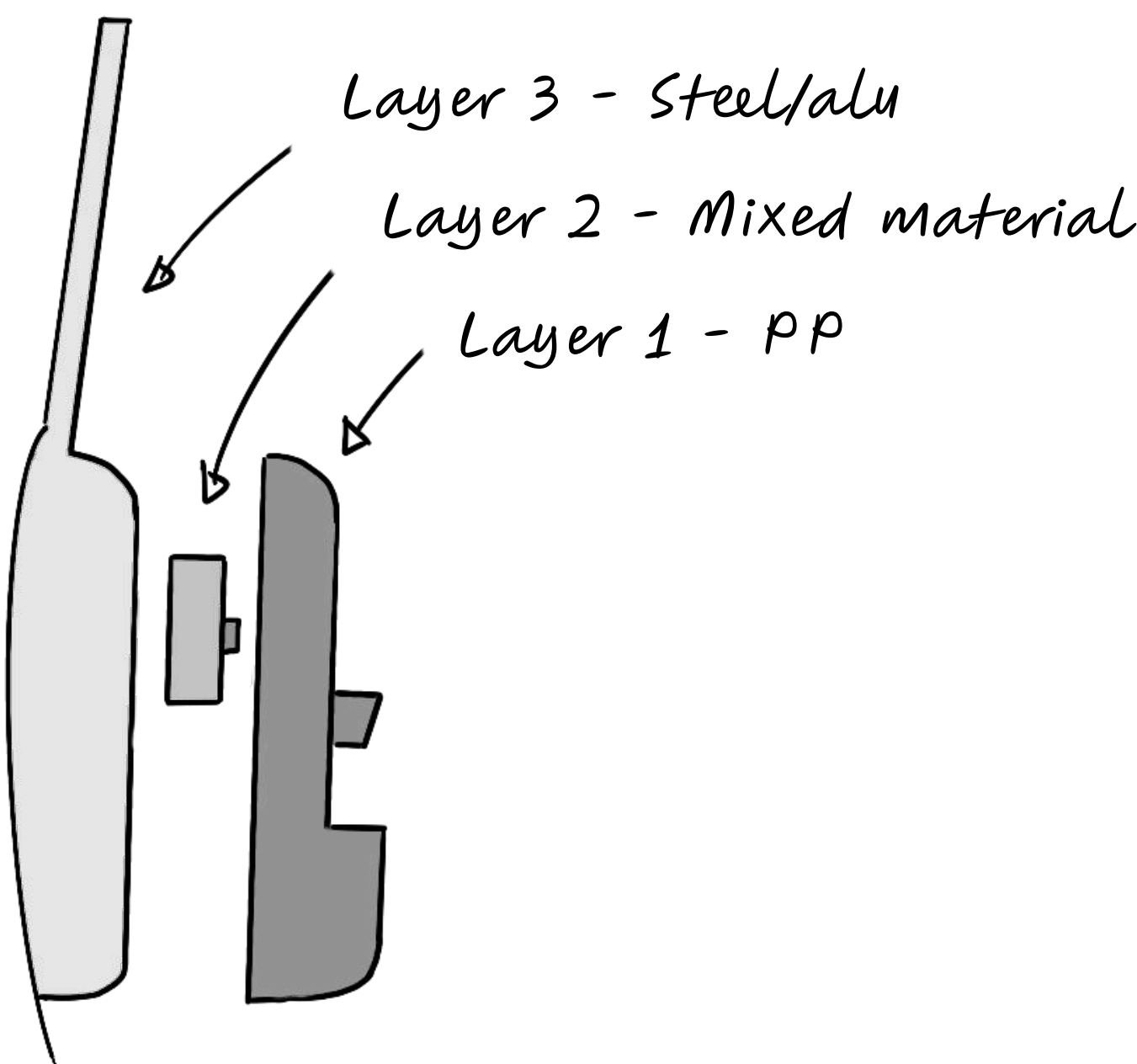


Figure 32 - Summary of Concept C - Recycling

4.5.1 | Design strategy

This concept focuses on improving material recovery at the end of the lifecycle by applying R8 Recycling more effectively (figure 32). Within the R-strategy hierarchy shown in chapter 1.6, R8 represents the longest waste loop and the least circular strategy, as it destroys most of the functional or economic value present in components. However, as recycling is the current strategy of Renault, making improvements to this strategy could still worthwhile for Renault.

The quality of recycled output is currently limited by two problems identified in Chapter 3: material mixing in the interior panel, which contaminates the plastic recycling stream, and copper from the wiring harness polluting the steel and aluminium stream, causing downcycling. CRMs present in electric motors introduce a further contamination risk for metal streams. This concept addresses both problems by separating the door into three distinct layers. The first layer consists of a monomaterial PP interior panel to improve plastic recycling. The second layer is a mixed material layer where most components are clumped together, components consisting of CRM's which can easily be removed here before entering the shredder. The third layer that remains is the steel/aluminum frame which can be recycled on higher quality as it has low pollution.

4.5.2 | PP layer

The first layer is a monomaterial polypropylene interior panel that can enter a dedicated plastic recycling stream, together with other large PP components such as bumpers. Ideally this layer is made from a single material. Using multiple plastics in the interior panel is only acceptable when functionally necessary, and even then, the connections between them must break apart during shredding. Otherwise, the materials end up contaminating each other instead of being properly separated for recycling.

4.5.3 | Mixed material module layer

The second layer is a module that clumps together components with mixed material compositions. Because these components are grouped, they can be removed in a single operation before the frame enters the shredder, preventing them from contaminating the remaining material streams. components that would pollute the metal or plastic streams are placed in the module. The module contains:

- the speaker, which contains magnets
- the window motor, an electric motor
- the lock mechanism, an electric motor
- the wiring harness, consisting of copper
- the control interface, which is attached to the frame rather than the interior panel.

4.5.4 | Mixed material module layer

The third layer is the structural frame, which at this stage contains the window mechanism, the window guides, the door frame, the exterior panel, and the side impact beam. Because the copper-containing components have been removed with the module, this layer is a cleaner assembly that could be recycled at higher quality.

Figure 33 shows how the recycling process could look like.

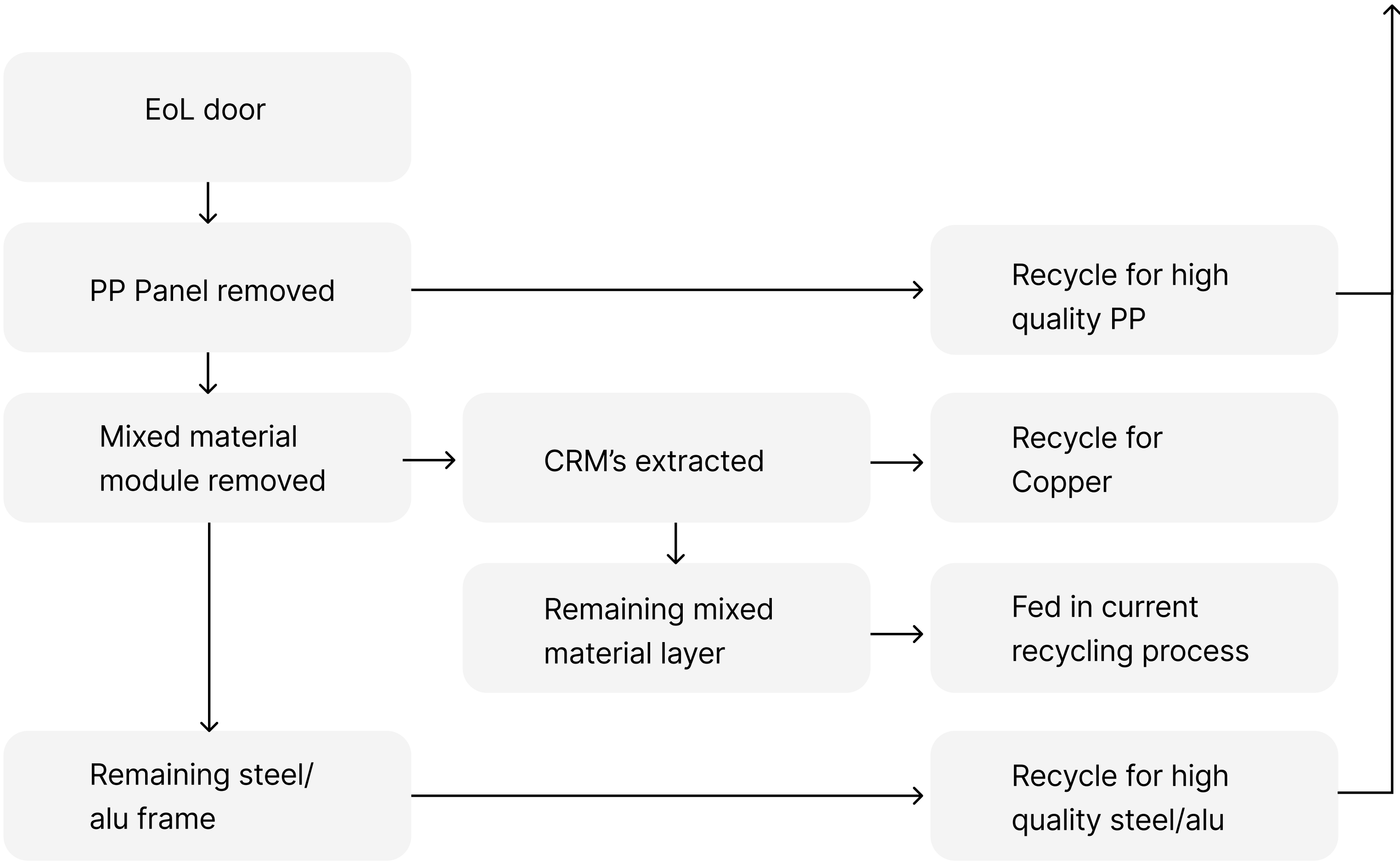


Figure 33 - Summary of Concept C - Recycling

4.6 | Concept selection

A truly circular product cannot rely on a single resource cycle, it requires improvement across narrowing, slowing, and closing simultaneously (Bocken et al., 2016, Bocken & Geradts, 2022). The three concepts were deliberately developed in isolation to make the design logic of each cycle visible. This synthesis therefore does not aim to select one concept over the others, but to assess the strengths and limitations of each and to determine which elements can be combined.

Concept A delivers the highest circular impact of the three. By refusing and reducing components, especially components containing CRM's, it sits highest on the R-ladder (Potting et al., 2017) and lowers material use, production energy, and end-of-life complexity. Its limitation is desirability. The stripped-down interior effectively moves the door a few steps back in perceived innovation. This would make it difficult to bring it to market. It remains a serious option should Renault Group pursue an ultra-simple, low-cost vehicle, where reducing material use is the main strategy. Though, one element of the concept can be applied. Exposing the frame to reduce the interior panel lowers material use without requiring the full stripped-down interior, and can therefore be carried into the other concepts.

Concept B focuses on fast disassembly. By clumping components into a removable module it directly targets the disassembly time identified as the one of the biggest barriers to recovery at Indra. Its strength is that it enables higher R-strategies than recycling alone. Faster component recovery opens reuse and remanufacturing opportunities that build on operations Renault Group already runs through the Remakers. This in turn strengthens the role of The Future is NEUTRAL. Its cost is that it requires a fundamental change to the door architecture, and on its own it does not address material contamination at end-of-life.

Concept C focuses on clean disassembly by removing contaminating components before shredding. Its strength is feasibility as it stays close to Renault's current recycling operations. It improves the strategy already in place, making it the most readily implementable of the three. Its limitation is ambition, as recycling is the lowest circular strategy and recovers only a fraction of the value built into the door.

The assessment shows that the three concepts are complementary rather than competing. Each addresses a different part of the same problem. Concept B answers the need for fast disassembly and Concept C the need for clean disassembly. The two conditions necessary to close the circularity gap. Concept B is therefore taken as the focus of the final design, as fast disassembly is the condition on which higher R-strategies depend and the direction with the strongest case for feasibility and viability. Clean disassembly of Concept C can be integrated into it. Because the module already groups components for removal, the same operation can extract the components containing copper before shredding. This way the design can deliver fast recovery of components while also delivering cleaner material streams. Finally, the material-reduction principle of Concept A is kept in mind and is applied where it does not compromise the module. The result is a single design direction: a door architecture built around a removable module that enables both fast component recovery and clean material separation, with material use reduced where feasible.

05

The Final Concept

This chapter presents the final concept. It begins with the design inspiration on which the concept builds, followed by a summary of the concept itself. The disassembly sequence is then explained in detail, as it is central to the concept's circular value. The chapter continues showing the system and how the concept contributes to circularity. It concludes by showing how the architecture retains design freedom across different vehicles and brands.

5.1 | Design Inspiration

Before presenting the final concept, this section introduces the design inspiration on which it builds. Inspiration is taken from the Centre Pompidou, a museum of modern art located in Paris (figure 34). The museum is known for its unconventional approach to architecture, in which the building's structural and functional systems are placed on the outside rather than hidden within the walls. This way of treating function as something to be expressed rather than concealed became the guiding principle for the final design

Expose rather than conceal

The design philosophy of the Centre Pompidou is that its components are not hidden. Pipes, ducts, and structural elements are placed on the outside of the building rather than concealed within the walls. The ambition is to bring this same philosophy to the car door. By exposing rather than concealing components behind the interior panel and surfacing them to the top of the assembly to make disassembly easier. Exposing features and components does not mean abandoning design. The Pompidou is thoroughly designed. The same discipline can be applied to the door, so that visible elements like cables and components read as intentional and become part of the vehicle interior's identity.

Legible

At the Pompidou, every system is colour-coded and traceable: blue for air, green for water, yellow for electricity, red for walkways. This legibility should be translated to the door: components need to become a visible, readable composition. A technician should understand how the door comes apart at a glance, while a passenger should be able to read the door's intended function. Just as a visitor understands the function of elements of the Pompidou.

Accessible

The Pompidou pulled its functional elements to the outside so the building could be maintained, modified, and adapted over time. In the same way, components meant to be recovered should be positioned at the surface of the door, not buried deep in the assembly. If a part is meant to be recovered it should be accessible and it should look like it can be recovered.

In the following section the final concept will be presented The final concept is a end result of multiple iterations. A visual overview of these iterations can be found in B.



Figure 34 - The Centre Pompidou

"A circular car door should be like the Centre Pompidou. A structure where components are visible, legible and accessible, while still evoking emotion for the user."

Exposed Cables



**Recoverable, Accesible
Module**

Figure 35 - The door concept in a Renault 5 Styling

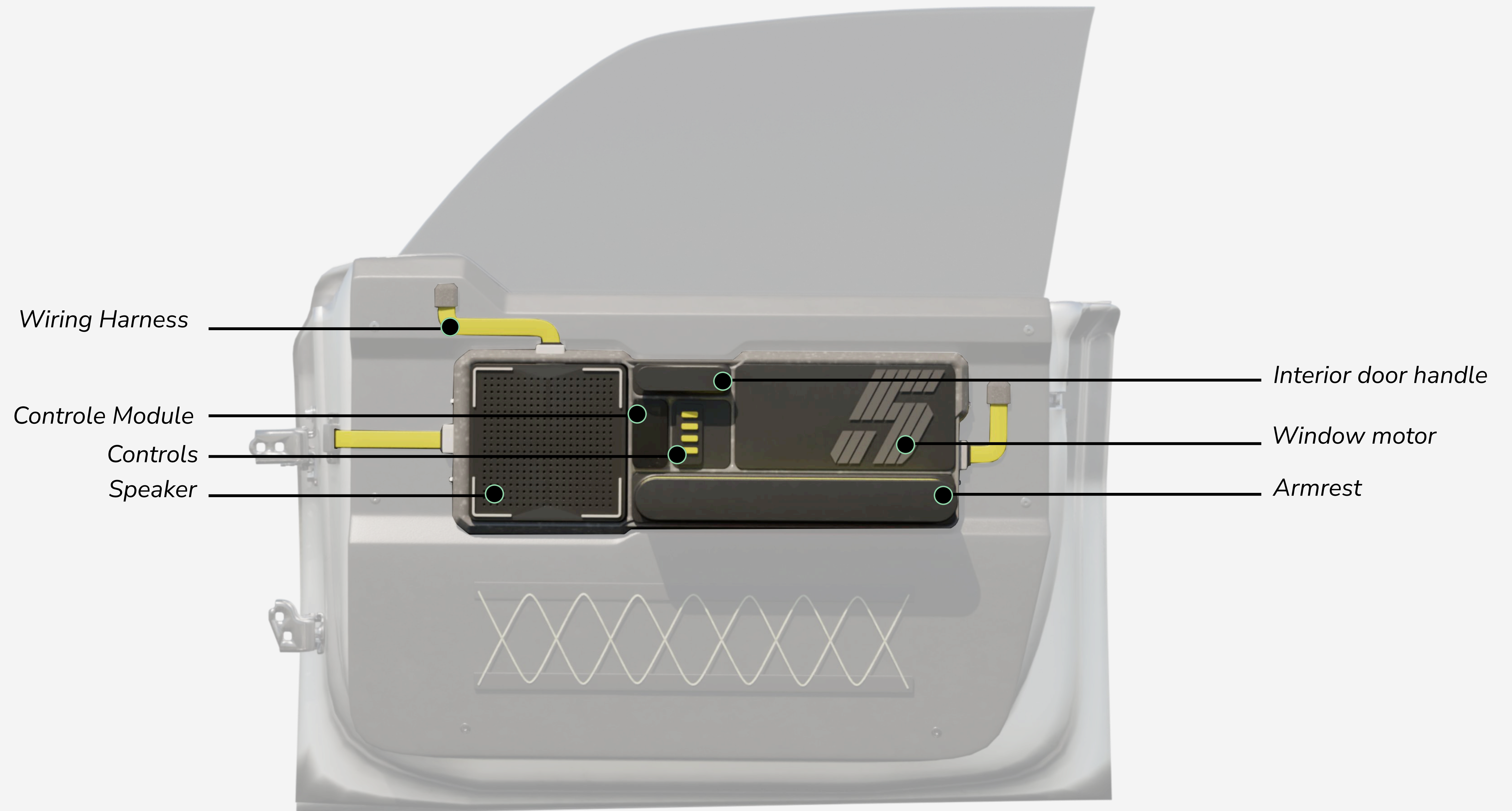


Figure 36 - The different components in the recoverable module



Figure 37 - Module disconnection

5.2 | The Concept: A New Door Architecture

This final concept is not a design for one specific car door. It envisions a new approach for Renault Group to design doors with a higher circular impact: an architecture in which the same underlying structure can be used with completely different styling designs, allowing it to be applied across different cars and brands. To demonstrate the architecture, it is presented here in a Renault 5 styling. The existing Renault 5 interior is shown in Appendix C for reference.

The circular value of this architecture comes from a single design decision. Components are clumped into one module that can be liberated from the door in a quick operation. This offers two advantages. First, it enables the harvesting of components, as components are reachable in a single step. Second, it increases the recycling quality, as copper-containing components can be cleanly separated from the steel or aluminium frame before shredding.

The architecture consists of four main parts, shown in figure 38. the frame, the interior panel, the module, the components. The frame is an aluminium structure carrying the door's safety and load-bearing functions. The interior panel is a monomaterial layer forming the visible interior surface. The module houses several components and is fixed to the frame with four bolts, allowing it to be removed during or at the end of the life cycle in a fast and clean. The components contain a standardized functional element as well as a customizable styling element.

A key strength of this concept for Renault Group is that this architecture does not require an identical frame, panel or module for every vehicle. Designers retain a certain level of freedom over the appearance and identity of both the interior and the exterior of the door while the circular benefits of the architecture remain present.

