SALIENT

Safer, Lighter, Circular, Smarter

» DELIVERABLE D2.1

ECO-DESIGN STRATEGY FOR THE STRUCTURAL COMPONENTS

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DISSEMINATION LEVEL

Abbreviation	Meaning	
PU	Public, fully open (Deliverables flagged as public will be automatically published in CORDIS project's page).	[X]

LIST OF ABBREVIATIONS

Abbreviation	Meaning
BIW	Body in White
CE	Circular Economy
CO_2	Carbon Dioxide
DFA	Design for Assembly
DfEoL	Design for End of Life
DFD	Design for Disassembly
DfR	Design for Repair
DFRe	Design for Reliability
DfRem	Design for Remanufacturing
DFX	Design for excellence
DOE	Design of Experiments
ELDA	End-of-Life Design Advisor
EOL	End-of-Life
FES	Front-End Structure
FMEA	Failure Modes and Effects Analysis
FTA	Fault Tree Analysis
LCA	Life Cycle Assessment
LED	Light-Emitting Diode
OEM	Original Equipment Manufacturer
RT	Reliability Testing
WEEE	Waste electrical and electronic equipment

TABLE OF CONTENTS

List of Figures

List of Tables

1. EXECUTIVE SUMMARY

The automotive sector is under pressure to diminish its carbon footprint to keep up with the EU Fit for 55 and zero carbon by 2050 goals. It has been estimated that up to 80% of all environmental impacts are determined during the design phase of products. That is why the refinement and development of Eco-design strategies and assessments are vital to the industry. It is essential to recognise that eco-design strategies are specific to each design target, and therefore customisability of ecodesign targets should be included. Next to customisability, ease of use should be priorities to reduce the time and complexity of assessment.

This report, designed as a deliverable, aims to provide robust strategy that end-users, and designers can use in tailoring and streamlining their approaches to eco-design. This document accomplishes this by presenting a range of assessments, each contributing a supplementary step to eco-design e.g. 1. tactics and guidelines with planned strategies to preserve product and material integrity, 2. tools that support the application of the strategy by providing user guidance and managing data to take decision (Material Matrix Assessment MMA).

The proposed strategies are tailored to align with the objectives of the SALIENT project to show the immediate applicability to a use case. Our strategies and assessment, within the context of the SALIENT project serve the purpose of evaluating the optimal material selection for various components. The assessment considers different eco-design considerations, including the potential for lightweight design, recyclability, ease of assembly/disassembly, reduction of dependencies, and compatibility with the existing assembly line.

2. AIM AND OBJECTIVES

This deliverable aims to provide designers with guided Eco-design strategies to build product design and systems with benefits from reducing environmental impact, improving efficiency, and promoting innovation. In other words, the suggested Eco-design strategies can help to create a more sustainable and prosperous future.

With the increase in consumers' awareness of the product's environmental impact in the last ten years, the automotive industry gets motivated to understand and consider Eco-design approaches. As seen from Figure 1, to shift from traditional linear production into the circular design, the eco-design strategies, including repair, reuse and refurbishment, and recycling, can limit the generation of waste products and reduce the pressure on the environment by reducing the need to extract raw materials.

Dozens of published studies explain the best approach to selecting the proper design strategies. However, more research needs to be done on how the design strategies can be applied to support product circularity. This report presents a punch of general circular design strategies and is tailored to map SALIENT objectives to enhance the Front-End Structure (FES) circularity. Additionally, the report relies on the "Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles" to support end-of-life vehicles, including their components and materials.

It is essential to highlight that the proposed strategies are **general** and can be adjusted to any product based on its type of used materials, product development process, environmental management system, and ecological and circular goals (i.e., cradle-to-grave or cradle-to-cradle).