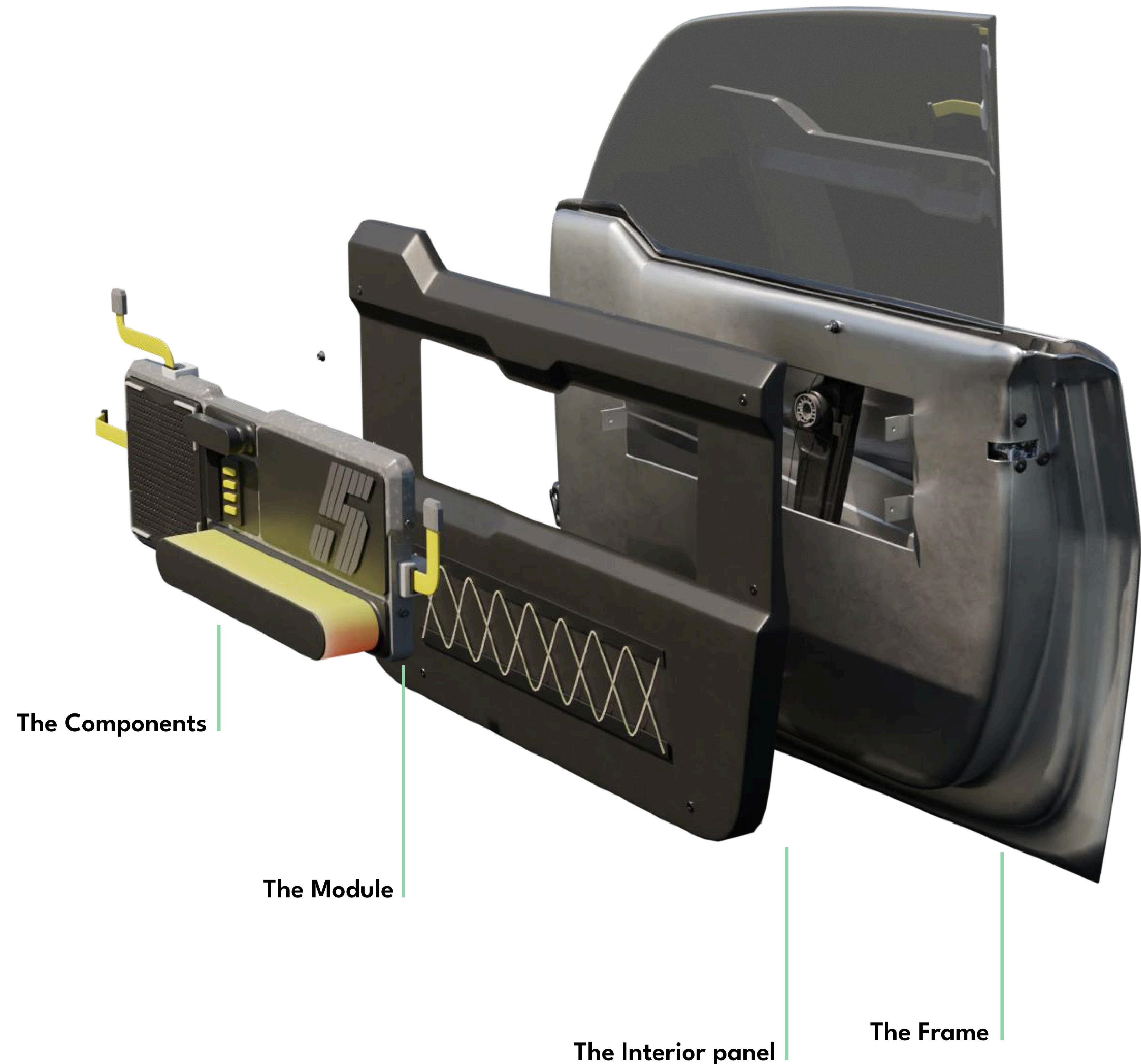


Figure 38 - The different elements of the architecture

5.3 | Disassembly & Recovery

This section shows how the architecture makes disassembly fast and clean. It first walks through the disassembly sequence step by step, then shows how the module enables automated disassembly, and finally explains which components are standardized

5.3.1 Disassembly sequence

The new door architecture is built around improving the disassembly sequence at the door's end-of-life. Figure 39 shows an overview of this sequence, starting after the door has been removed from the body of the car.

1. Three wiring cables are decoupled using a screwdriver: the main power connection, the connection to the side-view mirror, and the connection to the lock mechanism (figure 40).
2. Four bolts are removed located on both sides of the module (figure 41).
3. The module is moved slightly outward, which gives access to the steel cable attached to the interior handle. Once this cable is disconnected, the module can be taken out completely. During this operation the window motor disconnects from the window mechanism (figure 42 & 43).
4. The wiring harness is removed from the module by disconnecting the remaining cable plugs. The module then enters an automated disassembly sequence in which the individual components are harvested.
5. The remaining components are removed and recovered from the frame: the side-view mirror, the window mechanism, and the lock mechanism.
6. Finally, the interior panel is removed from the frame, leaving a clean aluminium or steel frame.

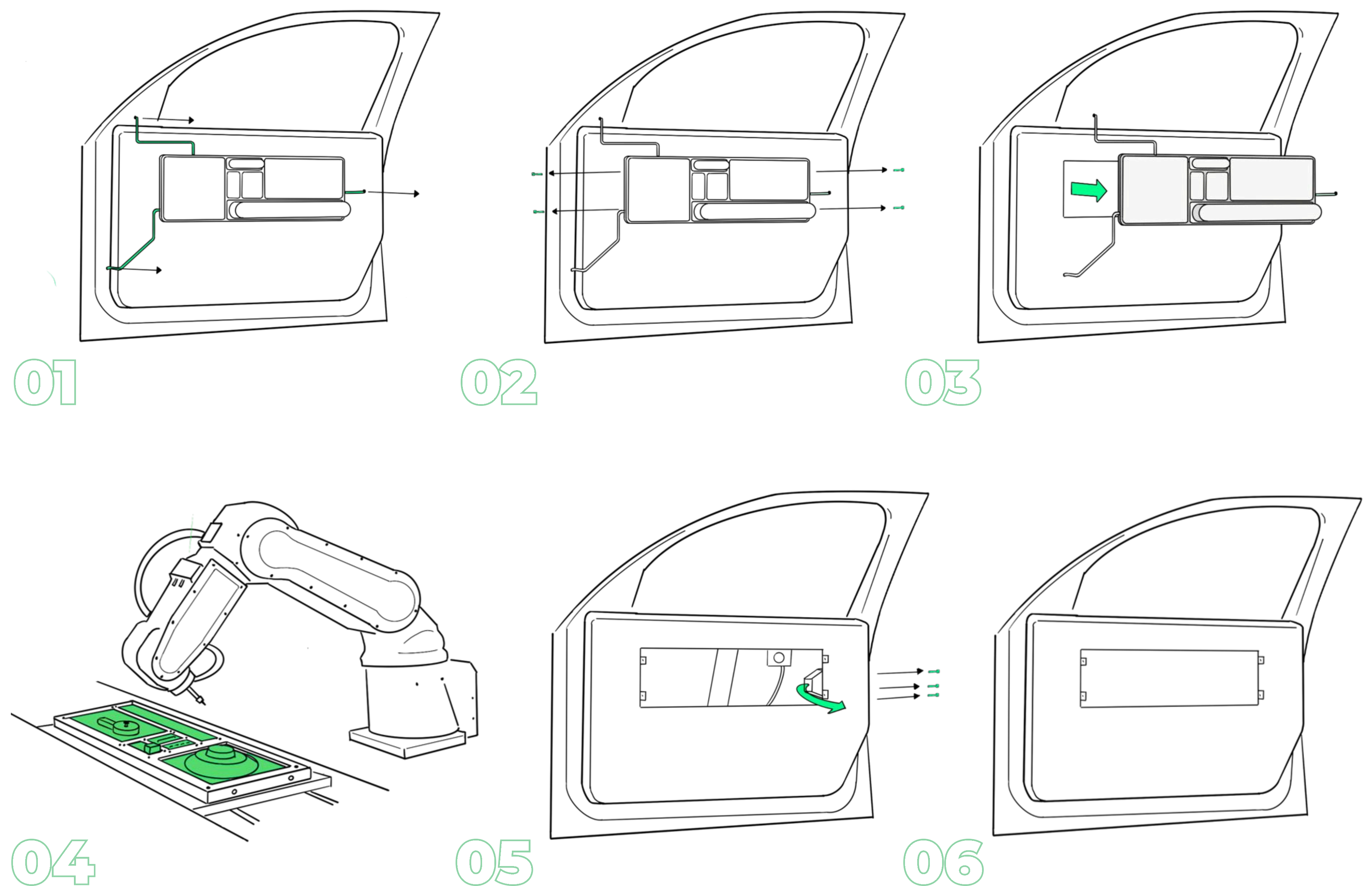


Figure 39 - The disassembly sequence



Figure 40 - Close-up of one of the cables (lock mech) that needs to be removed

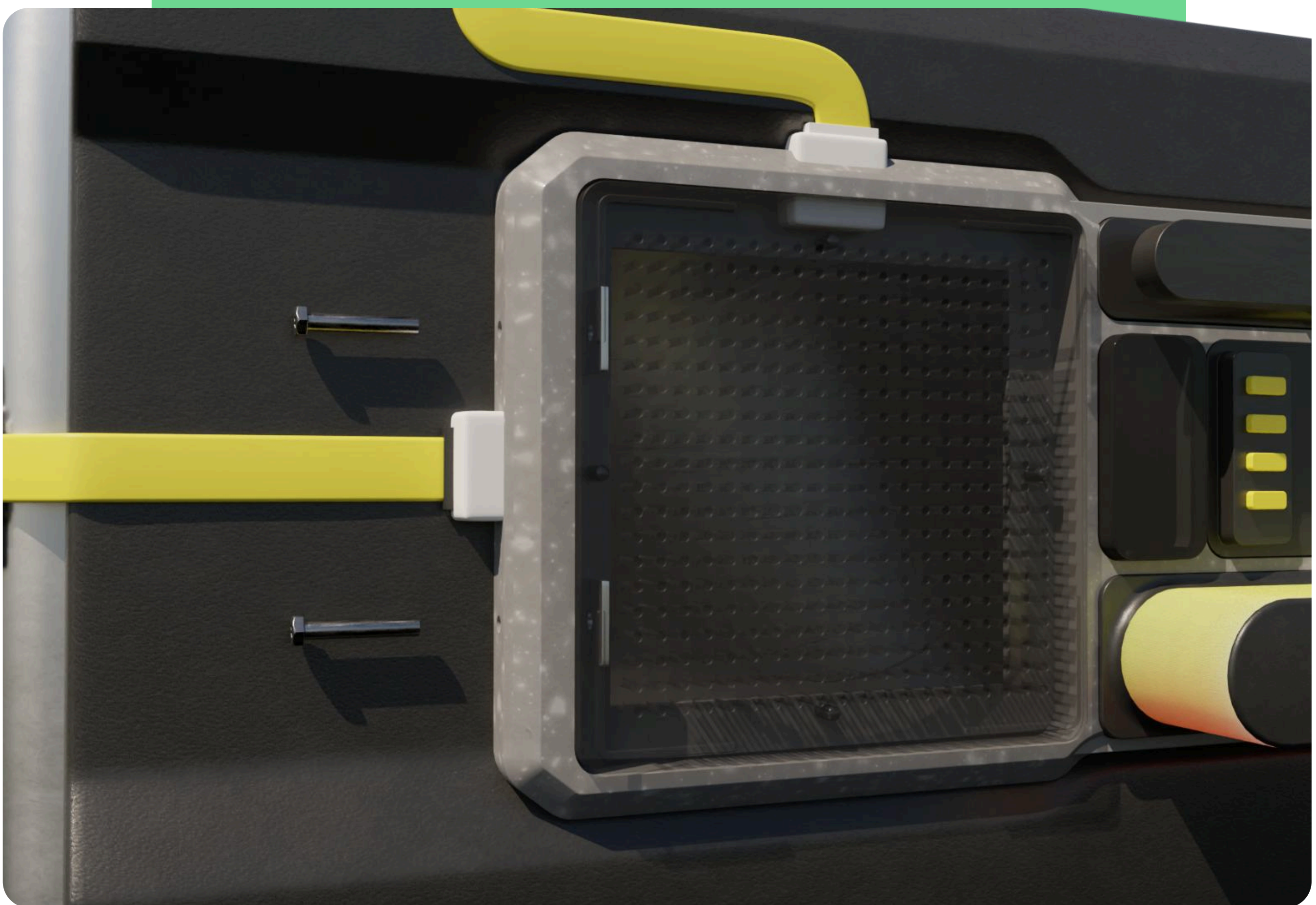


Figure 41 - Close-up of how the module is connected to the frame.

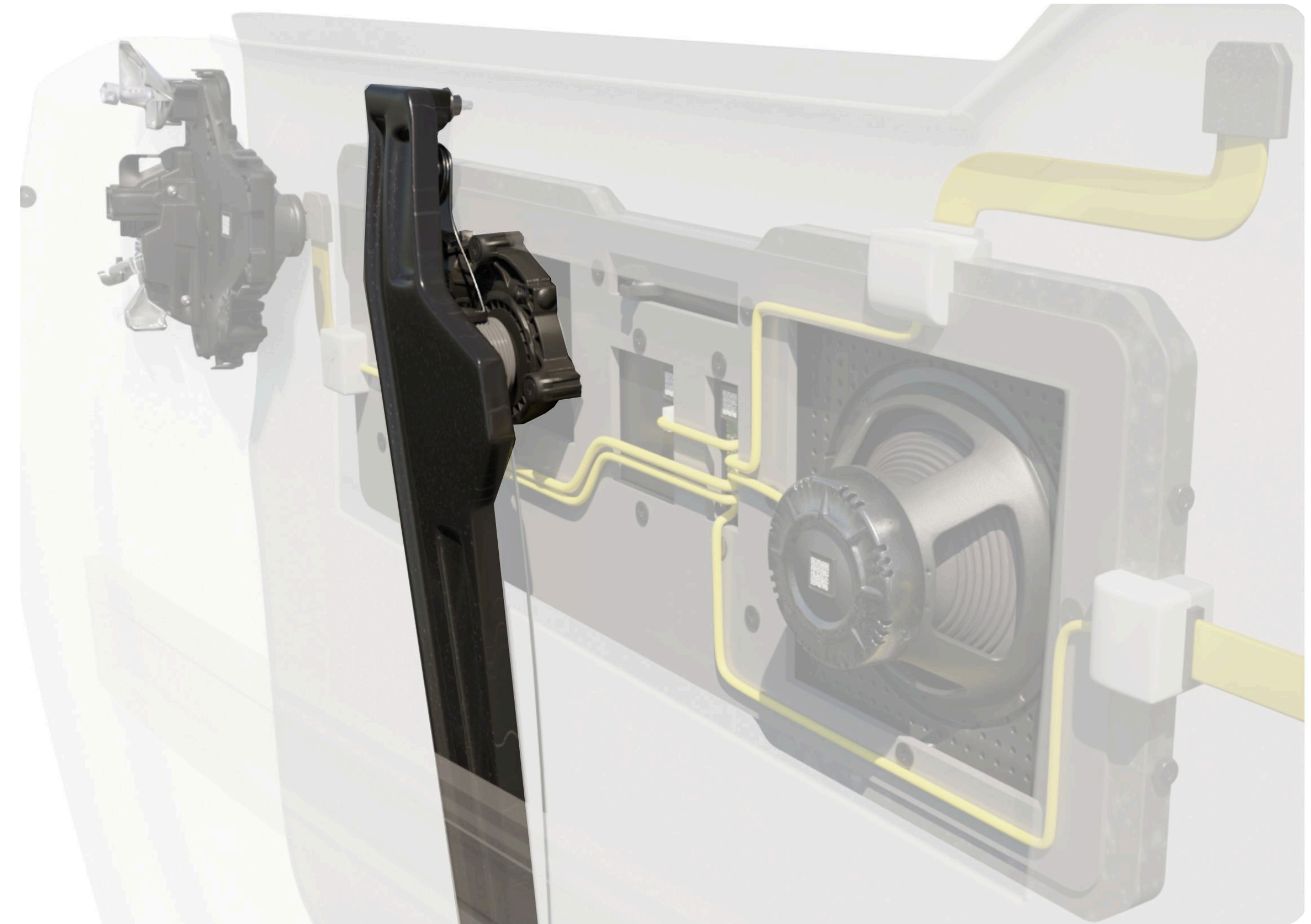


Figure 41 - Close-up of the window motor inside the window mechanism prior to disassembly

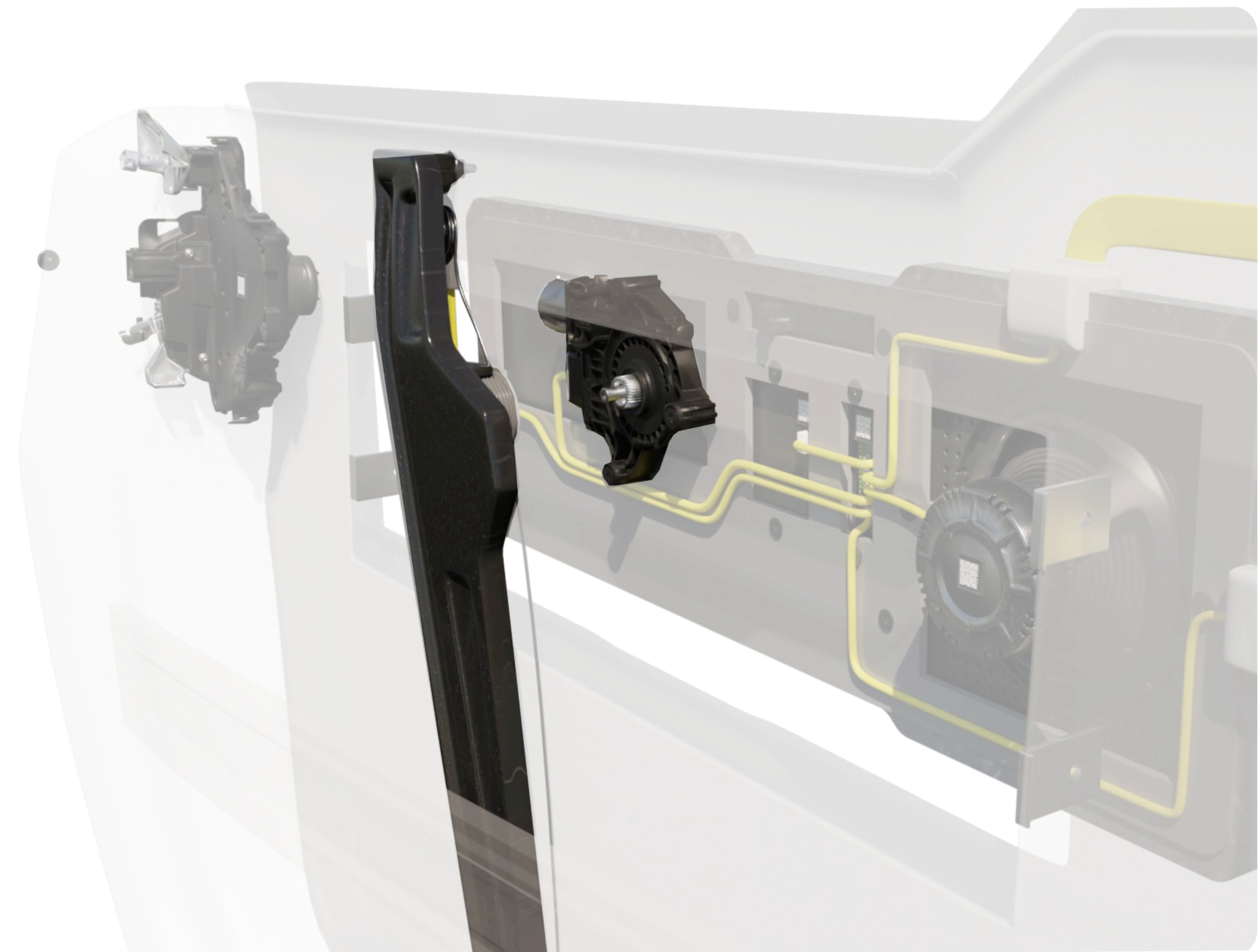


Figure 42 - Close-up of the window motor outside of window mechanism after the module is disconnected.

5.3.2 Automated disassembly

The architecture’s goal is to ensure faster disassembly to make it more viable. Automated disassembly can cut disassembly cycle time and cost relative to labor-intensive manual tear-down (Ameur et al., 2025). Therefore, the module could be disassembled autonomously with a single robotic arm. After the module is disassembled from the door’s body it can enter an automated disassembly sequence. The module uses a standardized screw to mount all components so the robotic arm can unscrew them from the back (figure 44). Literature already shows robots with computer vision being developed that are capable of automating unscrewing processes (Díaz et al., 2025).

Next to automating disassembly, these robots could also play an important role in acquiring product lifecycle data needed to asses the quality of the collected components. During the disassembly process they can scan the RFID tags storing the usage data (figure 44). A more detailed description on why this is important is discussed in chapter 5.5.



Figure 43 - The disassembled module front view

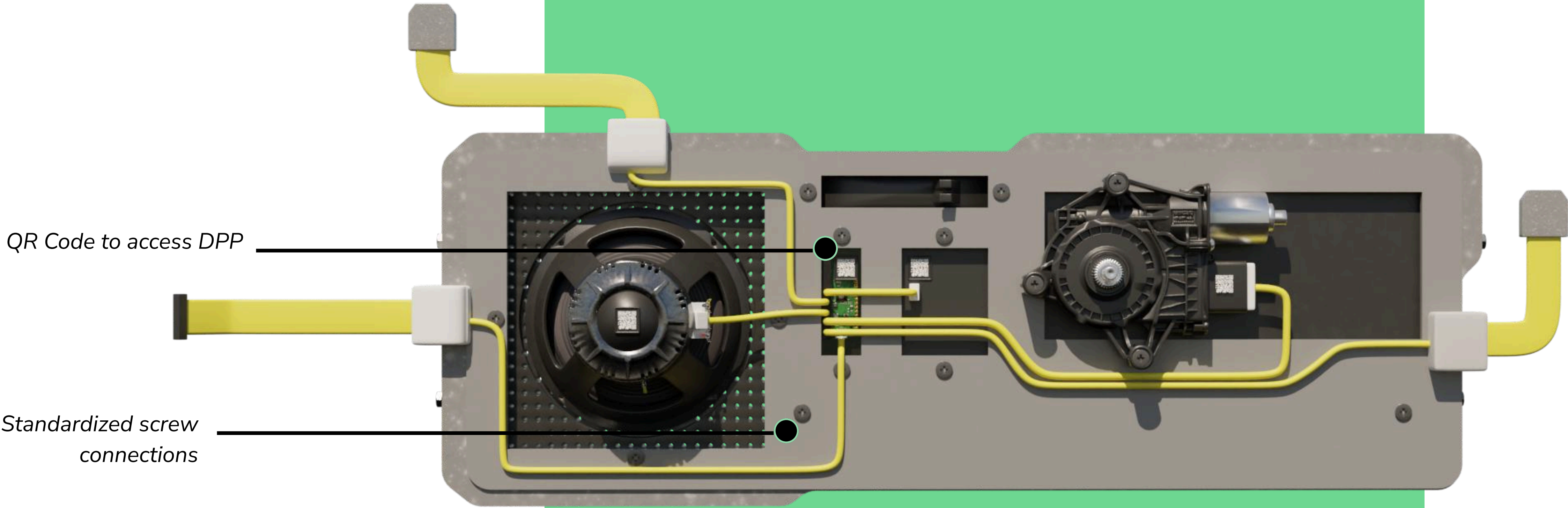


Figure 44 - The disassembled module back view

5.3.3 Standardized Components

The previous section showed how components can be disassembled and harvested quickly. To make these recovered components suitable for remanufacturing, several of them are standardized, so that the same components are interchangeable across Renault Group's different models and brands. This is already done in the automotive industry but mainly from a cost perspective. Standardizing components and their connections is an important enabler of remanufacturing (Balkenende et al., 2025). To support multiple lifecycles, these standardized components should additionally be designed for durability (Balkenende et al., 2025). Figure 45 shows which functional components are standardized, in what way and why some components can not be standardized.

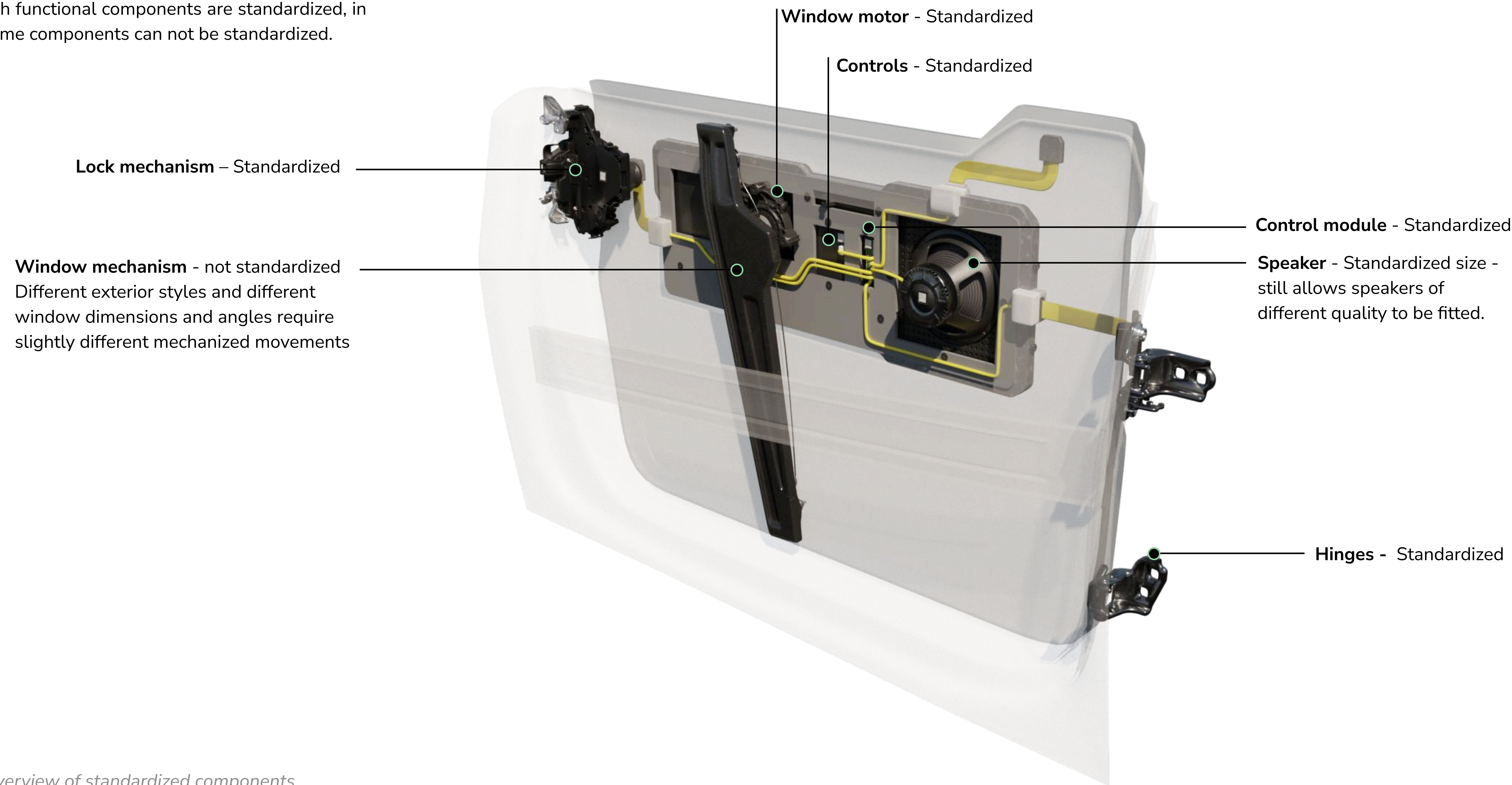


Figure 45 - Overview of standardized components

5.4 Materials & CRM recovery

5.4.1 Materials

Figure 46 shows an overview of the materials used in the door. This section explains why these materials were chosen and how they were designed to work as recycled input at the start of life. How the same materials are recovered and separated at end of life is covered in Chapter 5.5, which discusses the recycling system in more detail.

Recycled aluminium

The frame is made from recycled aluminium. At start of life this lowers the production energy of the frame considerably, since recycling aluminium requires only 10–20% of the energy needed to produce primary aluminium.

Recycled PP

The interior panel and the styling elements of the components are made from mechanically recycled polypropylene. Plastics recovered through mechanical recycling behave differently from primary plastics. Their properties are less consistent and generally of lower quality (Balkenende et al., 2025). Rather than working against this, the components are designed to accommodate it. Three guidelines proposed by Balkenende et al. (2025) were applied:
Textured surfaces were used instead of uniform high-gloss finishes. The components were given relatively simple geometries rather than highly complex shapes. This allows for easy flow paths and better venting during injection moulding. Finally, walls were made thicker to reduce the mechanical demands as recycled PP can have lower structural characteristics.

Cables

The wiring uses flat cables rather than conventional round ones. This is partly a styling choice, but it also serves a functional purpose. A flat cable sits flush against the interior panel, reducing the chance that they are snagged, damaged or destroyed during use or disassembly. Figure 47 shows a flat cable in more detail.

Functional components

Components such as the speaker, lock mechanism and window motor are still made from a mix of different materials. Optimising the material composition of these components lies at the level of individual component design, which is outside the scope of this project.

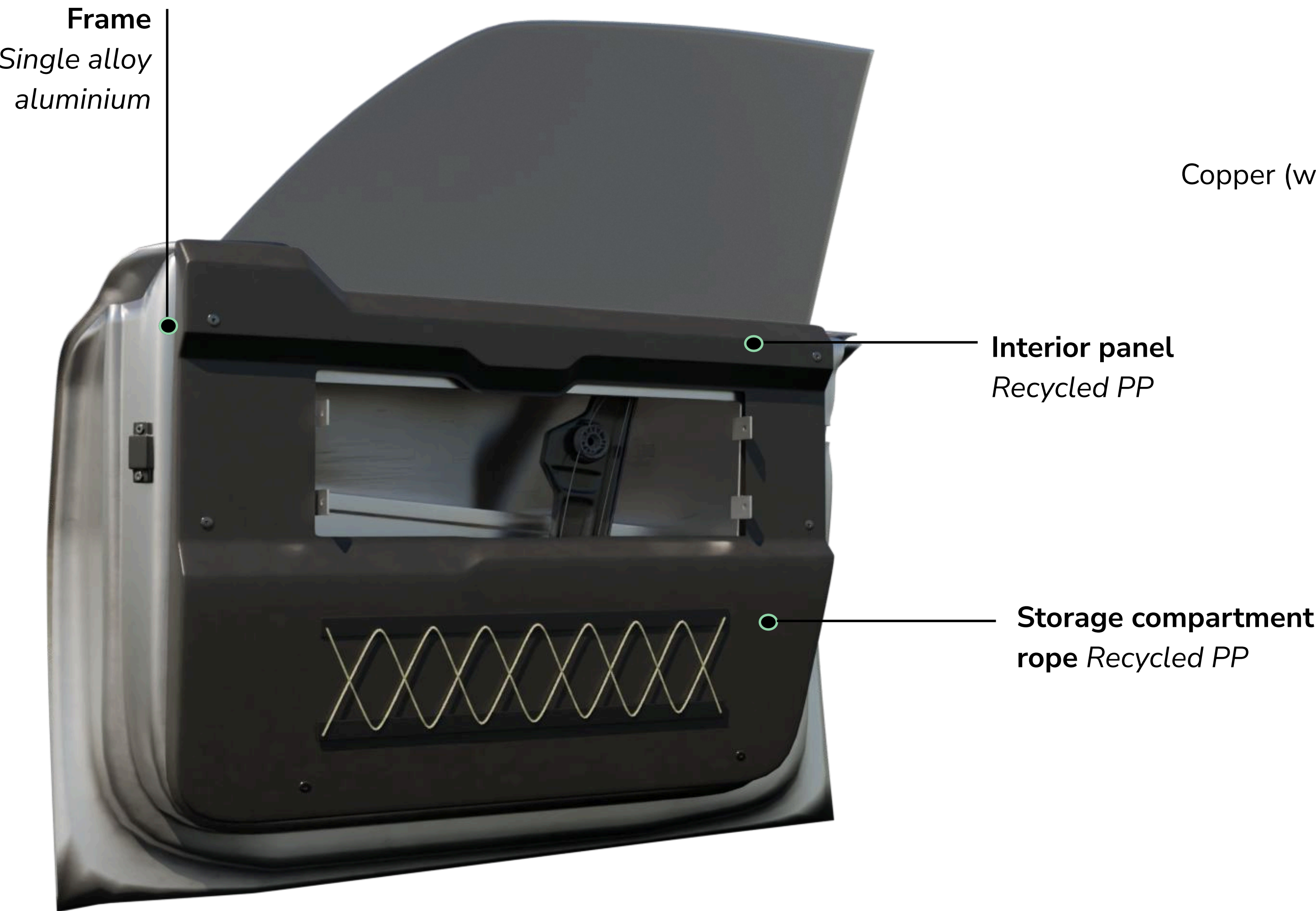


Figure 46 Overview of materials used in concept

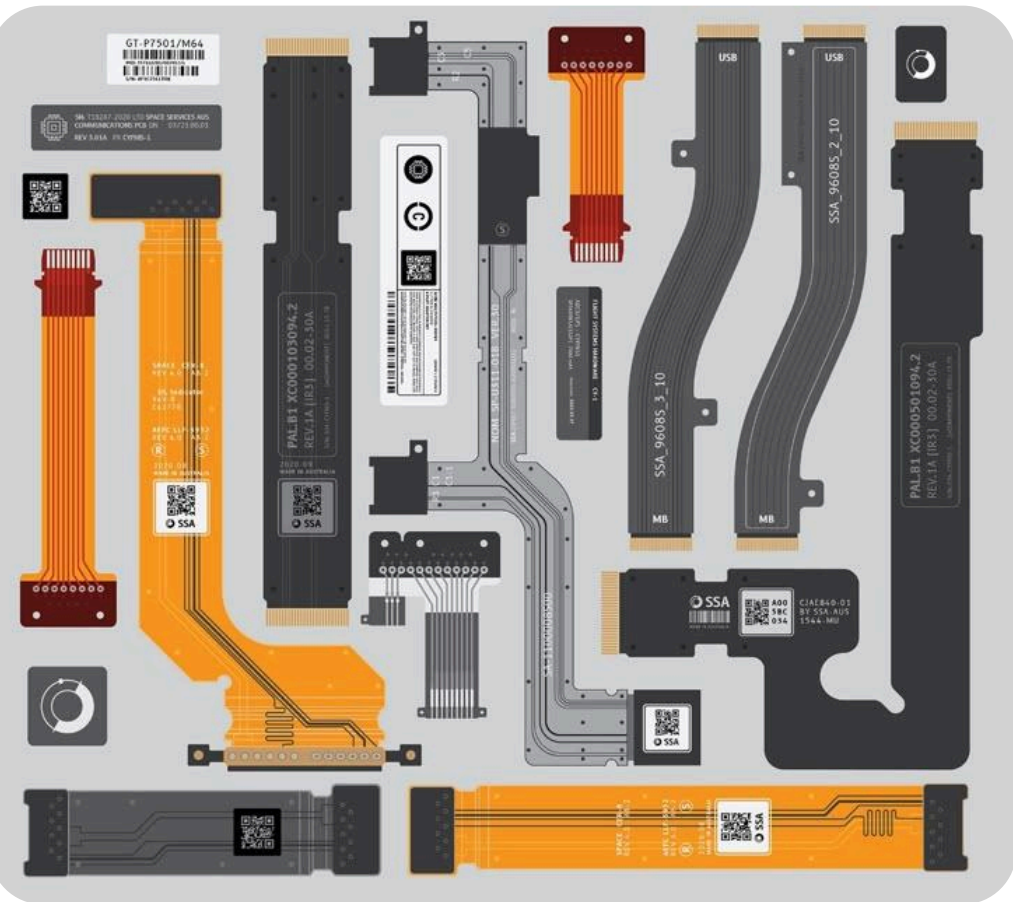
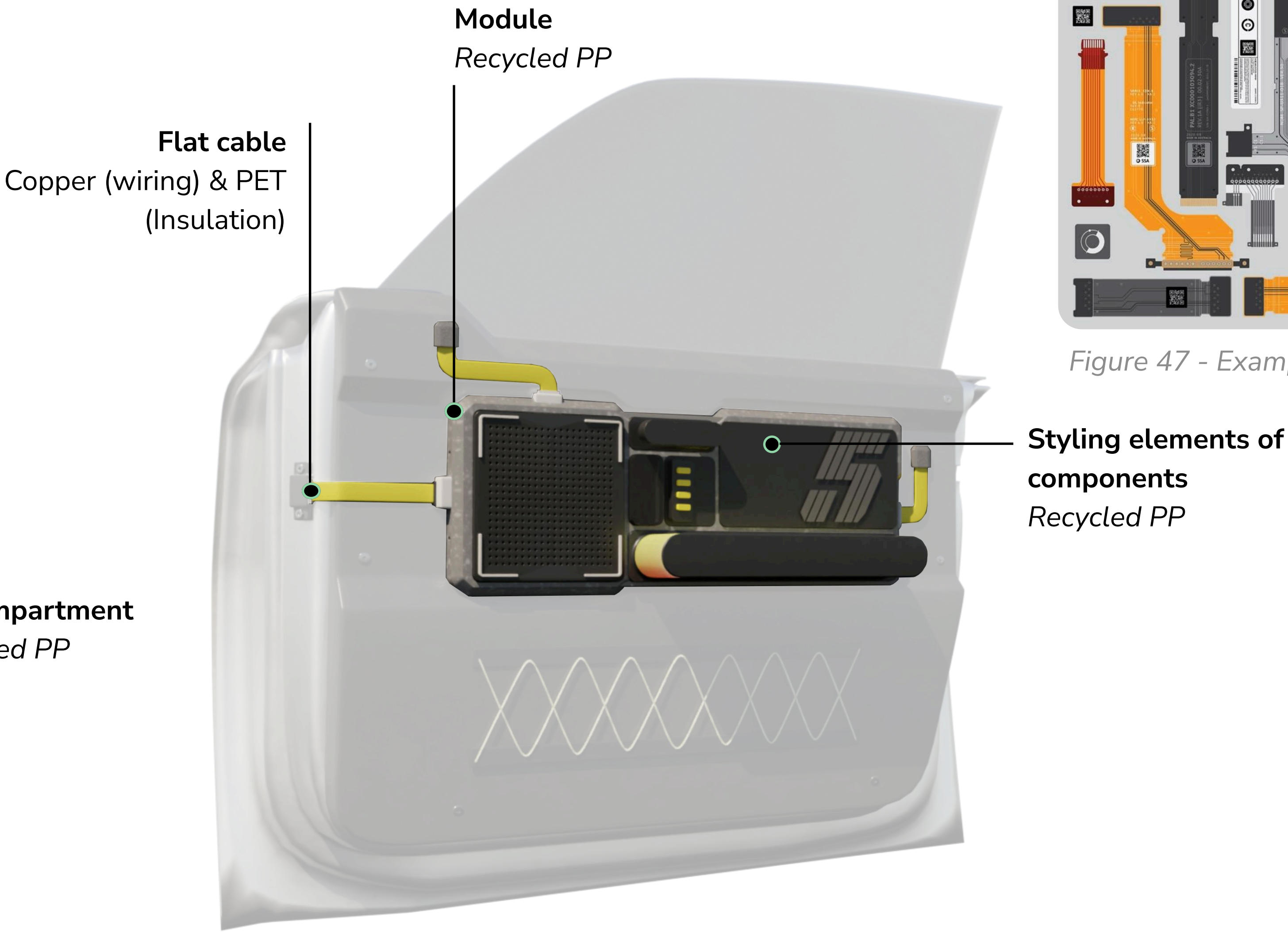


Figure 47 - Examples of flat cables

5.4.2 Recovery Of CRM's

Several components in the door contain critical raw materials: the wiring harness, the electric DC motors, the printed circuit boards in the control module and the speaker (chapter 3.1). To improve the recovery of these materials, several design decisions have been made.