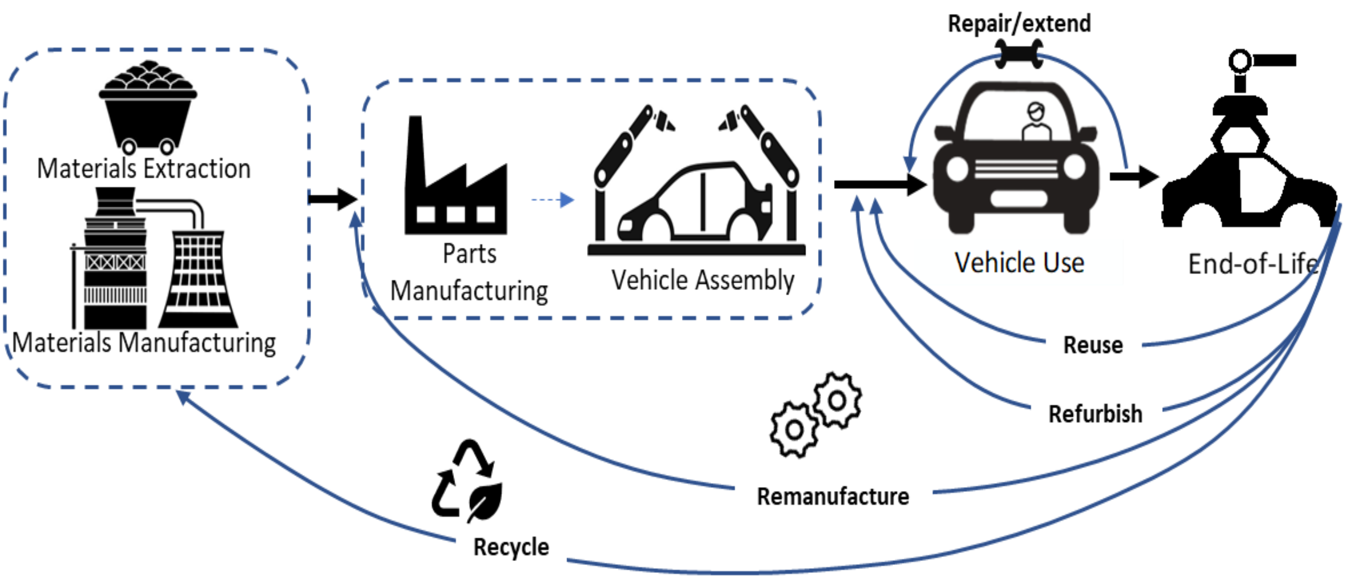

Figure 1. Product System, showing different production phases and Eco-design strategies that can be implanted to shift from linear to circular production.

3. INTRODUCTION

Eco-design refers to systematically integrating environmental considerations into product design and development processes to minimise the environmental impact of products throughout their entire lifecycle. This includes extracting raw materials, manufacturing, distribution, use, and end-of-life disposal[1]. Designers must consider the product's impact on the environment, such as greenhouse gas emissions, energy consumption, and waste generation, and identify areas where improvements can be made S. Ahmad et al.[2, 3]. Using Eco-design strategies to support product design is a fundamentally required approach toward a cleaner environment. Although initiating eco-design strategies is not new, their implementation is still not widely adopted in the product design industry. According to a report by the European Environment Agency, only a small percentage of companies are implementing eco-design strategies in their product design processes. The report attributes this to various reasons, such as lack of knowledge and awareness, limited resources, and lack of incentives.

According to the literature, the product should be designed with specific requirements to meet Eco-design obligations.

1. Products should be designed to be more *robust*, *increasing their operational lifespan* and *reducing the need for maintenance interventions[4]*.
2. Products should be designed to be more durable and reused in new products after disposal[5].
3. Products should be designed for disposal while ensuring proper functioning. Intervention during maintenance and disassembly should aim to minimise the required energy and auxiliary materials[2].
4. During the design process, every aspect of the product life cycle should be viewed as an opportunity to create value. For example, unusable products should be recycled as much as possible, and energy should be derived from non-recyclable parts by creating new synergies with the supply chain of the same or other products [6, 7].

Many authors have classified and identified strategies, methods, and tools that support product design for facilitating the transition to eco-design. These studies have emphasised the vast and diverse range of supporting approaches and the criteria for selecting the most appropriate eco-design approach, such as the type of waste to be recovered, the product generating the waste, and the strategy to be implemented. Despite the challenges, these researchers have highlighted that only one approach is inherently better than the other in proposing solutions for Eco-design strategies[4, 8, 9]. Additionally, It is essential to understand that implementing eco-design strategies can directly impact improving crashworthiness and vibration performance. This can be fulfilled by proper structure design optimisation, which involves the developed component's size, shape, and topology and aims to distribute materials within a component to reduce its use and enhance structural performance [10]. For example, according to aluminium developers [11], for the same crash performances, lightweight aluminium reduces both the production and operating costs of electric vehicles since a lighter car needs fewer batteries and less electricity to travel the same distance, consequently reflecting on the CO_2 emission.

In the automotive industry, eco-design strategies are becoming essential as the industry faces pressure to reduce its carbon footprint and comply with regulations to reduce greenhouse gas emissions. Some popular strategies usually vehicles manufacturers rely on. **First**, the most common implanted strategy is using *lighter materials* such as aluminium or carbon fibre to reduce the vehicle's weight. Using lighter materials has been proven to reduce fuel consumption and emissions, i.,e, a study by the International Council on Clean Transportation found that a 10% reduction in vehicle weight can lead to a 6-8% reduction in fuel consumption and CO_2 emissions [12]. **Second**, based on a study by the European Commission found that Design for Disassembly can reduce the environmental impact of a product by up to 50% [3]. This strategy means easily disassembling and recycling components at the end of their life, reducing waste sent to landfills and promoting the circular economy. **Third**, Fraunhofer Institute for Systems and Innovation Research conducted a study about a second life for vehicle components; they found that *Design for Remanufacturing* can reduce the environmental impact of a product by up to 80% [13]. Design for Remanufacturing is a strategy that involves designing a product to be easily remanufactured or repaired. **Finally**, much research was made to *use energy-efficient components* and systems to reduce the energy consumption of a vehicle, i.e. LED lighting, regenerative braking systems, and low rolling resistance tires.

The implementation of eco-design strategies is challenging. The main challenge is that product designers and manufacturers need knowledge and awareness. Consequently, incentives to implement eco-design strategies are still immature. Moreover, many companies are more focused on short-term profits than long-term sustainability. Finally, it can be costly, especially for small and medium-sized enterprises with limited resources, to implant eco-design strategies.

4. DESIGN APPROACHES AND STRATEGIES

As presented in Figure 2 in the SALIENT project, the consortium from academia and industry aims to Implant advanced methods to improve the front-end structure (FES) eco-design capabilities and create a new fundamental concept front-end structure (BCFES) through:

1. Maintaining/enhancing the crashworthiness performance.
2. Decreasing the vehicle weight by using lightweight materials and components
3. Increasing the vehicle lifespan
4. Optimising and enhancing the product recyclability through considering materials circularity and the eco-design assessment LCA
5. Developing efficient manufacturing assembly/disassembly.

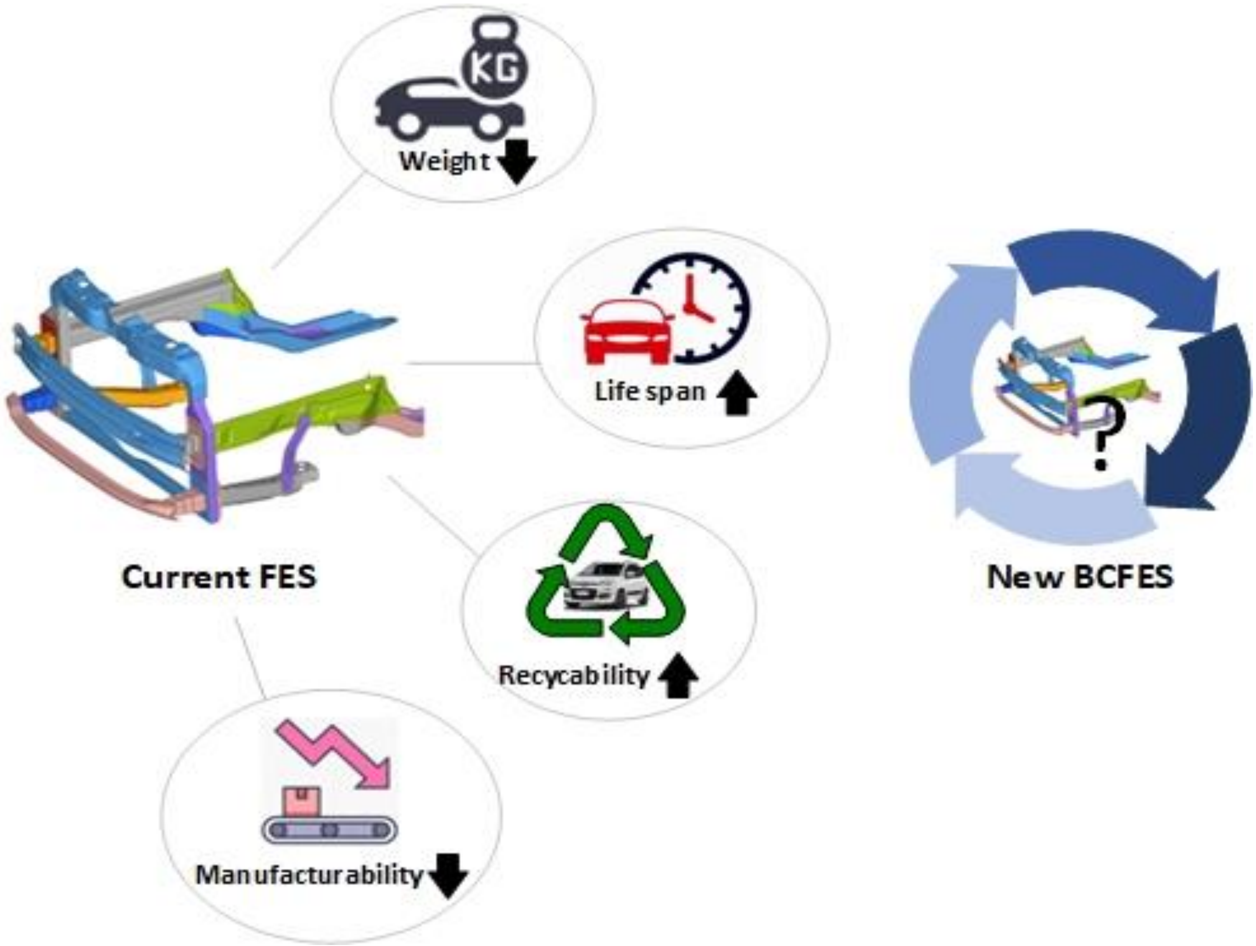

Figure 2. SALIENT objectives toward circular FES.

Vehicle safety during crashes is an essential aspect of vehicle design. A vehicle's performance during a crash is determined by its structural integrity, safety features, and overall design. Using high-strength steel and advanced composites can improve the vehicle's structural integrity, reducing the risk of injury to the occupants. Additionally, safety features such as airbags, seat belts, and advanced driver assistance systems can significantly reduce the severity of injuries sustained during a crash.