Wiring harness

In a conventional door the wiring harness runs throughout the structure and is difficult to extract fully, which is why it is often cut loose and partially left behind (Chapter 3.4). In this concept the wiring harness is clumped, surfaced, and fitted with cable plugs which are much more accessible after the module is removed from the frame (figure 48).

Several cables are exposed at the top of the interior panel, which allows the wiring harness to be removed together with the module. Because it remains a single harness, it can be easily taken out once all cable plugs have been disconnected from the module. This ensures the complete removal of the wiring harness, so that the copper no longer remains in the door to contaminate the metal frame.

Electric DC motors

Two guidelines from the master thesis of Grupstra (2026) are applied to make these the DC motors recoverable. The first is the connection type. Grupstra proposes a friction-fit connection, but because the door is exposed to strong vibrations, a visible standardized screw connection is used instead to mount the DC motors.

The second guideline is to avoid embedding components in non-removable subassemblies. By not enclosing the motor inside a plastic cover, as is currently the case in for example the lock mechanism, the recovery rate of the DC motors is greatly improved.

Printed circuit boards (PCB's)

In a conventional door the control module is located inside a subassembly of the control interface (Chapter 3.1). Although these boards are currently recovered by Indra (Chapter 3.4), they are still buried within this subassembly. To improve recovery, the concept positions the control module as a separate part inside the module allowing it to be extracted easily (figure 49).

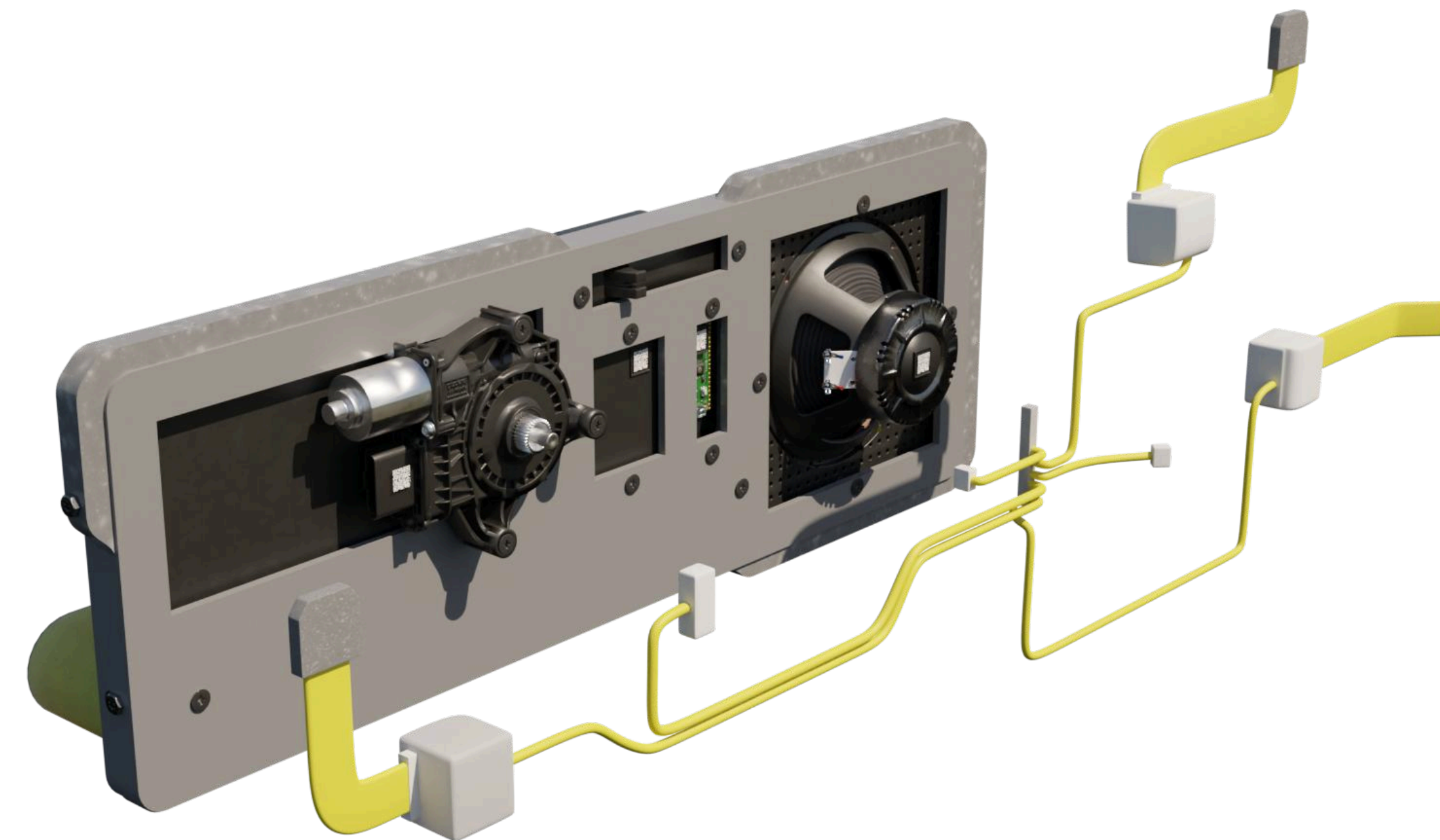


Figure 48 - Wiring harness removal

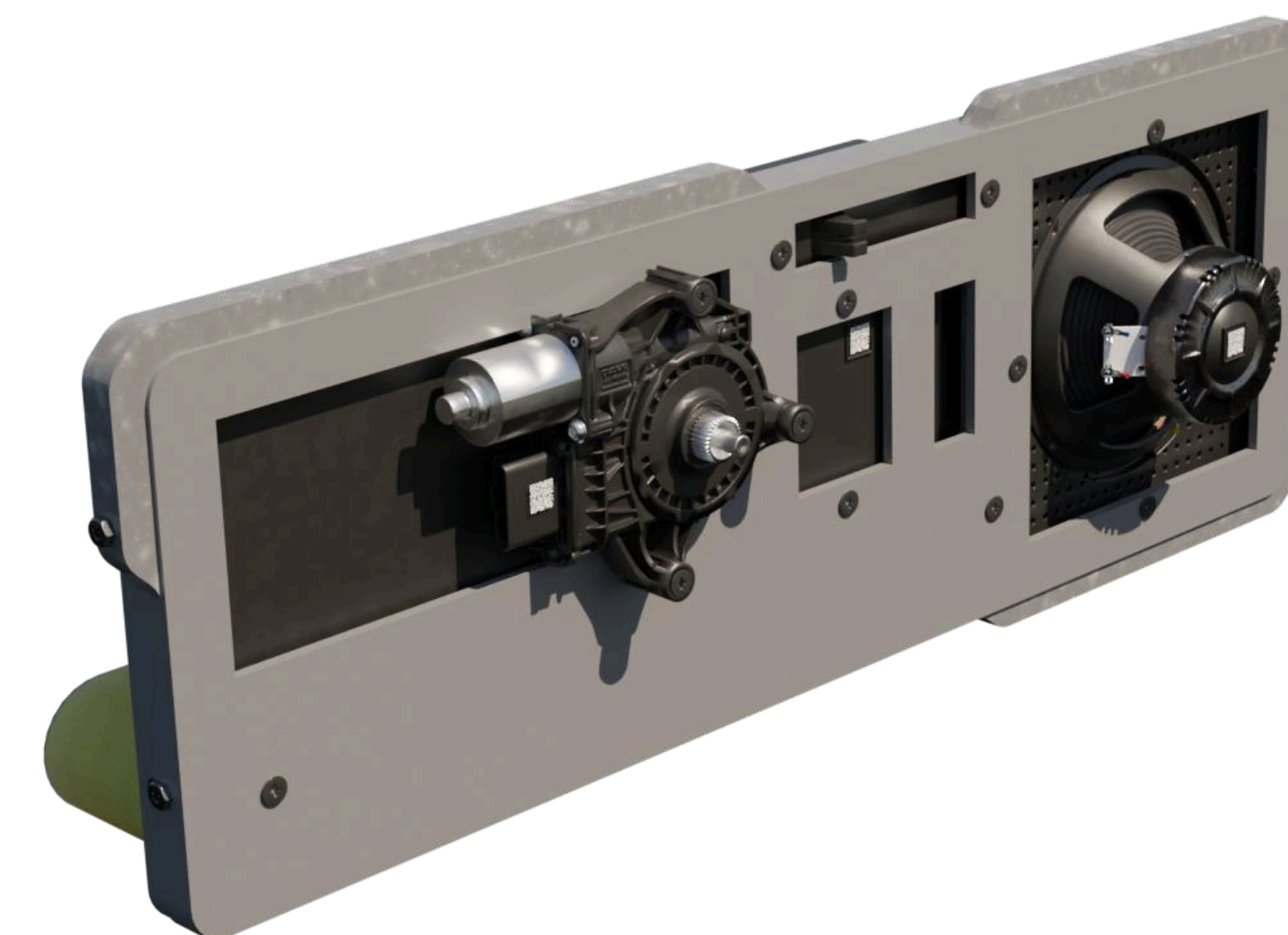


Figure 49 - Door control module removal

5.5 Circular system

The previous sections described the door as a product. This section discusses the system around it. It explains how recovered components and materials are processed through two systems: a remanufacturing system that recovers whole components, and a recycling system that recovers materials. The remanufacturing system is discussed first, followed by the recycling system.

5.5.1 The Remanufacturing system

For remanufacturing to succeed product architecture that enables fast disassembly is not enough, you also need a business model and support systems like collection infrastructure or a repair network (Balkenende et al., 2025). Vogt Duberg et al. (2020) identified different essential factors that need to be in place for a remanufacturing system to succeed. Several of these factors that are in scope of this project are discussed in the following section.

Core acquisition and reverse logistics

One of the significant requirements for remanufacturing is the availability of cores (Sakao and Sundin, 2019) and to know the arrival rate and quality of collected cores (Wei et al. 2015). In other words you need to know the timing, quantity, and quality of supplied cores. To acquire cores for remanufacturing a business model is needed. According to Östlin et al. (2008) there are seven different types of closed-loop relationships for gathering cores for remanufacturing. The relationships are incentive-based, ownership-based, service-contract, direct-order, deposit-based, credit-based and buy-back. Their full definition can be found in Appendix D.

Renault Group has two main channels to get their cores from. First, you have the vehicle repair facilities that can send broken cores back to the remanufacturing facility. For this stakeholder the deposit based is most obvious to use as this is already common in the automotive industry for certain parts (Östlin et al., 2008) this will also be seen a validation interview in chapter 6. When repair facilities buy a remanufactured product, they are obligated to return a similar used product, thus also acting as a supplier to the remanufacturer.

Second, cores can be acquired using recycling facilities like Indra within the Future is NEUTRAL. When these recyclers disassemble the door they recover broken or functioning cores which can be send to a remanufacturing facility. In this case the buyback relationship is most obvious in which the remanufacturing facility pays the recycling facility directly to acquire the cores. This would then in turn cover the cost of disassembly for the recycling facility. This relationship is already common in scrapyards and in the automotive industry (Östlin et al., 2008).

It is also important to know the quality of the collected cores (Wei et al. 2015) as proper quality grading prior to remanufacturing decisions ultimately improves the profit (Aras et al., 2004). Therefor the remanufacturing facility should be able to asses the quality of the collected cores. Product life cycle data is commonly used to help remanufacturers to cluster and categorize the used incoming cores and further determine the best End of Life recovery option for each cluster (Mashhadi & Behdad, 2017). Therefor each remanufacturable component carries a unique identifier (RFID/QR) linking it to its record in a Digital Product Passport. In this Digital Product Passport usage data logged by the door control module during the use phase is stored. This data includes e.g. the amount of locking operations, window opening and closing cycles and run time of the speaker. This way, the quality of the collected cores can be understood. This information can be read at the automated disassembly station explained in chapter 5.3. This allows the recycler to retrieve each core's usage history and make a decision to either forward it to a remanufacturing facility or recycle the component.

Remanufacturing facility, process & technology

After the cores are collected and have the right level of quality, they enter the remanufacturing facility. Renault Group and the Future is Neutral already have this in place: The Refactory. Although they only remanufacture the five components discussed in chapter 2, they can expand their operations to the door components specified in chapter 5.3. They already have the labour and skill which are needed for remanufacturing (Vogt Duberg et al. 2020).

Next to the need for skill and labour the process must be flexible. This is the only manufacturing output that helps to handle both the complexity and uncertainty of remanufacturing, as it sets up the production with the readiness to quickly adapt to changes (Vogt Duberg et al., 2020). There are different manufacturing philosophies with different levels of flexibility. The Future is neutral and the Remakers should further research which would be most optimal for each components's remanufacturing process. Figure 50 shows the steps that the recycling facility (Indra) and the Remakers need to perform to remanufacture a component.

The biggest challenge that remains is assuring quality, both of the collected cores and of the remanufactured components. The remanufacturing operations shown in figure 50 need to be set up so that a consistent level of quality can be guaranteed. Beyond this, the coordination of the system as a whole is complex. It comprises a large number of interactions and interdependencies among the different stakeholders in the value chain (Asif, 2024). Complex system modelling could offer a way to understand these interactions and should be carried out to assess whether the remanufacturing system is viable before committing to it.

INDRA

Remakers

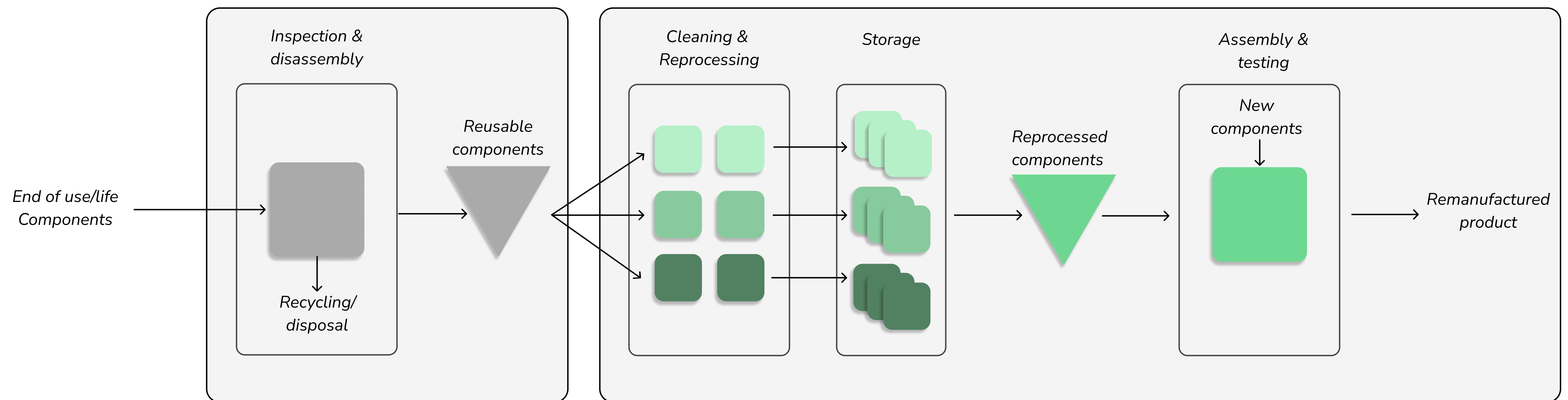


Figure 50 - Overview of the remanufacturing system across multiple stakeholders

5.5.2 The Recycling system

When components cannot be remanufactured, or do not allow for remanufacturing at all, they are recycled. To obtain high grade recycled material and to avoid downcycling it is important that materials are separated into homogeneous material fractions and that materials in the same stream are compatible with each other (Balkenende et al., 2025). An overview of which materials are compatible and which combinations result in material loss can be found in Appendix E.

The disassembly sequence described in Chapter 5.3 is therefore the first and most important step in achieving higher-grade recycled material as a large number of components is separated before shredding. The architecture leaves three groups that each enter a different recycling stream: the aluminium frame, the polypropylene interior panel, and the mixed components recovered. The following sections describe how each group is recycled and how the architecture improves the quality of its output.

Recycling of Aluminium

At the end-of-life stage, aluminium is attractive to recycle because processing recycled aluminium requires only 10–20% of the energy needed to produce primary aluminium (Balkenende et al., 2025). This is the reason recycled aluminium was chosen for the frame (Chapter 5.4). The grade of the recycled aluminium, however, depends on how homogeneous the fractions of the shredded frame are, and this is influenced by two factors. First, the frame should consist of as few aluminium alloys as possible, since a single, homogeneous batch is the most straightforward to recycle at high quality (Balkenende et al., 2025). Second, the copper-containing components are removed in the disassembly step prior to shredding (Chapter 5.3), so the frame entering the shredder is already free of the contamination that would otherwise force it to be downcycled. Steel components that separate into homogeneous fractions during shredding, such as the window guides and the window mechanism, can enter this stream as well, since steel and aluminium can be sorted afterwards using magnetic and eddy current separation (figure 52). Together, a single-alloy frame and the removal of copper before shredding could enable a high-quality aluminium recycling stream. If this quality is high enough It could re-enter new door or vehicle production and thereby close the material loop.

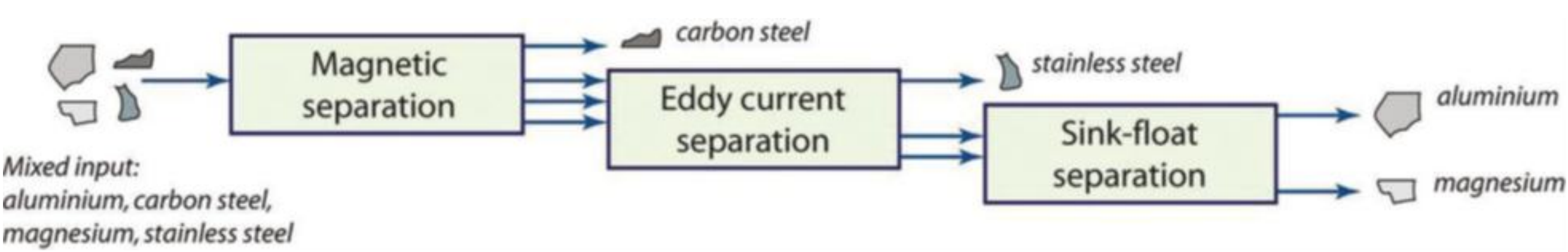


Figure 51 - Metals separation using a sequence of separation machines Source: Tempelman et al. (2014).