Based on that, we implanted the best design approaches to fulfil the project-assigned target. The vehicle FES will be re-designed to last and to be repaired. As presented in Figure 3, the suggested framework aims to create a product that excels in the FES circularity and weight reduction by changing the proposed design. Usually, the best design strategies are found under the Eco-design umbrella [14]. DFX is a set of methodologies that optimise a product's design for specific objectives, such as manufacturing, assembly, maintenance, Reliability, safety, and sustainability. By applying DFX strategies to ecodesign, companies can create environmentally-friendly products while reducing costs and improving their overall sustainability performance. The selected approaches framework was adapted from Den Hollander[8], and supported by implementing suitable DFX strategies.

The designers can follow this general framework to improve the current design considering the material utilisation and the impact of materials emissions. In addition, designers should consider the material integrity (recycling) as efficiently and effectively as possible in all design stages and how the material will be looped back into the economic system.

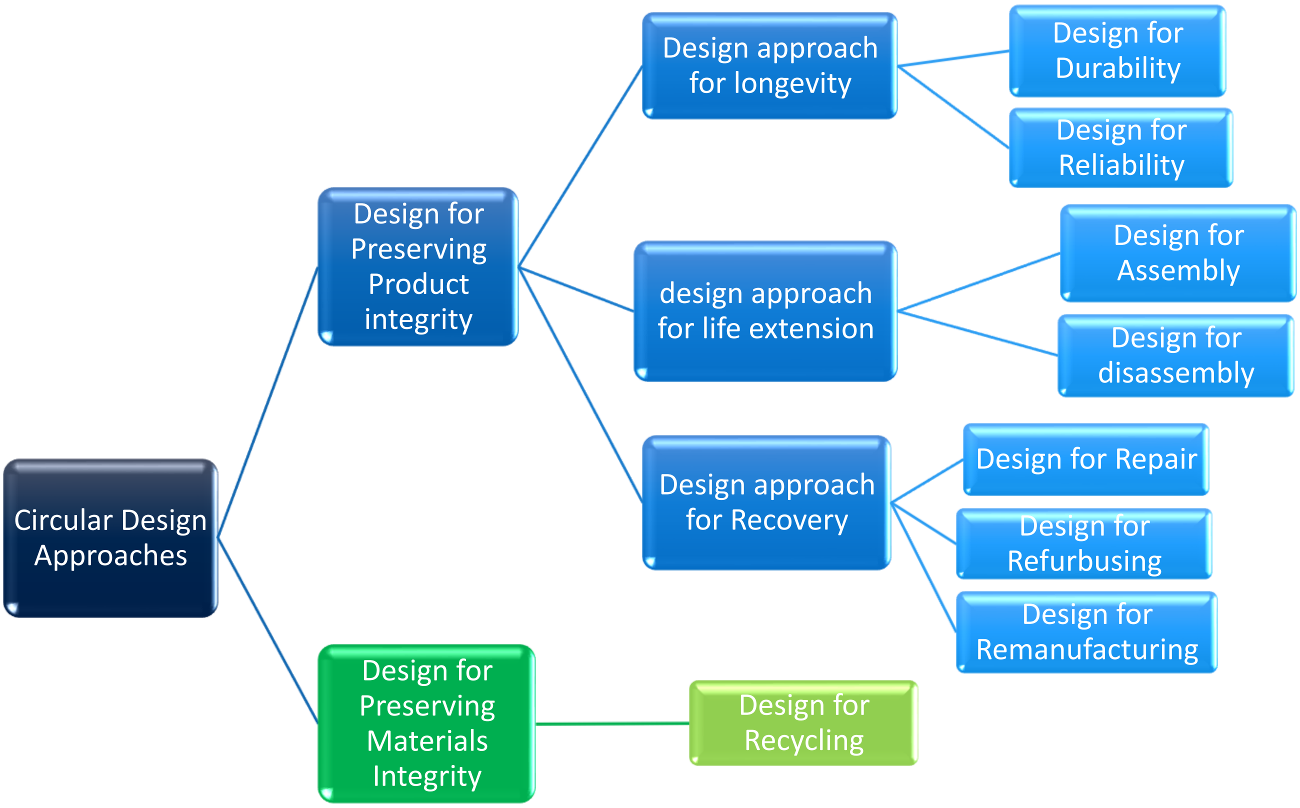

Figure 3. The typology for design approaches is based on circular objectives. The chart also shows an example of related DFX strategies that should be implanted.

4.1 DESIGN FOR PRODUCT INTEGRITY

Product integrity was defined for the first time as the extent to which a product remains identical under the loads encountered during its life cycle[15]. To obtain a high degree of product integrity:

- Reliability should be the index used to measure the uncertainties.
- Good design with quality measures should be created. In SALIENT, quality is defined as the consistent product of low defect content and long life with the possibility to maintain and upgrade, thus enabling extended use.
- Designers must develop a design that is easy to manufacture, repair or refurbish to simplify recovery

Based on that, we have identified three main circular objectives to preserve product integrity:

1. Design for Longevity
2. Design for Life span Extension
3. Design for Recovery.

4.1.1 Design Approach (1): Design for Longevity

Product longevity is a concept with two dimensions, desired service life and actual or real service life. According to S. Carlsson, the Design for Longevity approach involves meticulously evaluating a product's life cycle[16]. Longevity is determined by how long a product can perform its intended function over a given period of time, whether as a set of resources or an object used to perform that function. As a result of Design for Longevity, products are designed with a long lifespan that considers user needs, business objectives, and resource efficiency.

The product's physical durability refers to the rate at which the performance of a product degrades over time relative to other comparable candidates. Many factors may contribute to product degradation, including wear, fatigue, creep, and corrosion, which can be influenced by a product's design and components. Extensive research has been conducted on designing products for durability, as evidenced by various studies [8, 17, 18]. Under this approach, we can implant two essential DFX strategies: a design for Reliability and a Design for durability.

4.1.1.1 Design for Reliability (DFRe)

Based on the IEEE definition, the Reliability of a part is defined as "The ability of a component or system to perform its required functions under stated conditions for a specified time." Design for Reliability aims to build Reliability into a product starting from the design's earliest stages and evaluated at all the preceding steps. The benefits of this strategy in the automotive industry are numerous. Manufacturers can eliminate the risk of product failure by designing for Reliability and improving safety and customer satisfaction. There are several measures and precautions the designer should follow to design a reliable product.

1. Due to reliability variability across different parts, industry standards for quantifying it are lacking. In addition, besides acquiring knowledge of reliability testing methodologies, it is equally crucial to be well-versed in integrating Reliability into a product.
2. Designers utilising design for Reliability must focus on identifying sources of failure and strive to eliminate this risk. In cases where elimination is not feasible, the designers must endeavour to delay the failure until a timing equal to or greater than the product lifecycle. As depicted in Table 1, there are numerous techniques, such as Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Design of Experiments (DOE), and Reliability Testing, which aid in testing and designing reliable products.

Table 1. Tools to Support Design for Reliability Strategy

Test	**Purpose of the test**
Failure Modes and Effects Analysis (FMEA)	FMEA is a process that identifies potential failure modes and their effects on a product. It is used to prioritise design changes that can improve Reliability.
Fault Tree Analysis (FTA)	FTA is a systematic and deductive approach used to identify the causes of a system failure. It involves the construction of a graphical representation of the system and its potential failure modes, called a fault tree. The fault tree is composed of events

	that may cause or contribute to the failure of the system, as well as the logical relationships between these events.
Design of Experiments (DOE)	DOE is a statistical method used to identify the factors that affect the Reliability of a product. It is used to optimise the design parameters to ensure Reliability.
Reliability Testing (RT)	RT is a process that validates the Reliability of a product through testing under different conditions.

Several tools are available to reliability engineers, but not all will be necessary for all parts, only those that apply to a particular use case. It is crucial to monitor the cost of the product as it is inversely related to its Reliability, and in pursuit of enhancing Reliability, product costs can sometimes exceed budgetary constraints. Therefore, it is essential to strike a balance between the two attributes of a product and reach a middle ground.

4.1.1.2 Design for Durability

Durability refers to the materials' capability to withstand, with regular maintenance and for a specific period, all the effects to which they are exposed, such that there is no substantial change in their functionality. In the *automotive industry*, designing for durability involves selecting robust materials, considering the impact of the environment on the vehicle's components, ensuring regular maintenance, and subjecting the vehicle to rigorous testing and analysis. Testing can include everything from accelerated durability testing to computer simulations of real-world driving conditions, allowing manufacturers to fine-tune their designs to maximise durability. By adopting this design approach, manufacturers can increase the Reliability and longevity of their products, reducing overall costs and increasing customer satisfaction.

There are several factors the designer/engineer should consider to adapt this strategy:

1. Choosing **suitable materials** is an essential aspect of designing for durability. Materials used in the manufacture of vehicles must be capable of withstanding mechanical stresses, high temperatures, and corrosive elements encountered throughout their lifetimes. i.e., high-quality steel alloys, composites and aluminium alloys can provide strength and durability, while a suitable coating or plating can prevent corrosion. As a result, the designer should follow a straightforward tactic to select the best material for the component, such as Material Matrix Assessment.
2. The designer must consider all the **environmental factors** that significantly impact the vehicle's components' durability, such as temperature and humidity, to protect against damage and deterioration. For example, Corrosion-resistant coatings can protect against rust, while protective covers can shield sensitive components from the elements.
3. Manufacturers must incorporate features that make maintenance more accessible and cost-effective, such as easy-to-reach service points and user-friendly diagnostic systems. As a result, regular maintenance can impact product longevity and reduce the **overall cost** of ownership for the customer.

4.1.2 Design Approach (2): Lifespan Extension

Designing for lifespan extension is a critical consideration in the automotive industry, particularly as consumer demands for durability and sustainability continue to climb. Manufacturers can create vehicles capable of withstanding prolonged use while minimising their environmental impact by selecting durable materials, optimising maintenance schedules, and implementing sustainable design practices. However, manufacturers must also balance the desire for longevity and sustainability with the practical realities of cost and technological limitations.