Recycling of PP

The interior panel and styling elements are made from recycled PP. This is done for two reasons. First, PP is mechanically recyclable and already commonly recycled, although not to the same extent as PE or PET. The energy associated with mechanical recycling is typically about 20% of the energy needed for primary plastic production (Balkenende et al., 2025). Second, recycling cannot be carried out efficiently on a small scale, as efficiency of scale require many different products to be treated simultaneously in a bulk process (Balkenende et al., 2025). Several other large components of the car are also made from PP, such as bumpers, dashboards and fenders. Where the design allows for it, these large PP components are also disassembled at Indra. This was observed during the visit described in Chapter 2.4. This creates the opportunity for all of these components to enter the same PP recycling stream at large scale rather than only the interior panels. Just like the aluminium stream, this recycled PP could then be used again in new vehicle production, contributing to a higher share of recycled plastic in new vehicles.

Recycling of Copper & CRM's

Components containing copper and CRM's are recycled in the same stream. Copper can be processed together with several precious and specialty metals, which means these metals can be recovered from a copper mixture. For this reason, electronic printed circuit board assemblies are best treated alongside copper waste (Balkenende et al., 2025). Because these components are removed from the frame, the copper and critical raw materials they contain can be channelled into this dedicated stream rather than being lost to contamination of the metal fractions. Recovering these materials is particularly valuable given the material specific recycling targets discussed in Chapter 2. Beyond meeting these targets, the recovered copper and CRMs can re-enter the European supply chain. This way Renault Group can contribute to the resource security and resilience the EU must build towards by 2030.

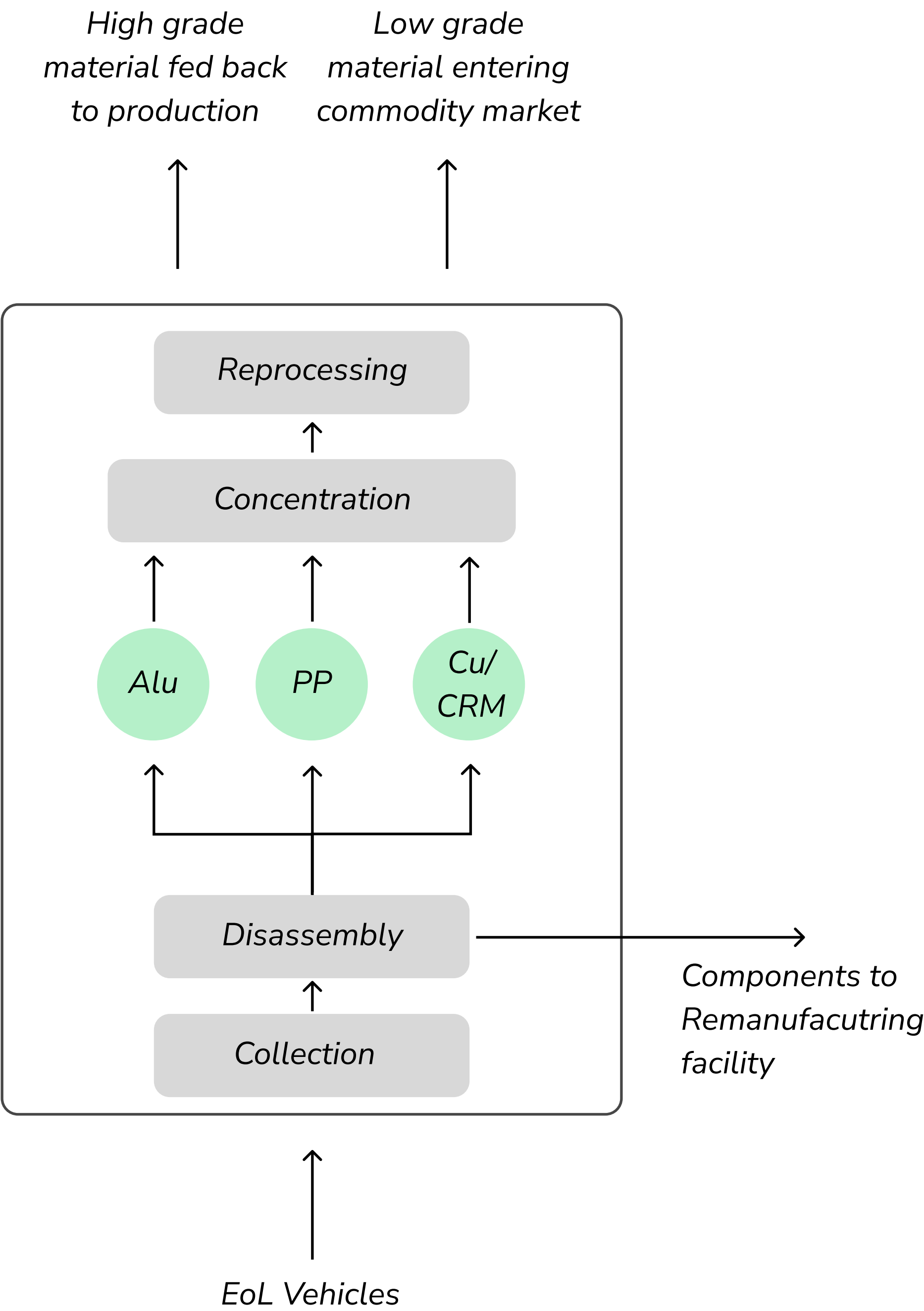


Figure 52 - Examples of flat cables

5.6 Styling & Design Freedom

A argument for the desirability of this concept is that the architecture allows the designers to retain some level of design freedom. This section explains how each of the four parts of the architecture allows for variation, and how the same architecture can be used to design interiors in different styles.

5.6.1 The Frame

The frame retains the structural and safety functions of the door. Because the frame is still produced using the same methods as a conventional door frame, its manufacturing feasibility is unaffected, and it can still be shaped to facilitate different exterior designs.

The main change to the frame is a single larger opening in its centre (figure 53). This opening creates the space into which the module is fitted and also provides the access needed to assemble and disassemble the components that remain inside the frame. Around this opening, four metal flanges extend outward. These flanges are used to mount the module, so that the frame continues to carry the structural and safety load of the door.

5.6.2 The Interior panel

The interior panel is a single part and holds the storage compartment. The main change compared to a conventional panel is again an opening in its centre, which allows the module to be fitted onto the frame (figure 54). As long as this hole facilitates that the module can be placed in this hole you can create different designs.



Figure 53 - The frame



Figure 54 - The interior panel

5.6.3 The Module

The module's design is not fixed but can be shaped in different ways as long as it provides enough space to house its components. Figure 55 shows several possible module designs, ranging from straight to rounded to chamfered.

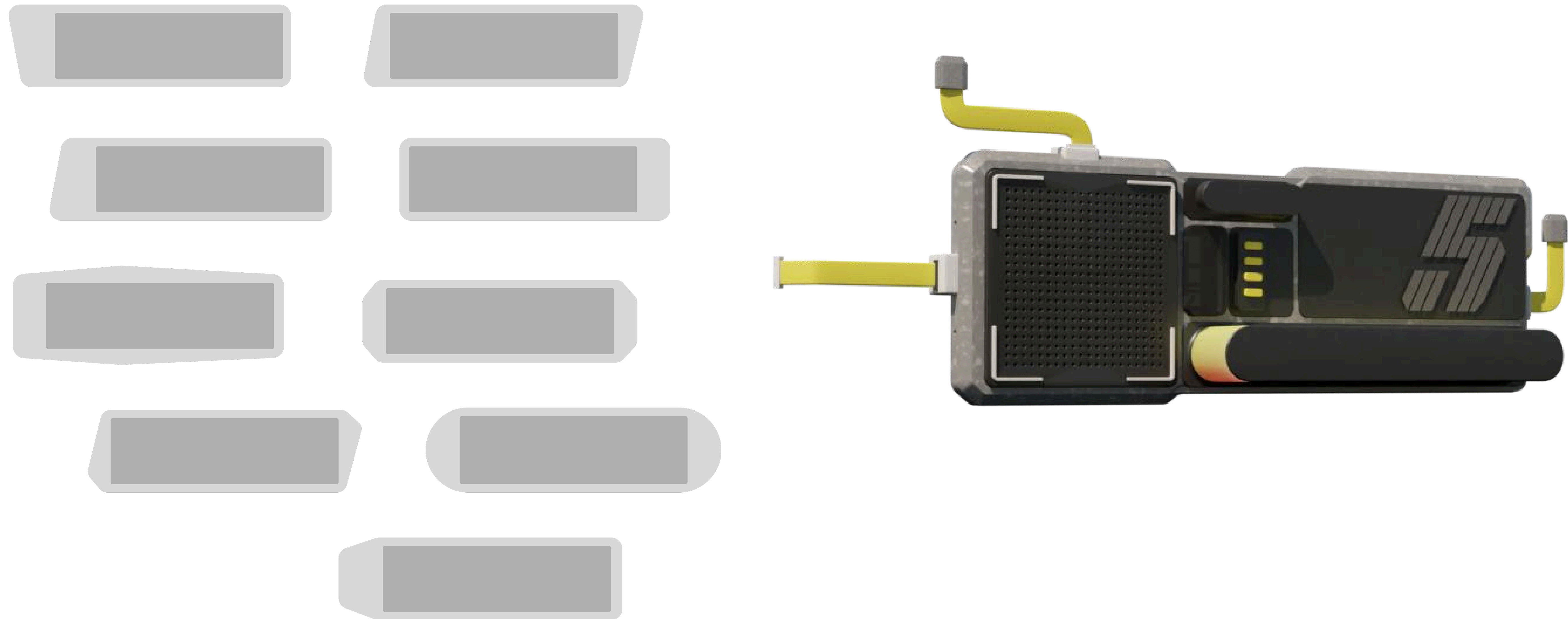


Figure 55 - the module in Renault 5 styling with components (right) and different styling ideas (left)

5.6.4 The Components

Each component consists of a functional element and a styling element. The functional element is standardized across different vehicle models (Chapter 5.3, while the styling element can be customized to fit the identity of a specific vehicle interior.

The styling elements can be customized to fit the identity of a specific interior. They mainly use shape and CMF (Colour, Material, Finish) to give each door a distinct character. Figure 56 shows different examples of different styling elements.

This distinction on component level contributes to making the architecture retain its design freedom. Standardizing the functional elements is what enables remanufacturing across models, while the styling element enables different designs, so the door is able to express a unique character and style.

It must be said that this architecture does not offer designers the same freedom they have today. Where components can currently be placed anywhere in the door and the interior panel can be shaped without constraint. This architecture fixes the position of the module, the mounting of the components, and the overall layering of frame, panel and module. These are real constraints. What the architecture does not do, however, is prescribe a single style. It defines a structure, not an appearance. Within that structure designers remain free to interpret the door in their own way through the shape of the module, the styling elements, and the CMF of each component. In this sense the architecture is closer to a design language than a fixed design. It sets the rules of the composition while leaving the style open.

To demonstrate how the same architecture can produce different styling designs, additional designs where made for the Renault Twingo (2025) interior, and the Dacia Hipster concept (2025), which can be seen in appendix F.

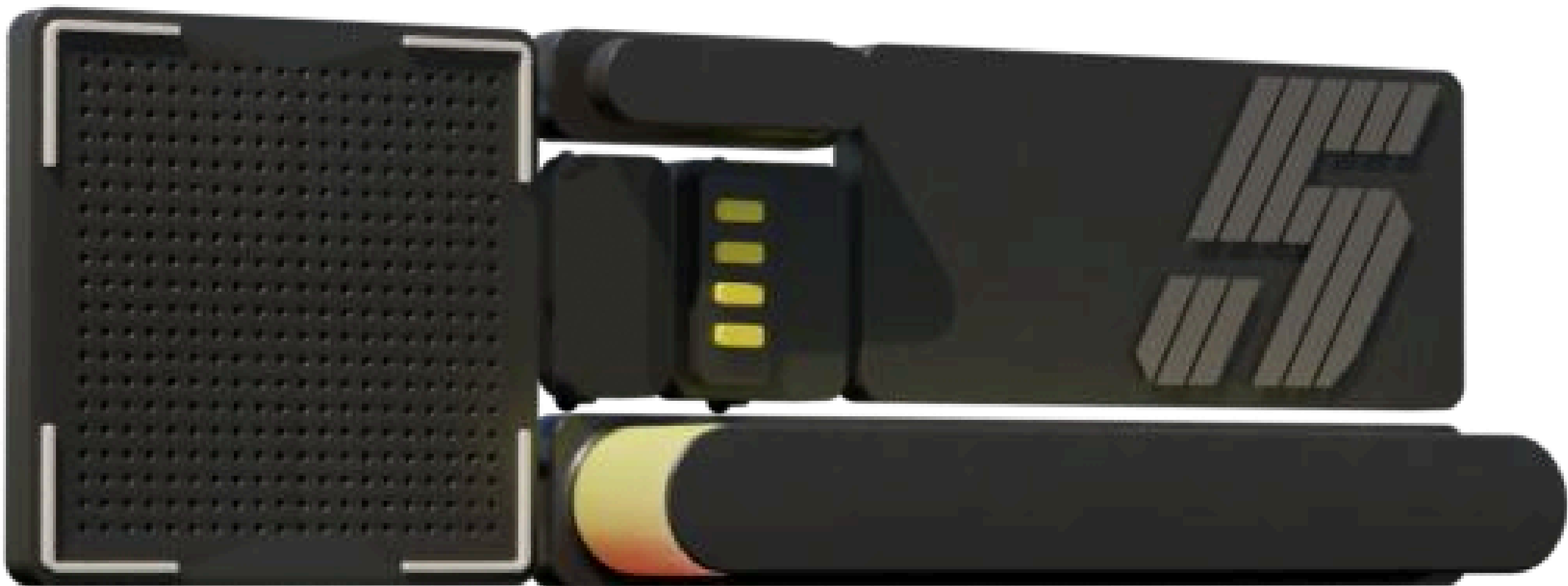
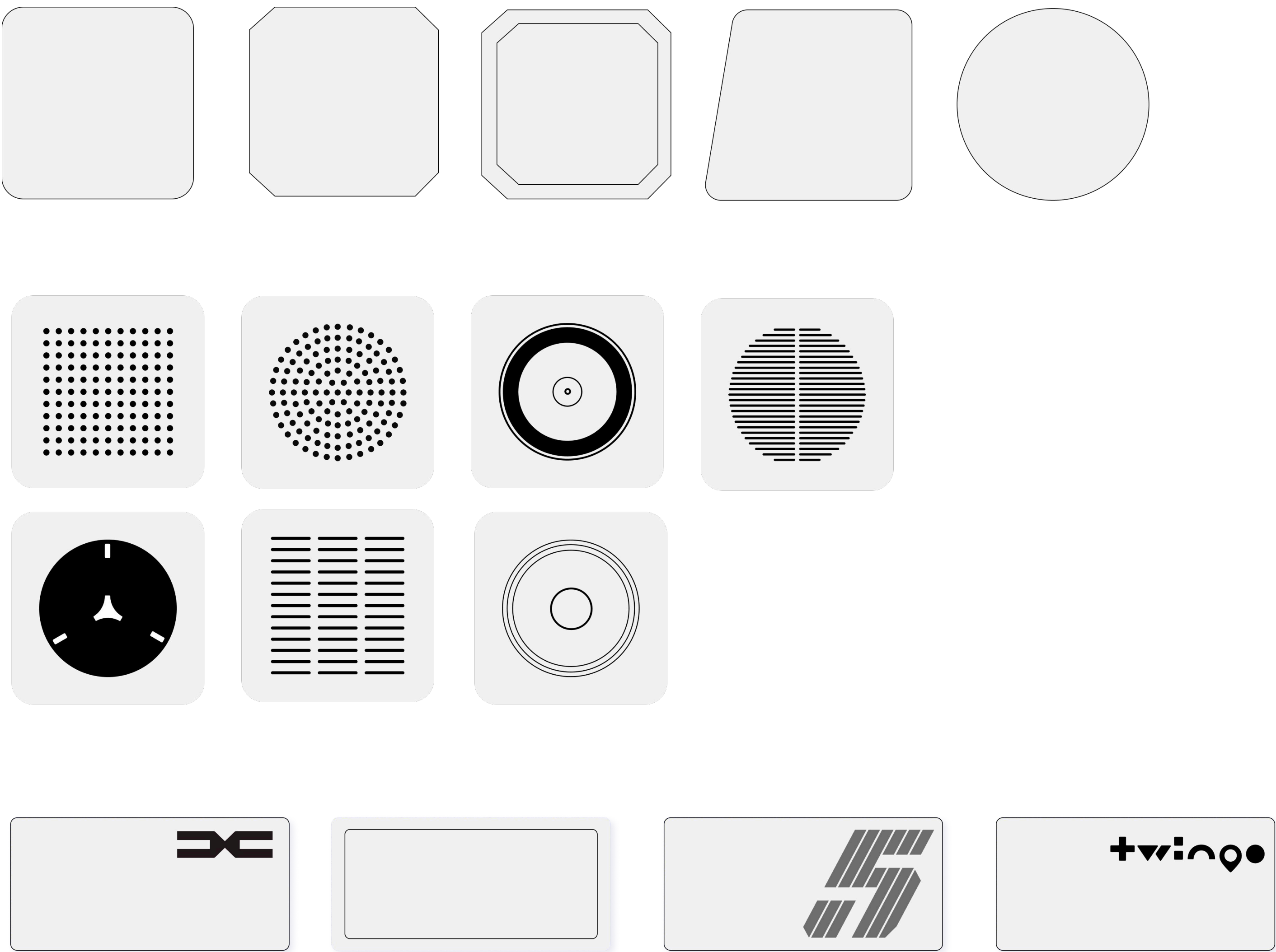


Figure 56 - the components in Renault 5 styling (right) and different styling idea's (left)

06

Validation

To assess whether the proposed architecture is desirable, feasible and viable for each stakeholder several validation interviews were performed. Four stakeholder groups were consulted, each positioned at a different point in the lifecycle. Designers and engineers at the start of life, a mechanic at the use phase and Indra at the end-of-life stage. Together they cover the full lifecycle the concept.

The design interview focused mainly on desirability and feasibility. The engineering interview on technical feasibility. The mechanic interview and the Indra interview on desirability, operational feasibility and viability during and at end-of-life. Every interview followed the same structure. It began with an introduction to the assignment, followed by a presentation of the concept tailored to the stakeholder's perspective. After this their reactions and concerns were gathered. In the next section the results of the interviews are summarized.

6.1 Design

The design interview was held with the head of interior design of Renault together with two lead designers. Because the desirability of the concept depends heavily on whether designers themselves see value in it, the interview focused on two questions: would designers find the architecture inspiring? And would it still leave them enough freedom to express the identity of a vehicle interior in different ways?

The response to the concept was positive. They described the architecture as strong and inspiring. Next to this they noted that its graphic, “exposed styling” as they called it, was new for car doors. The designers responded well to the idea that the same architecture can carry different styling designs across models and brands. They agreed that you could achieve a large contrast between designs after the R5 interior and the Dacia interior was shown.

A key insight during this interview that shows that the concept inspires designers, is when one of the lead designers spontaneously began sketching an alternative design based on the door architecture (figure 57). They also suggested that the styling could go even further than described in chapter 5.6.

For example by covering some components with fabric to align the door more with existing interior styling, or on the other hand, exposing the technical components even more deliberately.

The interview also raised some concerns. One of the lead designers observed that mounting components individually to the frame rather than grouping them in a module would give designers even more freedom. This is true, but it would directly undermine the disassembly benefit the module is built to deliver, which is precisely why the components are clumped. We came to the conclusion that this new architecture does limit some of the design freedom if you compare it to the old architecture.

Lastly, they confirmed the architecture is feasible from a design perspective, but the cabling cannot be left as exposed as it is now, as this would be unsafe.

“Inspiring concept with a new graphic style for car door interiors” – Head of interior Renault

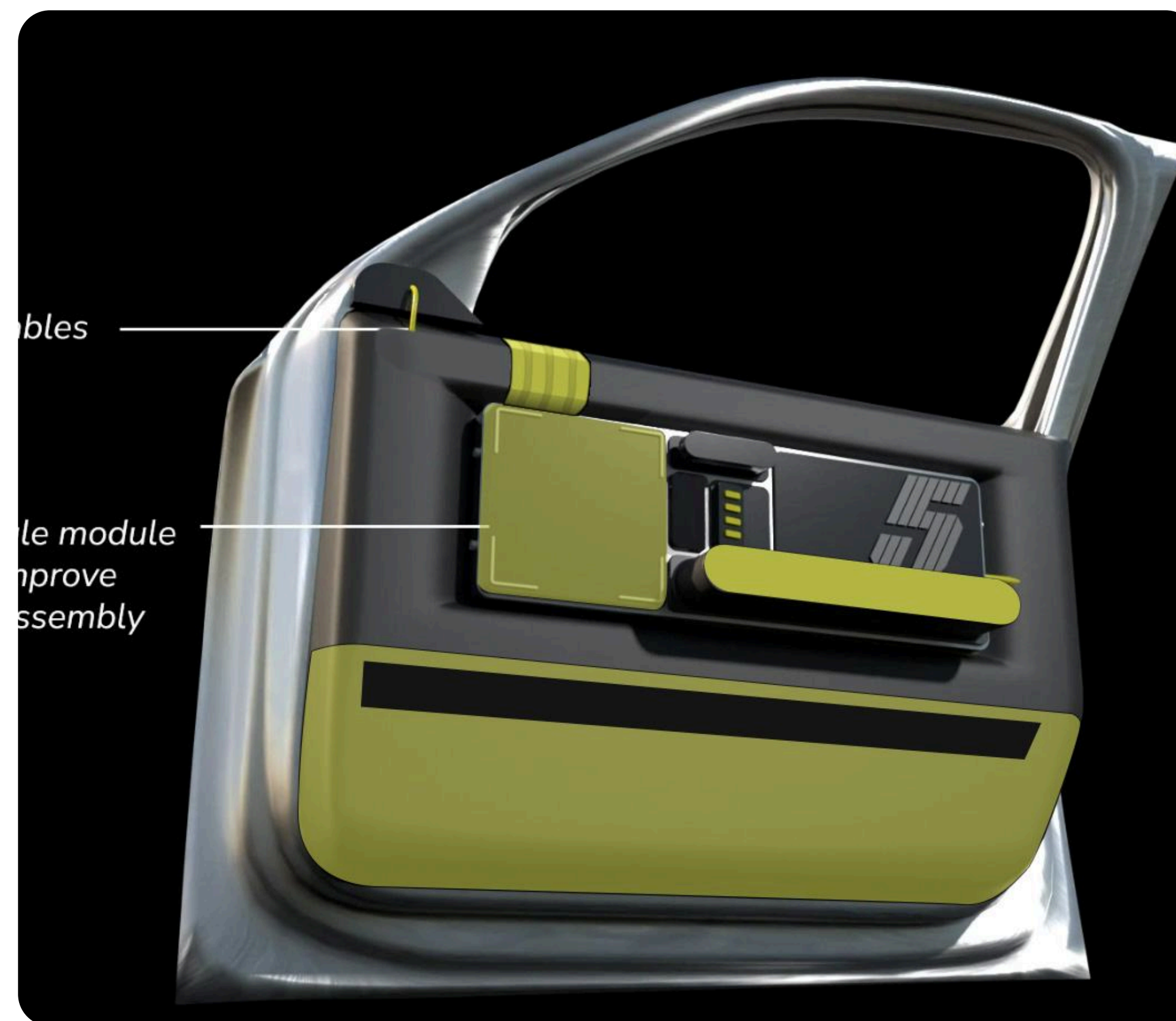


Figure 57 - Redesign proposed by interior designer during meeting

6.2 Engineering

The engineering interview was held with a Lead Engineer. Its goal was to test whether the door architecture is technically feasible to engineer and to produce.

The engineer said the architecture is technically feasible but the main risks identified were weight and cost. Weight is important as electric vehicles need to be kept as light as possible. Any change to the door must be assessed against its weight impact. Just as in the design interview, exposed wiring was raised as a concern as they could create dangerous situations. Next the connection between the window motor and the window mechanism was also identified as a challenge, since it differs from the way they do it now. But nonetheless considered it technically achievable.

From a production standpoint, the standardized screw connection has mixed implications. At the assembly stage, screws are slower to fit than the snap-fits currently used, which would add time to production. At the disassembly stage, however, screws are efficient and predictable. He responded well to the principle of a single standardized screw and recognised the value of a consistent connection across the entire assembly.

The engineer also saw economic potential in the architecture. Because the module groups functional components, it can be offered in different specifications: a bare-minimum version or a higher-specification version which makes the architecture flexible across vehicles from a cost perspective.

“So far as I can tell, this architecture seems technically feasible” – Lead engineer Renault

6.3 Mechanic

The mid-life stage was validated with a vehicle mechanic. The goal of this interview was to test whether the architecture improves reparability.

The mechanic's assessment of reparability was positive. In his view, repairing a door built on this architecture would become easier. Components and fasteners are far more accessible, and the working space created once the module is removed makes it simpler to reach the parts that are in the frame. He estimated that replacing a door lock mechanism could be reduced from often taking two to three hours to roughly one hour with this design. He also liked the fact that the interior panel no longer needs to be removed for most repairs. Current interior panels rely heavily on plastic clips (chapter 3.3) that harden over time and break when you remove the panel. Next to this, he considered the decision to keep the lock outside the module to be a good one, because the lock is one of the components that need repair most often. The exposed cabling was again raised as a possible problem as he believed it could get caught by other objects.

The mechanic also raised a concern regarding his own position. Because the door becomes easier to take apart, car owners may be more motivated to carry out repairs themselves, which could negatively impact the role of the professional mechanic. He suggested this could be avoided through a warranty structure, or by using uncommon tools that limit who can open the module.

Finally, the mechanic confirmed that a deposit-based return is already used in the automotive industry as seen in chapter 5.5. For certain parts, such as EGR valves and catalytic converters, ordering a new part requires returning the old one or paying a deposit. This way the old part can be remanufactured. This confirms the choice made in Chapter 5.5 to select a deposit-based relationship for the repair-network channel.

“Sometimes a repair on a lock can take up to 3 hours with this design this would maybe take me around 1 hour.” – Car mechanic

6.4 Indra

The The end-of-life stage was validated with Nicolas Paquet of Indra. This interview had the goal of testing the desirability, the feasibility and the viability of the concept at end-of-life. More specifically if the architecture would decrease disassembly time and enable higher component recovery and if material could be recycled with a higher quality.

Paquet's overall reaction was positive. He described the approach of the architecture as a good one and appreciated that the architecture makes components accessible and that each functional element sits independently within the module, as this improves recovery. He confirmed that the disassembly sequence seems possible for Indra to perform. He expected the architecture to affect disassembly time positively but could not estimate by how much. He recommended this be examined further. The same applied to disassembly costs: an economic assessment is needed to determine whether the sequence pays off from a cost perspective.

On recycling quality, Paquet confirmed the core mechanism behind the concept. The more wires and motors that can be removed before shredding, the higher the quality of the recovered metal. In that sense the architecture should improve the quality of the recycled material. However, he was uncertain whether the resulting quality would reach automotive grade.

Paquet also stated that qualification of parts is necessary before they can be reused or remanufactured. "To certify a recovered component you must know how often a lock has been operated or how many cycles a window motor has completed." This confirms from practice an insight already established in chapter 5.5, which stated that core quality must be known before a recovery decision can be made. It also validates the design decision explained in chapters 5.3 and 5.5. Which explained that accessing the Digital Product Passport through a QR code on the components enables a disassembly operator to read this usage data and asses a component's quality.

Paquet observed that the concept makes it possible to carry out a broader value assessment of a door. One that does not stop at production cost but also accounts for the value recoverable at end-of-life. This would allow Renault to evaluate how designing for circularity could increase the total value and thus the profit, generated across a door's full lifecycle.

6.5 Disassembly map

To assess the architecture's disassembly more quantitatively, a disassembly map of the new architecture (figure 57) was created and compared to the map of Door A from Chapter 3.6. Because the architecture is a concept rather than a physical prototype, it does not include the penalties, force intensity, or time per activity (chapter 3.6), as these cannot be reliably measured on a door that has not been built. Though it does capture all activities required to fully disassemble the door.

The most direct measure is the number of activities needed to reach a completely clean steel or aluminium frame, which drops from 28 to 18 in the new architecture (Table 6). Door A is used as the reference here because it was the only physically disassembled door for which a fully clean frame was actually achieved. The reduction comes mainly from clumping components into the module which enables a more parallel disassembly sequence instead of linear one. Beyond the total amount of activities, the amount of activities to reach the target components is reduced as well (Table 6). In both original doors, almost all components carrying an economic, environmental, or priority indicator sat deep in the tree. This required many sequential steps before they could be reached. In the new architecture these components are surfaced by the module and become accessible earlier compared to the process of Door A.

These results provide the first quantifiable indication that the new architecture could reduce disassembly time, as the number of activities reduced for all target components. This remains a projection based on a digital model rather than a measurement. To obtain truly quantifiable results, a physical model would need to be built and assessed against time, force intensity, and the disassembly penalties just as in chapter 3.6.

Target components	Door A	New Architecture
Structural frame	28	18
Wiring harness	10	4
Window motor	11	5
Controle module	11	5
Locking mechanism	9	5
Side view mirror	2	2

Table 6 - Activities required to reach each target component, Door A versus the new architecture

1. Side view
2. Wiring harness
3. Speaker
4. Control interface
5. Door control module
6. Interior door handle
7. Window motor
8. Armrest
9. Module
10. Lock mechanism
11. Interior panel
12. Horizontal window sealing strips
13. Window mechanism
14. Window guides
15. Window
16. Structure

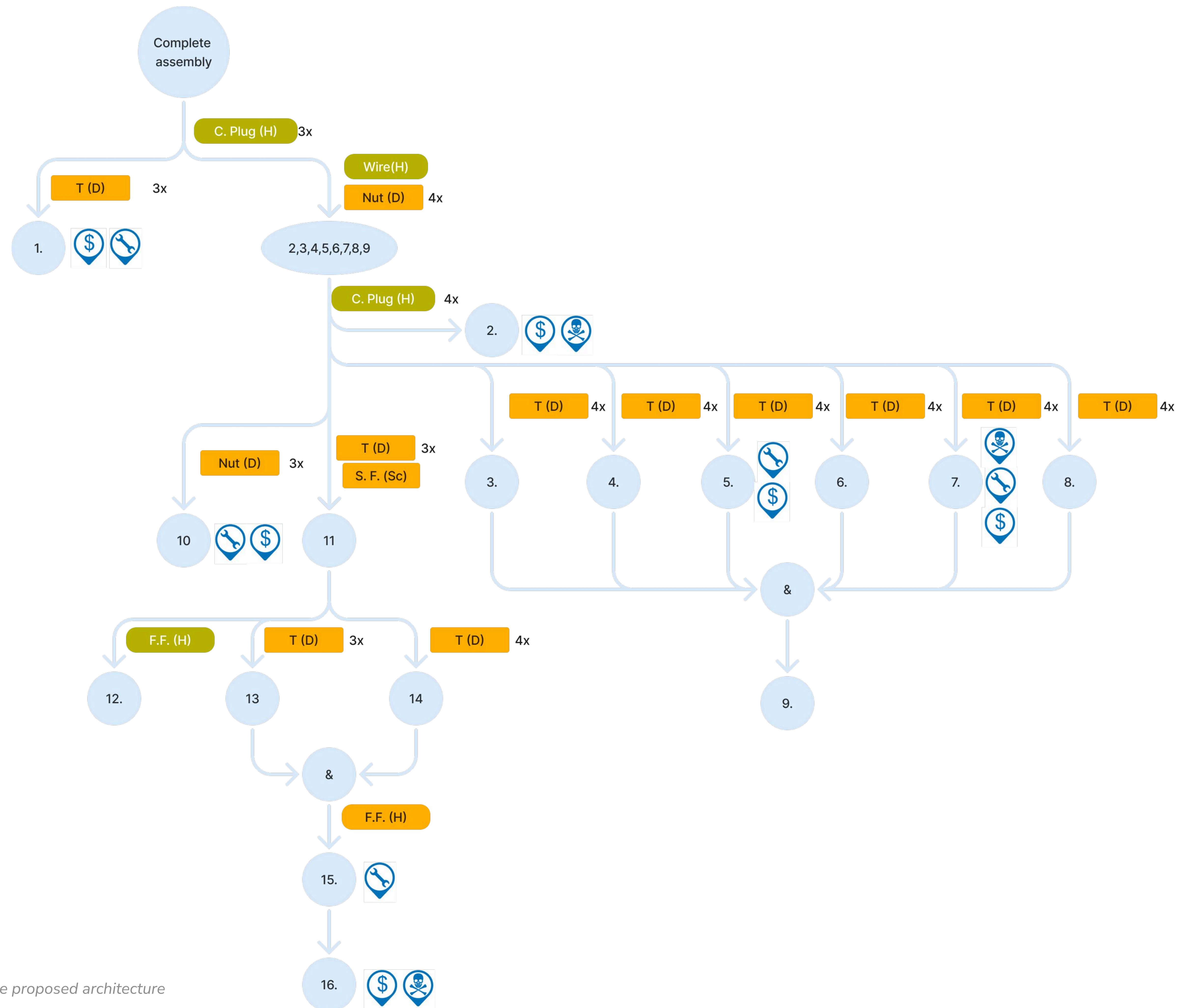


Figure 58 - New disassembly map using the proposed architecture



Discussion & Conclusion

This chapter reflects on the project as a whole. It first discusses the broader implications of the work for circular design research and for Renault Group, before setting out the limitations of the analysis, validation and concept. It closes with the conclusion of this thesis.

7.1 Implications

7.1.1 Insights to circular research

First of all, this thesis confirms a known insight from circular design research: the circular impact of a product is largely decided during the design phase, long before it reaches its end of life (Soo et al., 2020, Balkenende et al., 2025). This project adds to that insight by showing what it means for a company in practice. Renault Group can be seen as a best-case scenario. The ambition, the infrastructure and the partnerships for a circular system are already in place. Still, the analysis showed that this system cannot reach its potential, because the products entering it were never designed for it. This suggests that the circularity gap is not mainly an operational problem that can be solved with more infrastructure or better recycling technology, a route that Soo et al. (2020) also describe as limited. It is a design problem. Design should therefore not be seen as one step among many in the circular transition, but as the step that sets the conditions for all the others. It decides which R-strategies are technically possible and, through disassembly time, which of them can become economically viable (Vanegas et al., 2018; Tian & Chen, 2016). For Renault Group, this changes where the responsibility for circularity lies. It cannot be handed over to The Future is NEUTRAL at the end of the lifecycle. It has to be built into the development process itself.

Shu and Flowers (1999) found that design strategies aimed at different end-of-life routes can conflict with each other. The analysis in Chapter 4 showed this conflict. In the current door, fast disassembly and clean disassembly stand in direct trade-off. The proposed architecture shows that this trade-off is not a fixed property of the product, but a result of its design. In the new architecture, a single design decision serves both strategies at once. The same operation that makes components fast to recover, and therefore worth to refurbish or remanufacturing, also removes the copper-containing components that improves the recycling quality. This suggests that the conflict between end-of-life strategies can, at least in some cases, be dissolved through design.

7.1.2 Insights for Renault Group and the automotive industry

This thesis also contributes to Renault Group itself, and to the design department of Renault. Within Renault, circularity has mostly been treated as an operational topic, handled at the end of the lifecycle. For designers, sustainability requirements are then easily experienced as a constraint. Something that limits their freedom. This thesis shows that it does not have to be that way. The design philosophy of exposing, surfacing and clumping components turns circular requirements into a visual identity. A design feature rather than a limitation. This is also seen in the validation. The concept was described as inspiring and new by Renault's designers, while the visual language that inspired them is the same design decision that delivers the circular benefits. This suggests that circularity, when it is brought in at the start of the design process, can be a source of creativity instead of a constraint. Beyond the design studio, the architecture can be seen as the beginning of a bridge between three parts of the company that currently work separately: design, engineering and end-of-life operations. The analysis showed that decisions made in the studio determine what Indra and the Remakers can do years later, yet these stakeholders are barely connected in the current development process. This thesis is a first demonstration of what that capability could look like in practice. It showed a way of designing in which end-of-life stakeholders are treated as users of the product, whose requirements are part of the design brief from the start.

Finally, the findings are not limited to the door. Other subassemblies of the interior, such as the dashboard, the instrument panel or the seats, share the same characteristics that limit their circular performance. The door should therefore be read as a use case. The real contribution to Renault Group is the way of thinking it demonstrates, which can be carried into the rest of the vehicle.

7.2 Limitations

This section discusses the limitations of the analysis and the concept, and the future work that follows from them.

7.2.1 Limitations of analysis

The capability analysis in chapter 2 was derived from EU regulation and Renault Group's own initiatives. Two limitations follow from this. First, the policy landscape itself is still in motion. The targets proposed are unspecified, meaning the three trends are projections rather than certainties. Second, the analysis excluded broader strategic pressures on the European automotive industry, such as competition from Chinese OEMs. Including these could result in a broader or differently prioritised set of capabilities. The product analysis in chapter 3 was based on two doors rather than the three recommended by De Fazio et al. (2021), and both were from older vehicles. Newer doors could contain more electronics and more integrated components. The disassembly problems identified may differ from, or even understate, those of current designs. The component value assessment used indicative values excluding the operational costs of disassembly and recycling. To have a better understanding of value these should be taken into account.

7.2.1 Limitations of validation

The validation carries three main limitations. First, it is qualitative and based on a single interview per stakeholder. Multiple experts per stakeholder group would need to be interviewed to compare and confirm individual answers. Second, it tested a presented concept rather than a physical prototype. Stakeholders responded to drawings and renders, which leaves room for assumptions and cannot fully account for how the architecture would behave once built. Third, it set a first basis for quantifiable assessment but was not performed in real life. The disassembly map comparison indicates that activities could be reduced, but this is created from a digital model. Time, force, and penalties could not be measured, so the results should be read as an indication of potential rather than a measured outcome.

7.2.3 Limitations of the concept

The architecture should be interpreted as a way of thinking rather than a finished design. As stated in the discussion, it is not a design for one specific car door but a demonstration of how a door can be designed for the circular economy. The concept should be read with that intention in mind.

Because the architecture is a concept and not a finished prototype, the design has not been developed at component level. Detailed decisions on component level still need to be designed. These decisions will also have an impact on how fast and clean the recovery will be in practice. And therefore the feasibility and viability of remanufacturing and recycling the architecture aims to enable.