Maintenance is an essential component of asset management that aims to keep equipment, machines, buildings, and infrastructure in good condition to ensure their reliable and safe operation. The EN 13306:2018 international standard provides a framework for defining maintenance and related terms [19]. According to the standard:

"*Maintenance is a combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.*"

In this definition, retaining a product in a functioning state and restoring a product to a functional state are both considered maintenance. Additionally, the standard outlines four types of maintenance: corrective, preventive, condition-based, and predictive.

In practice, it is crucial to implant design for Assembly and Disassembly strategies to fulfil successful maintenance. To incorporate maintenance and assembly/disassembly in the design phase of vehicles, automotive manufacturers should consider the entire life cycle of a car. As a result, designers should create products with easily accessible components, modular design, and labelling to aid in maintenance and assembly/disassembly processes. This approach can also help reduce the costs associated with maintenance, assembly, and disposal[3].

4.1.2.1 Design for Assembly (DFA)

Design for Assembly (DFA) is an approach that aims to simplify product design to reduce assembly costs. As a result, integrating DFA principles into product design typically leads to cost savings in assembly and improved quality, Reliability, and reduced production equipment and part inventory. It has been consistently observed that these secondary benefits often outweigh the cost reductions achieved through the assembly.

By prioritising simplicity and ease of assembly during the design process, DFA can result in a more efficient and effective manufacturing process, leading to higher overall product quality and Reliability. Thus, the positive impact of DFA on product performance and manufacturing efficiency can extend beyond just assembly cost savings. Overall, DFA is a practical approach that can yield multiple benefits throughout the entire product life cycle, making it an essential consideration for companies seeking to optimise their manufacturing processes and improve their products' competitiveness in the market. In other words, the automotive industry must incorporate DFA principles into its product development processes to achieve optimal results.

Design for Assembly (DFA) is a systematic strategy that aims to simplify a product's structure and manufacturing process, making it easier, faster, and more consistent. This strategy involves addressing critical questions during the design phase, such as:

1. Does the part need to move in relation to other components during assembly?

2. Is the part made of different materials for aesthetic or functional reasons?
3. Does the part need to be separate to ensure access to other parts or for ease of repair and maintenance?

DFA has some basic principles, and these are:

- Minimise the number of identical components, for instance, by replacing a large number of small bolts with a smaller number of larger ones;
- Combining several parts into one more prominent part through integral construction.
- Utilising pre-assembled (bought-out) assemblies and facilitating the combination of multiple operations by appropriately arranging locating surfaces and connectors, allowing for simultaneous tightening of multiple bolts.
- Designing parts to be symmetrical for easy assembly orientation or asymmetrical for clear identification and orientation.
- Ensure that parts automatically verify the presence and correct location of previous parts.
- Designing parts to reduce re-orientation during assembly.
- Design parts with simplicity and ease of handling, manually or automatically.

A further requirement is the provision of simple assembly operations. For instance, using standard tools rather than expensive special ones is advantageous in one-off production. However, the cost of individual operations depends greatly on the available assembly equipment and the staff, so it is impossible to make general pronouncements on what is simple and cost-effective. Even though the production planning department determines the precise sequence of assembly operations and not the designer, the latter should try to provide a logical sequence, thus obviating mistakes and ensuring simple repair and maintenance.

4.1.2.2 Design for Disassembly (DFD)

There is no doubt that the automotive industry has a substantial impact on the global economy. However, it develops significant waste, including end-of-life (EOL) vehicles, which can pose a significant environmental hazard. To mitigate the impact of waste generated by the automotive industry, design for disassembly (DFD) has emerged as an essential concept. DFD is a crucial strategy for product design that considers the ease of disassembly of products at the end of their useful life to facilitate recycling, reuse, and recovery of valuable resources [3].

As environmental awareness grows, EOL objectives such as component reuse, remanufacturing, and recycling are essential for disassembling products. In the automotive industry, designing for disassembly has several benefits

- It can make it easier for the vehicle to be repaired or upgraded, prolonging its useful life.
- DFD also promotes using recycled materials in vehicle manufacturing, reducing the carbon footprint of producing new materials. Additionally, DFD can help reduce greenhouse gas emissions by reducing the need to extract and process new raw materials.
- Economically, DFD can lead to **cost savings** in the manufacturing process. By designing vehicles for easy disassembly, manufacturers can reduce the time and labour required to disassemble vehicles at the end of their useful life, translating into significant cost savings.

- Additionally, DFD can improve the **quality of recycled materials** used in vehicle manufacturing, leading to better-quality vehicles and reduced warranty claims.
- Complying with regulations that prescribe removing substantial parts, materials, and substances for environmental and safety reasons, such as removing working fluids such as engine oils and lubricants.

Several design guidelines for disassembly can be followed to minimise the assembly work, achieve a predictable product configuration, simplify the disassembly, and fulfil easy handling and separation. These guidelines are described in Table 2.

Table 2. DFD guidelines description

DFD Guideline	**Description and references**
Consider Disassembly during Product Design	Research has shown that considering disassembly during the product design phase can significantly enhance disassembly efficiency. Designers should aim to create products that are easy to disassemble, with minimal or no damage to the components. Consideration should be given to the number of components, their size and shape, and how they fit together. Parts should be designed to be easily separated, with fasteners and connectors that can be easily removed[20].
Use Modular Design	The modular design has been identified as a practical approach to DFD. Products designed with modular components can be easily disassembled, with each module separated and replaced as needed. Modularity can also make it easier to repair products, reducing the need for replacement and waste generated by the manufacturing process[21].
Select Recyclable Materials	Materials selection is a critical aspect of DFD. Researchers have identified that using recyclable materials promotes the reuse of resources, reduces waste, and reduces the environmental impact of manufacturing. When selecting materials, manufacturers should consider the availability of recycled materials in the supply chain and the ease of recycling.
Minimise Material Diversity	Minimising material diversity can make disassembly more manageable, reducing the number of materials that need to be separated and recycled. In addition, when selecting materials, manufacturers should aim to use compatible materials, reducing the need for sorting and processing during recycling [22]
Consider Product Lifetime	Researchers have shown that product lifetime can impact the ease and efficiency of disassembly. Products designed for shorter lifetimes may not require the same level of disassembly and recycling as products designed for longer lifetimes. Designers should consider the product's expected lifespan and design it accordingly[20].
Design for Automation	Researchers have identified that using automation in the disassembly process, including robotic tools and machinery, can reduce the risk of

	injury to workers and reduce the time and labour required for disassembly[22].
Establish Reverse Logistics	Reverse logistics involves collecting, sorting, and transporting end-of-life products for recycling or reuse. Researchers have identified that establishing reverse logistics systems can ensure the efficient and effective recycling of end-of-life products. Reverse logistics systems should be designed to minimise waste and maximise the recovery of valuable resources[21].

4.1.3 Design Approach (3): Design for Recovery

The design for recovery is a sustainable design approach that aims to salvage the economic and ecological value of products, components, and materials to minimise waste generation[3]. In 1995, Thierry et al. introduced a product recovery management approach that outlines four levels of product recovery: product, module, part, and material, where returned products can be recovered. Generally, product recovery options achievable by disassembly may be classified into repaired, refurbished, remanufactured, and recycled products[23]. As a result, design for repair; refurbishing; and remanufacturing will be considered for preserving product integrity and design for recyclability for maintaining material integrity.

4.1.3.1 Design for Repair (DfR)

The design for repair strategy aims to make repairable products, thereby reducing waste generated by disposing of products that no longer function. DfR is rooted in the broader sustainability movement, which strives to minimise environmental impact and promote long-term economic viability. Significant benefits can be fulfilled through the implantation of design for repair in the automotive industry, including

1. Reducing the need for manufacturing new products contributes to a more sustainable and responsible sector[17, 24].
2. Reducing maintenance, repair, and product disposal and replacement costs leads to a more sustainable and economically viable system[25].
3. Extending product lifespan
4. and increased customer satisfaction.

The designer can face a challenge while implanting design for repair strategy as designing affordable products that are easy to diagnose, maintain, and repair can present design constraints that may impact the overall design and functionality of the product. To address these challenges and promote adopting design for repair strategy in the automotive industry, some guidelines/tactics the manufacturers can follow to design products that are easy to repair[2, 26].

Guideline (1): Use standardised parts to reduce maintenance and repair costs by making it easier to find replacement parts. Standardisation ensures that components can be easily sourced from third-party suppliers, reducing the reliance on proprietary components.

Guideline (2): Develop a simple assembled/disassembled product design to make it easier to repair, reducing repair costs and increasing customer satisfaction.

Guideline (3): Use proper labelling and diagnostic tools. Labels should be used to identify components and their function, making identifying and replacing faulty parts easier. Diagnostic tools can also specify the source of a problem, reducing the need for trial-and-error repairs.

4.1.3.2 Design for Refurbishing (Reconditioning)

Design for refurbishing or reconditioning is the strategy of returning an obsolete product to a satisfactory working condition that may be inferior to the original specification. This strategy is a promising approach to extending the useful life of products, reducing waste, and improving resource efficiency. However, in most cases, the resultant product has a lower warranty than the newly-manufactured counterpart, which applies to all significant parts prone to wear and tear. Nevertheless, implementing design for refurbishing in the automotive industry presents several challenges.

Table 3. Challenges and suggested recommendations during implanting design for refurbishing

Challenge	Recommendations
The vehicle design is complex and composed of numerous components, making it challenging to identify critical elements that need refurbishing or reconditioning.	Develop standardised designs that allow for easy disassembly and replacement of critical components.
Automotive products are often highly customised, making it challenging to develop standardised designs that can be easily refurbished or reconditioned.	Use compatible and durable materials that can be easily refurbished or reconditioned. Using compatible and durable materials can reduce the risk of damage and improve the longevity of the products. However, the selection of materials must also consider their compatibility with existing components and the automotive industry's strict safety and performance requirements.
The availability of components for refurbishing or reconditioning can be limited, especially for older vehicles or specialised features.	Collaborate with refurbishing or reconditioning service providers to develop a more extensive network of available components and expertise.
Reconditioning requires specialised knowledge and skills, which may not be readily available or widely distributed in the industry.	The industry can invest in training programs and knowledge-sharing initiatives to develop specialised knowledge and skills for refurbishing or reconditioning.