This applies in particular to the remanufacturing system. As explained in Chapter 5.3, a successful remanufacturing system depends on many factors beyond the product architecture itself, such as durability, core acquisition, quality assessment and the coordination between stakeholders within The Future is NEUTRAL. Fast disassembly that the architecture aims to achieve is a condition that opens up the opportunity for a remanufacturing system, but not a guarantee of a viable system. The viability of remanufacturing the door's components therefore still needs to be assessed before Renault Group commits to it.

From these limitations, several next steps follow. First, it should be tested whether designers can apply this architecture in practice, alongside the other constraints they work with, such as cost, weight and brand identity. And to see if the philosophy can be applied to different subsystems. Second, a physical prototype should be built to quantitatively assess the disassembly sequence against time, force and the disassembly penalties used in Chapter 3.6. Third, a business case for remanufacturing should be developed, together with an assessment of the extent to which recycling quality can be increased and whether the recovered material can re-enter vehicle production at automotive grade.

7.3 Conclusion

This thesis began by showing that the European automotive industry is under pressure. The industry is one of the largest consumers of primary raw materials, over six million vehicles reach their end of life in Europe every year, and the sector remains dependent on dominant suppliers for critical raw materials. At the same time, regulatory pressure through the proposed ELV Regulation and the Critical Raw Materials Act is pushing the automotive sector away from its linear model and towards circular practices. Renault Group initiated this thesis to bring circular design strategies further into its design process.

This led to the following design goal:

"Design a circular car door concept to demonstrate the potential created by remanufacturing and recycling, for Renault and its stakeholders within the 2030 sustainable mobility context."

To work towards this goal, three research questions were formulated:

RQ 1 What circular capabilities must Renault Group develop by 2030, based on legislation and the future policy landscape, and how do these relate to Renault's existing circular initiatives?

RQ 2 To what extent is the current Renault car door designed for the circular economy, and which characteristics limit its circular performance?

RQ 3 How can circular strategies be applied to the design of a car door to improve its circular impact within Renault's 2030 context?

Answer RQ 1.

The analysis of the ELV Regulation, the CRMA and the future policy landscape identified three capabilities Renault Group must develop by 2030: the ability to recover more materials and components and separate them more cleanly, the ability to secure recycled material inputs for new vehicle production, and the ability to embed circular design principles into new vehicle design. When these capabilities are compared with Renault's existing initiatives, it becomes clear that the operational foundation is largely in place through The Future is NEUTRAL, but that intervention at the design stage has stayed limited. Embedding circular design principles is the most important capability of the three. As improving recycling technology yields only limited gains, it is the design of a vehicle that determines for a large part what can be recovered and at what quality, and thus directly influences the other two capabilities.

Answer RQ 2.

The product-level analysis showed that the current Renault car door is not designed for the circular economy. The door is an integrated subsystem in which components are scattered throughout the depth of the door, sit deep in the disassembly tree and are individually fastened, making disassembly slow and costly. Poor material separation, most notably copper from the wiring harness and electric motors, contaminates the steel and aluminium streams and forces the recovered material to be downcycled. As a result, the value built into the door through design, engineering and manufacturing is largely destroyed at end of life. This contrast defines the circularity gap. While Renault Group is building a circular system, the products entering that system are still designed according to a linear logic, limiting the potential of this system. Closing this gap requires disassembly that is both fast, so that part harvesting becomes economically viable, and clean, so that materials can be recycled at higher quality instead of being downcycled.

Answer RQ 3.

The final design answers this need with a new door architecture built around a removable module. By clumping components into the module and surfacing them in the assembly, the architecture enables disassembly that is both fast and clean. The module can be liberated from the frame in a quick operation, enabling remanufacturing of standardized components, while the removal of copper-containing components before shredding allows the aluminium frame to be recycled at higher quality. The validation with stakeholders across the lifecycle and the disassembly map comparison indicate that the architecture improves disassembly while retaining the design freedom needed to apply it across Renault Group's models and brands.

This project is therefore not only a door, but a new approach to designing one. The architecture demonstrates that circular value is created upstream, in decisions made during design, long before a vehicle reaches its end of life. If circularity can be decided at the design stage, the same thinking can change how Renault Group approaches the rest of the vehicle interior, and how it judges the value of a product across its whole lifecycle rather than only at the moment of sale. The architecture should therefore be seen not as a finished design but as a starting point. Above all, this thesis shows that circularity, applied from the start of the design process, can be a source of inspiration and freedom rather than a constraint.

7.4 Reflection

This project has been quite a rollercoaster and made me learn a lot about the automotive industry, circularity but most of all about myself.

Managing expectations

One of the things I struggled with most during this project was managing the expectations of two parties at the same time. Renault and the TU Delft. I think I underestimated what it would mean to work inside a design studio where almost everything revolves around aesthetics, form, emotion and interaction. I was surrounded by impressive work, and for a while I caught myself trying to match it, chasing the same visual style I saw in the designers around me.

But my assignment was broader than that. It combined design, engineering and strategic decision-making, and at its core it kept asking an uncomfortable question. Why is a door designed this way, and is this really the best way when you look at it through the lens of circularity? That question often ran against the grain of how Renault's designers were used to working. For them the emphasis still sat firmly on aesthetics, and the way of thinking I was bringing was new and unfamiliar to them.

On the other side stood the TU Delft, which expects critical, well-substantiated research. Aesthetics matter there too, but they are not the core of the work. So I was constantly moving between two stakeholders pulling in different directions. One wanting to dive straight into how the door looks, the other wanting the reasoning and the evidence underneath it. For a long time this left me with the feeling that, whichever way I turned, I was somehow missing the mark for someone. Eventually this uncertainty, pressure to perform and keep everyone satisfied with my work, built up to a point where I had to step back and recover before I could keep going.

Embracing uncertainty

After this time, I could slowly embrace the uncertainty more, and I realized that what the project asked of me was not to resolve this uncertainty but to navigate it. To rely on my own judgement as a designer and decide, at each moment, which questions deserved my attention and which could wait. Focusing on what mattered most at a given stage, instead of trying to address everything at once, let the project develop more clearly, step by step. And as it developed, something shifted on the other side too. The designers began to see the real intention behind the project rather than only the form of the door. Which made it easier to communicate.

Looking back, learning to work with several stakeholders at once, each with their own priorities, expectations, and at times even language, turned out to be one of the most valuable things this project taught me. It is rarely about finding the single answer that satisfies everyone, but about understanding what each party values, communicating in a way that actually reaches them, and relying on your own skills while doing so. It is a skill I expect to rely on in almost any project I take on, and one I feel far more capable of now than I did at the start of this project.

With that being said I think I can be proud of the end result I managed to achieve. Receiving positive reactions as well from both the designers and an important stakeholder like Indra. I think I have created a concept that resonates with the designers of Renault and sparks creativity and ask a question to the designers can we approach design differently. Which was exactly the goal of the project and a goal I set for myself in the project brief.

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09.

Appendices

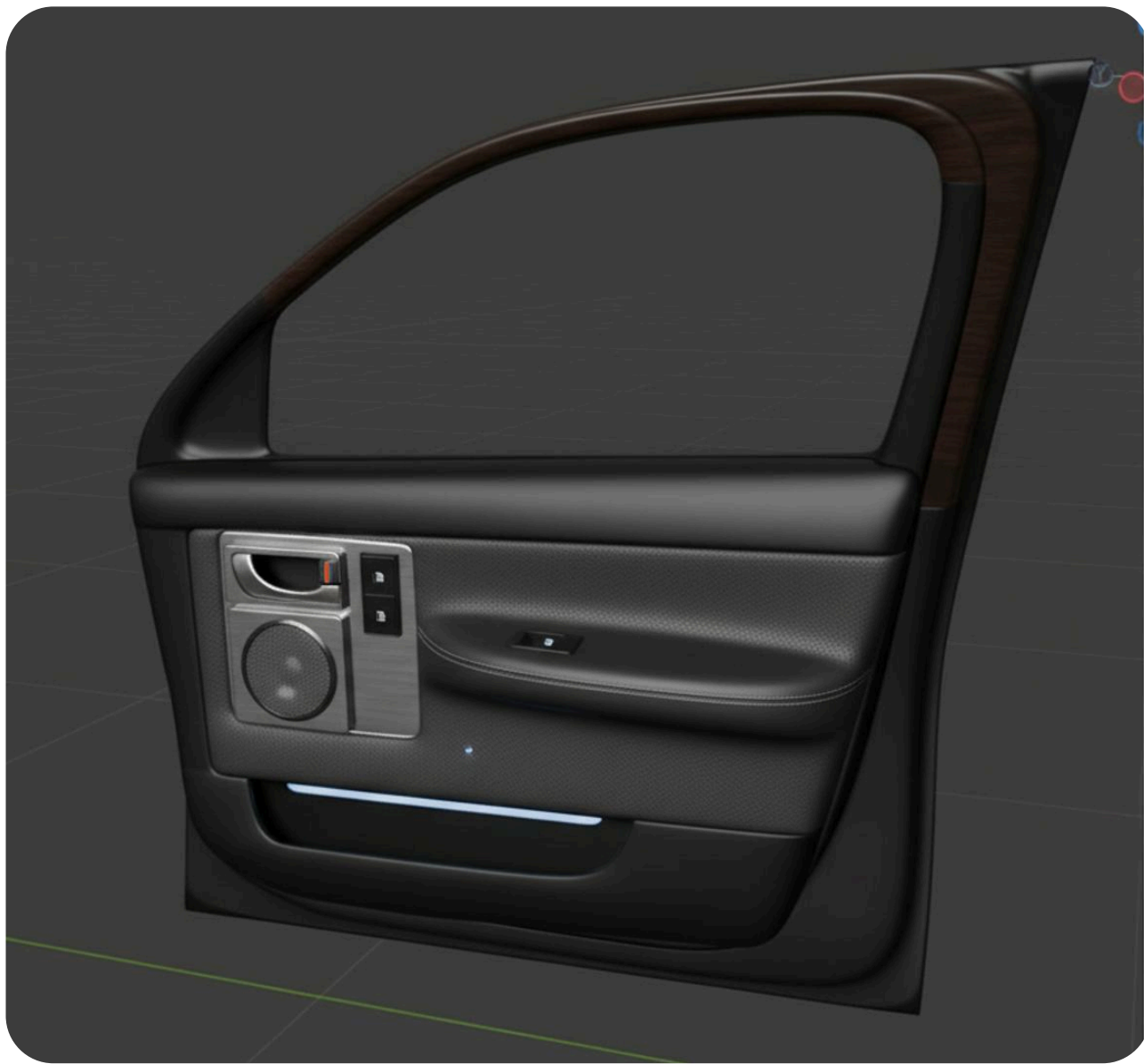
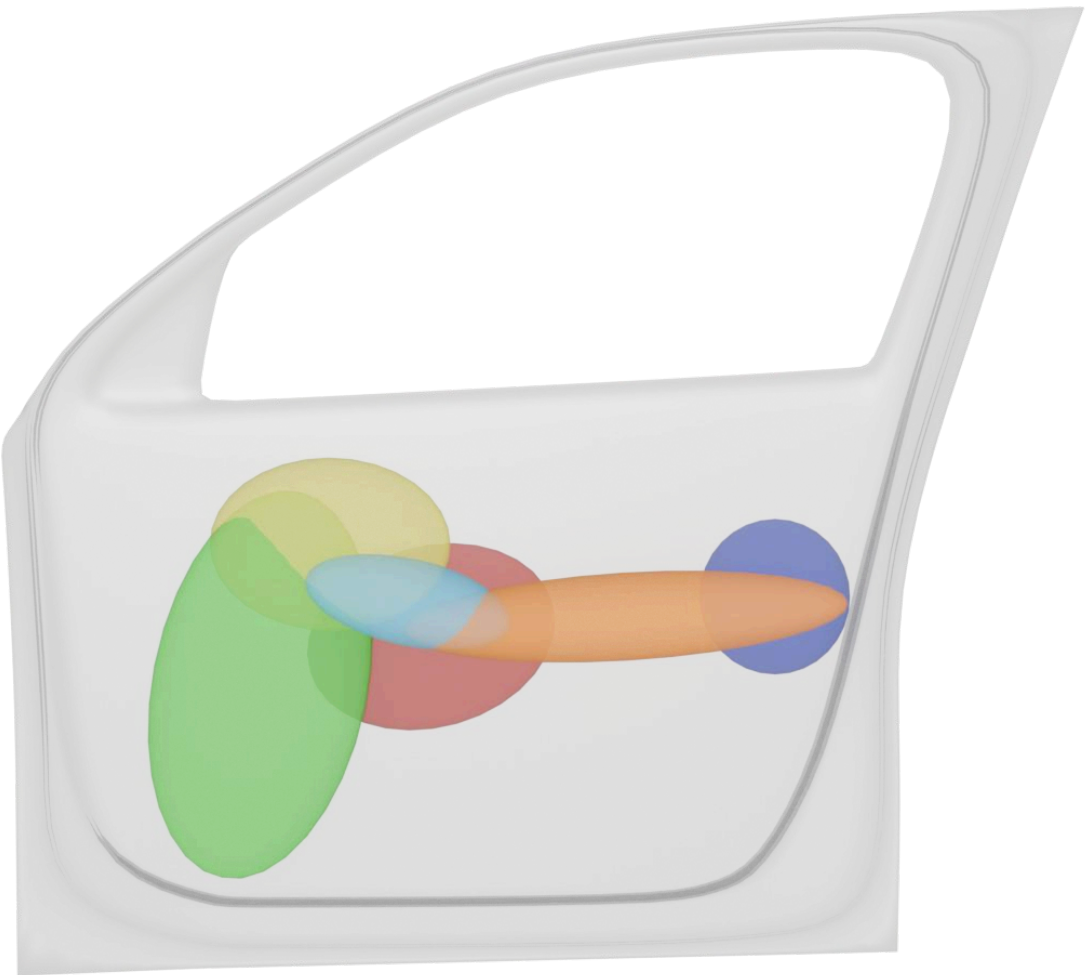
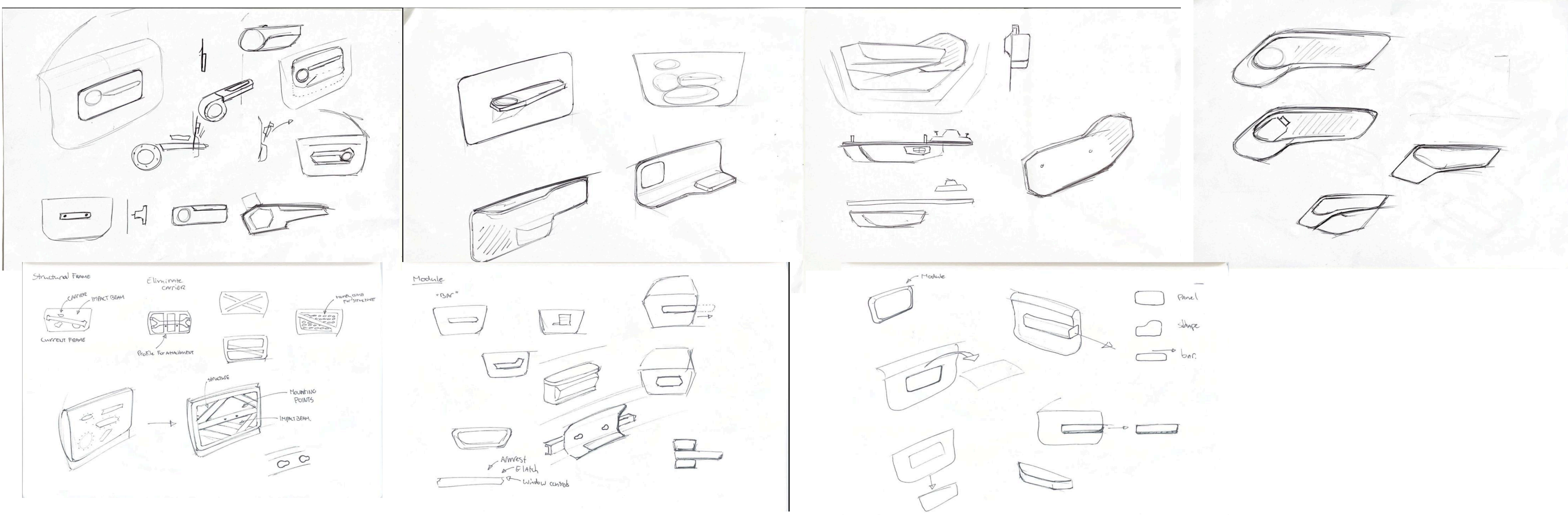
Appendix A

List of strategic raw materials
The following raw materials shall be considered strategic:
(a), bauxite/alumina/aluminium
(b), bismuth
(c), boron — metallurgy grade
(d), cobalt
(e), copper
(f), gallium
(g), germanium

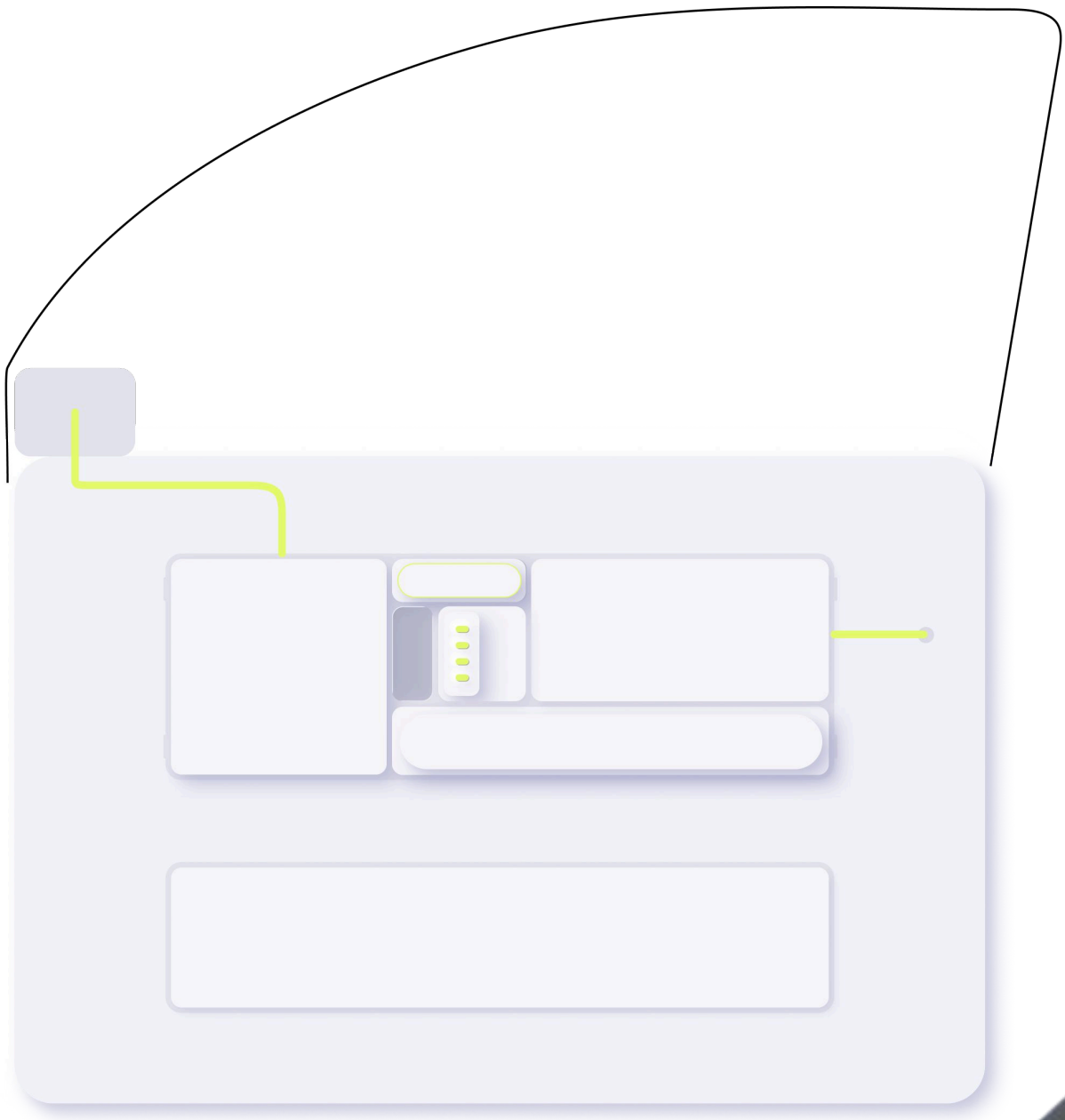
(h), lithium — battery grade
(i), magnesium metal
(j), manganese — battery grade
(k), graphite — battery grade
(l), nickel — battery grade
(m), platinum group metals
(n), rare earth elements for permanent magnets (Nd, Pr, Tb, Dy, Gd, Sm, and Ce)
(o), silicon metal
(p), titanium metal
(q), tungsten

Appendix B

Overview of the design iterations
Iteration 1 - ideation and intial concept



Iteration 2 - styling, sizing core princples in 2D



Iteration 3 - 3D modelled for Disassembly sequence & Renault Styling



Iteration 4- final concept



Appendix C

Image of the Renault 5 interior



Appendix D

Overview and description of the different closed-loop relationships for gathering cores for remanufacturing.

- Ownership-based: this type of relationship is common when the product is owned by the manufacturer and operated by the customer, as for example in a rental, lease or product-service offer. Here, the control of the installed base is high and often regulated by contracts.
- Service-contract: this type of relationship is based on a service contract between a manufacturer and a customer that includes remanufacturing.
- Direct-order: the customer returns the used product to the remanufacturer, the product is remanufactured and the customer gets the same product back (if it is possible to perform a remanufacturing operation).
- Deposit-based: this type of relationship is common in the automotive industry. When the customers buy a remanufactured product, they are obligated to return a similar used product, thus also acting as a supplier to the remanufacturer.
- Credit-based: when the customers return a used product they receive a specific number of credits for the returned product. These credits are then used as a discount when buying a remanufactured product.
- Buy-back: the remanufacturer simply buys the wanted used products from a supplier that can be the end user, a scrap yard or similar, or a core dealer.
- Voluntary-based: the supplier gives the used products to the remanufacturer. The supplier can also be a customer but do not have to be.

Appendix E

Overview of recycling compatibility

		Copper	Aluminum	Steel	
Ferrous metals					
Alloy steel	Fe	●	●	✓	Housing, mechanical parts, connections
Carbon steel	FeC _x	●	✗	✓	Structural components (housing, frame)
Stainless steel	FeCr _x Ni _y	●	✗	✓	Food appliances, medical products
Non-ferrous metals					
Precious metals					
Copper	Cu	✓	●	✗	PCB conductor; wiring; thermal conductor; structural parts
Gold	Au	✓	✗	✗	Electronic contacts electroplating, bonding wires
Mercury	Hg	✓	●	✗	(restricted in EU) Fluorescent lamps, some cell batteries
Osmium	Os	✓	✗	✗	Ballpoint / fountain pen; electrical contacts; incandescent lamp
Palladium	Pd	✓	✗	✗	Fuel cell electrode
Platinum	Pt	✓	✗	✗	Electrode in high-end equipment(pacemaker), thermocouple
Silver	Ag	✓	✗	✗	Electronics (contacts, switches, antennas); printed electronics
Other metals					
Aluminum	Al	●	✓	●	Thermal conductor; structural components; wiring
Antimony	Sb	●	✗	✗	GaSb semiconductor: infrared LEDs & sensors; flame retardant
Bismuth	Bi	✓	✗	✗	Solder material; thermoelectric component
Cadmium	Cd	✓	✗	✗	(restricted in EU) Ni-Cd batteries; pigments (orange, yellow, red)
Chromium	Cr	✗	✗	●	Stainless steel alloy element
Cobalt	Co	✓	●	●	Electrode material in lithium-ion batteries
Lead	Pb	✓	✗	●	(restricted in EU) Solder; lead batteries
Lithium	Li	✗	✗	✗	Lithium ion batteries
Magnesium	Mg	●	●	●	Alloy element in aluminum; light-weight structural components
Nickel	Ni	✓	✗	●	Batteries, capacitors, switches, transformers; stainless steel alloy
Rare earth metals	RE	✗	●	●	High performance magnets
Silicon	Si	●	●	●	Semiconductor (ICs, PV cells); alloy element in aluminum
Tin	Sn	✓	●	✗	Solder; main alloy element in bronze
Titanium	Ti	✗	✗	●	Lightweight corrosion resistant structures; medical implants
Zinc	Zn	✓	✗	●	Main alloy element in brass
Osmium	Os	✓	✗	✗	Ballpoint / fountain pen; electrical contacts; incandescent lamp
Palladium	Pd	✓	✗	✗	Fuel cell electrode
Platinum	Pt	✓	✗	✗	Electrode in high-end equipment(pacemaker), thermocouple
Silver	Ag	✓	✗	✗	Electronics (contacts, switches, antennas); printed electronics
Other metals					
Aluminum	Al	●	✓	●	Thermal conductor; structural components; wiring
Antimony	Sb	●	✗	✗	GaSb semiconductor: infrared LEDs & sensors; flame retardant
Bismuth	Bi	✓	✗	✗	Solder material; thermoelectric component
Cadmium	Cd	✓	✗	✗	(restricted in EU) Ni-Cd batteries; pigments (orange, yellow, red)
Chromium	Cr	✗	✗	●	Stainless steel alloy element
Cobalt	Co	✓	●	●	Electrode material in lithium-ion batteries
Lead	Pb	✓	✗	●	(restricted in EU) Solder; lead batteries
Lithium	Li	✗	✗	✗	Lithium ion batteries
Magnesium	Mg	●	●	●	Alloy element in aluminum; light-weight structural components
Nickel	Ni	✓	✗	●	Batteries, capacitors, switches, transformers; stainless steel alloy
Rare earth metals	RE	✗	●	●	High performance magnets
Silicon	Si	●	●	●	Semiconductor (ICs, PV cells); alloy element in aluminum
Tin	Sn	✓	●	✗	Solder; main alloy element in bronze
Titanium	Ti	✗	✗	●	Lightweight corrosion resistant structures; medical implants
Zinc	Zn	✓	✗	●	Main alloy element in brass

Appendix F

Image of the Renault twingo interior and new architecture using this styling



+twingo

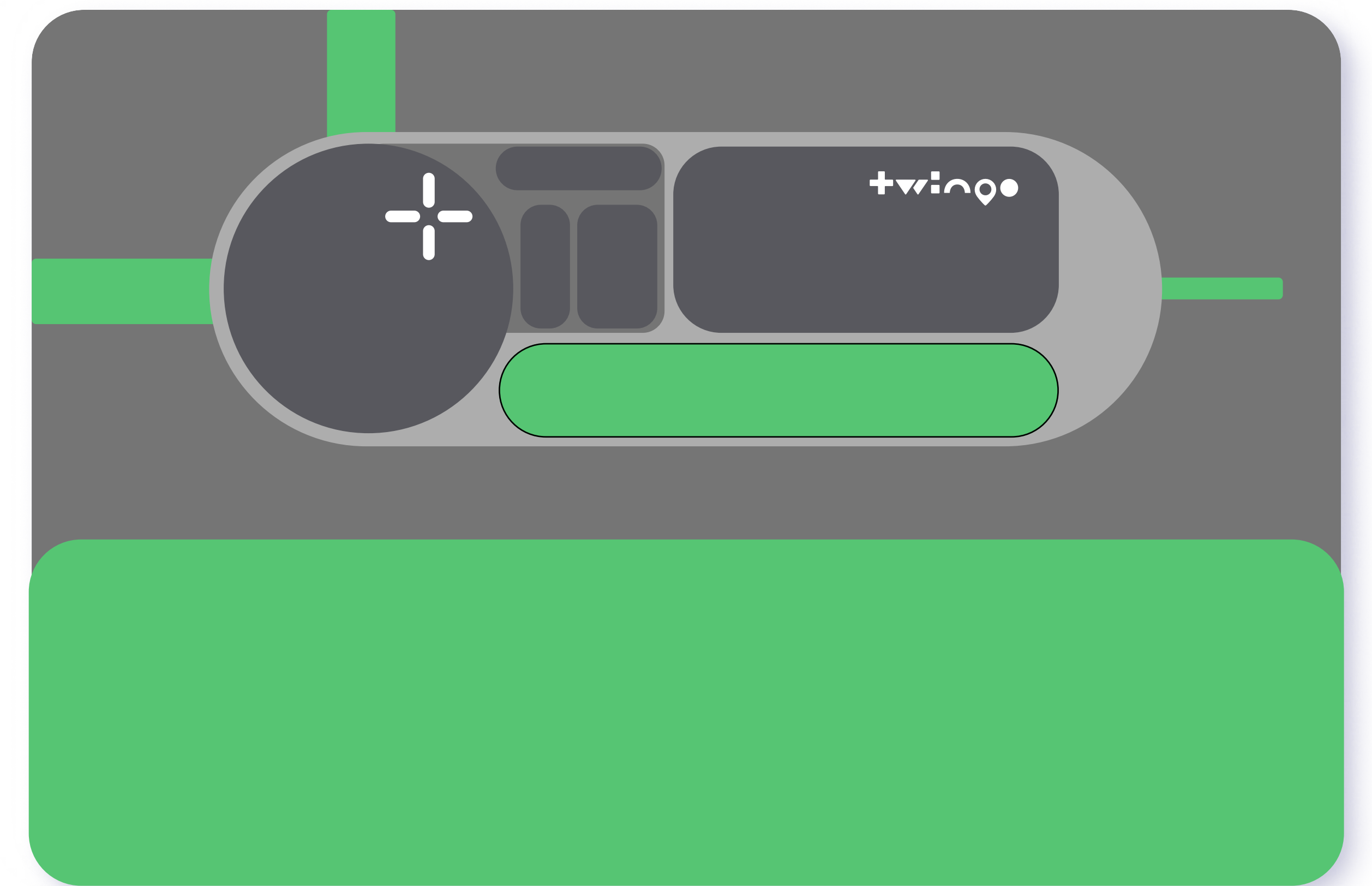


Figure 45 - Renault twingo (2025) interior. Renault (2026)

Image of the Renault twingo interior and new architecture using this styling

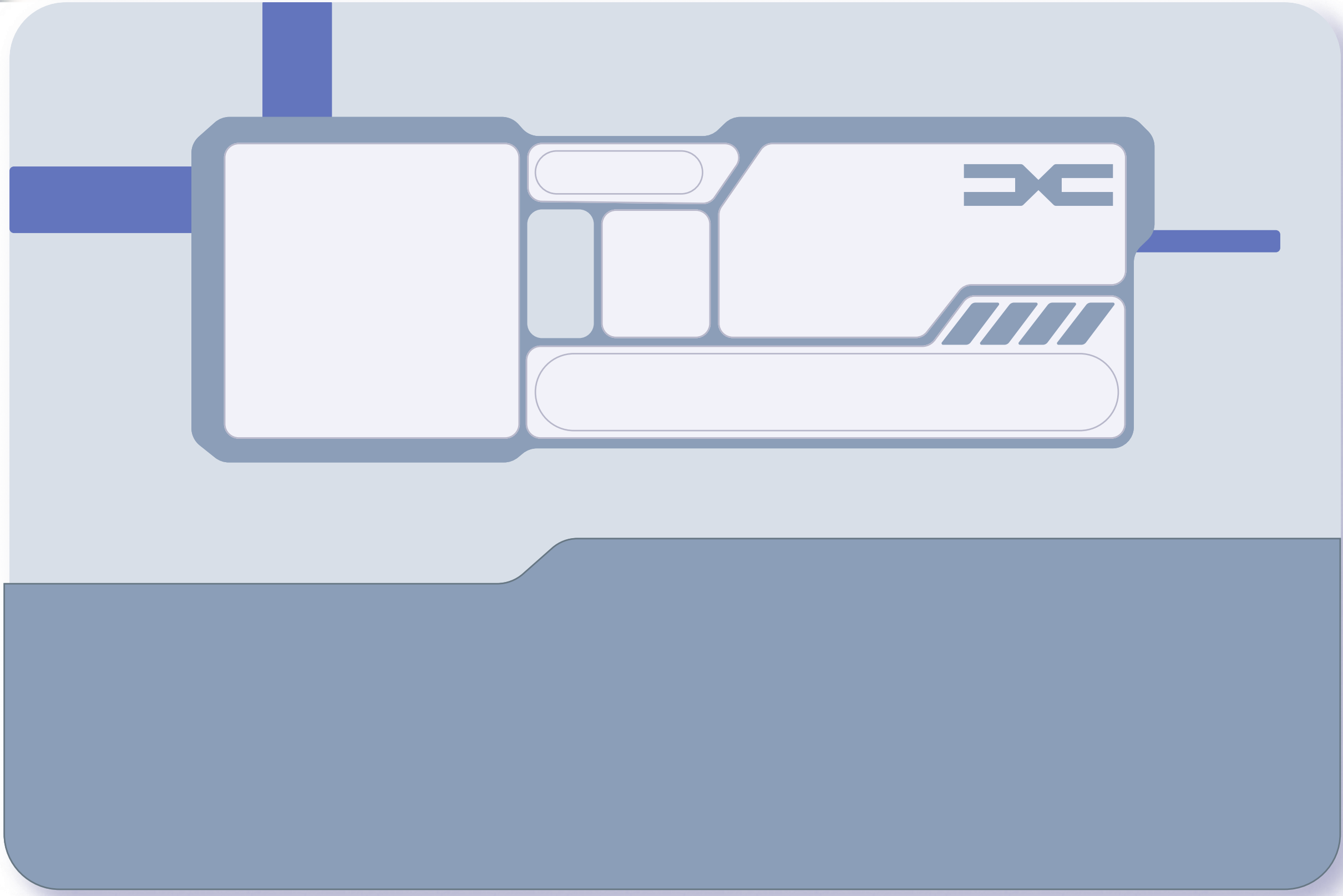


Figure 48 - Interior of Dacia Hipster Concept (Dacia, 2026)

Appendix G



Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice. (max 200 words)

The main problem is that although companies like Renault want to transition toward a circular business model, they often lack concrete methods and examples of how to translate circular economy principles into product design. Circularity is still abstract at the subsystem level, and without clear design strategies, it is difficult to know how components should be created for reuse, remanufacturing, repair, or recycling. This project addresses that gap by demonstrating how a car door (a complex subassembly with different parts and features) can be designed as part of a larger circular system.

The extra value of this project for Renault is that this project can be seen as a concrete example/ pilot of how to design a subassembly with the circular strategy in mind. From this a replicable design approach can be generated that can be applied to other subassemblies as well. This ensures Renault designers and engineers have a uniform approach to developing future products, which can accelerate the company’s transition toward circularity.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design a circular car door prototype & system to demonstrate the potential created by reuse, repair, remanufacturing and recycling, for Renault and its stakeholders within the 2030 sustainable mobility context.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

The project will start with a kick-off with Renault to define the outcome and scope of the project, ensuring that the design direction aligns with the company’s circular ambitions. The next phase will focus on analysis: examining the industry & context, understanding the supplier and stakeholder network, benchmark competitor initiatives, seeing from which components and materials a door assembly exist by visiting assembly sites and taking a door apart, seeing from which components a door assembly exists and studying value retention strategies and future trends within this 2030 context. Building on this research, a roadmap will be developed to show how Renault can transition towards a circular model over time. From this roadmap, the 2030 milestone will be selected as the basis for design and certain hotspots of parts/subassemblies will be identified. Circular strategies (Modularity, repairability, disassembly etc) will be defined for each of these hotspots allowing for ideation of the product and the circular system. Idea’s will be transformed in to concepts and validated together with circularity experts and Renault. The most promosing concept(s) will be designed in more detail, resulting in a prototype/demonstrator of the circularity principles used and a graduation report.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a kick-off meeting, mid-term evaluation meeting, green light meeting and graduation ceremony. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).

Make sure to attach the full plan to this project brief. The four key moment dates must be filled in below

Kick off meeting20 okt 2025

Mid-term evaluation17 dec 2025

Green light meeting20 feb 2026

Graduation ceremony27 mrt 2026

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five. (200 words max)

I began my studies at TU Delft with the ambition to become a car designer. But during my studies, I began to recognize some of the limitations of the automotive industry. Despite its technical innovation, its somewhat of a conservative industry. This realization pushed me to broaden my perspective. Throughout my masters program I became increasingly drawn to Sustainability and Circularity and explored this further in an exchange program to Stockholm. The idea of designing products that have a genuinely positive impact on society inspired me. This assignment, therefore, feels like an exciting challenge, an opportunity to see whether I can integrate principles of circularity into an industry that has always fascinated me.

Finish with a project that Renault can actually use: As the topic of circularity is somewhat of a paradox in a highly competitive, profit driven industry It would be a very nice goal to end up with a well-grounded feasible concept /that inspires people at renault even the ones that are more skeptical about the concept of circularity.

Grow as a designer: as there is a lot of knowledge around me in the design studio as it is an amazing oppourtuny to work inside a automotive design studio. Therefor I want this experience also to be a chance to upgrade my design skills. I would be amazing if I could learn drawing and modelling software at a professional level (photoshop and Alias).

Appendix E

DESIGN
FOR our
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TU Delft

IDE Master Graduation Project

Project team, procedural checks and Personal Project Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

STUDENT DATA & MASTER PROGRAMME

Complete all fields and indicate which master(s) you are in

Family name

Hootsmans

Initials

LLH.

Given name

Lenne

Student number

4880366

IDE master(s)

IPD

☒

Dfi

☐

SPD

☐

2nd non-IDE master

Individual programme
(date of approval)

Medisign

☐

HPM

☐

SUPERVISORY TEAM

Fill in the required information of supervisory team members. If applicable, company mentor is added as 2nd mentor

Chair

Conny Bakker

dept./section

Circular design

mentor

Joost Alferink

dept./section

Design aesthetics

2nd mentor

client:

city:

country:

optional comments

!

Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

!

Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.

!

2nd mentor only applies when a client is involved.

APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in by the Chair of the supervisory team

Sign for approval (Chair)

Name

Date

Signature

DESIGN
FOR our
future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student

Lenne Hootsmans

Student number

4,880,366

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title

Circular Car Door

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The automotive industry is at a turning point, transitioning toward more sustainable, circular practices in design and production. One of the most critical yet complex components in vehicle design is the car door — a subsystem that integrates mechanical, electronic, aesthetic, and safety functions. Car doors are traditionally designed with a linear approach in mind: extract, produce, use, dispose. However, with growing pressure to reduce environmental impact and material waste, there's a need to rethink the design of these components through the lens of circular economy principles.

This assignment will explore how circular value retention strategies, such as reuse, repair, refurbishment, remanufacturing, and recycling can be effectively applied to the design and lifecycle of a car door, without compromising on performance, safety, or user experience.

The main stakeholder is Renault. For Renault, circular design reduces material consumption, waste and creates new value over a vehicles lifetime. Other stakeholders include:
Suppliers: who seek long-term business opportunities for parts
End customers: who value safety, durability, affordable maintenance and more sustainable products
After-sales and service networks:who benefit from easier repair and upgrades;
Recycling and remanufacturing companies: who depend on efficient material recovery and component reuse.

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