4.1.3.3 Design for Remanufacturing (DfRem)

Design for remanufacturing is a strategy where the designer should consider returning the product performance to its original status or better than the newly manufactured one[27]. Hollander upgraded this definition to add information related to the brand's intellectual property, where the difference between remanufacturing and conventional manufacturing was explained [8].

The link between design and remanufacturing should be well established to obtain more remanufactured products and an efficient design process. When adapting products for remanufacturing, it is essential to consider all operational steps, including inspection, disassembly, reprocessing, reassembly, and testing[28]. The primary objective of remanufacturing is the reuse of parts, so the ease of cleaning or reassembly will have less value in remanufacturing if the component cannot be reused as is or after repair. Therefore, putting much effort into product design is possible without obtaining the expected benefits.

Design guidelines for Design for Remanufacturing guide the product design process to facilitate the remanufacturing process. These guidelines take into account the product's life cycle and aim to maximise the value of the product by minimising waste and reducing the need for virgin materials

Guideline (1): To design products for disassembly, which involves creating products with easily separable parts that can be efficiently disassembled for reuse. The product design should consider the ease of disassembly, the location of fasteners and connectors, and standard interfaces to facilitate the separation of parts[29].

Guideline (2): To minimise the use of adhesives and other permanent bonding techniques. Using permanent bonding techniques can make it difficult to disassemble and separate parts during the remanufacturing process and damage the components. Therefore, the product design should consider using fasteners, snaps, and mechanical connectors.

Guideline (3): The product design should also consider using durable and robust materials that can withstand multiple use cycles and disassembly. Using such materials can help reduce the need for virgin materials, minimise waste, and increase the value of the remanufactured product.

Guideline (4): Several tools and metrics are available to assess the remanufacturability of products. For example, the Boothroyd and Dewhurst design for assembly metrics can be used as a foundation to create remanufacturability assessment metrics based on product design features[30]. There are also tools for Design for End of Life (DfEoL) to aid in decision-making at the EoL stage, such as an End-of-Life Design Advisor (ELDA)[31].

Overall, the design guidelines for DfRem aim to create products that can be easily and efficiently remanufactured, thus reducing waste, minimising the need for virgin materials, and increasing the product's value.

4.2 DESIGN FOR MATERIAL INTEGRITY

Materials integrity significantly contributes to the safety and environmental success of any product/vehicle circularity. Design for recyclability is the leading player in preserving product material integrity.

4.2.1.1 Design for Recyclability

Design for recyclability is a crucial eco-design strategy that aims to reduce product environmental impact throughout the product life cycle. Designing for recyclability is a strategy that ensures products never become "waste" but allows for closed-loop material recovery.

This strategy has become essential in the automotive sector due to the high number of vehicles produced globally and their environmental impact. Designing for recycling in the automotive industry involves using materials that can be easily recycled. A critical phase in making recycling economically viable is ensuring that recyclable materials' quality and disassembly can be easily performed[3].

To use design for recyclability in the automotive industry, the designer should consider the following points:

- Materials used in the automotive industry must meet specific criteria to be considered recyclable. For example, metals such as aluminium and steel are easily recycled and are commonly used in vehicles. Recycling aluminium, for example, requires only five percent of the energy needed to produce new aluminium. Therefore, the use of recycled aluminium in the automotive industry can reduce carbon dioxide emissions by up to 95 percent.
- Composite materials have become increasingly popular in the automotive industry due to their lightweight and high-strength properties. However, composites can be more challenging to recycle and must be designed with recyclability in mind. Using recycled materials in vehicle construction can also help reduce the environmental impact by reducing the need for virgin materials.
- Designing for disassembly is another critical aspect of design for recycling in the automotive sector. When a vehicle reaches the end of its life cycle, it must be dismantled to recover valuable materials and components. Designing for disassembly involves designing vehicles that can easily separate parts, which can be reused or recycled. This design approach reduces the vehicle's environmental impact at the end of its life cycle and reduces the costs associated with dismantling and recycling.
- The designer should ensure the quality of the recycled materials. Recycled materials may not be as durable as new materials, which can impact the safety and performance of the vehicle. To ensure the quality of recycled materials, the manufacturers must conduct extensive testing that meets the necessary standards.
- The cost of recycling composite materials is another significant challenge for the designer to bear in mind. The recycling process for composite materials is complex and requires specialised equipment and techniques, which can be expensive.

5. THE LIFE CYCLE ASSESSMENT (LCA)

Many tools consider the eco–design aspects in all life stages of the product, e.g. ECODESIGN PILOT, waste electrical and electronic equipment (WEEE), and Life Cycle Assessment (LCA). Implementing eco-design tools and methods in the automotive industry leads to complex processes requiring efficient management of the parties involved. Therefore, in automotive applications, tools for Eco-Design, such as life cycle assessment (LCA), are widespread to evaluate the environmental benefits guaranteed on the product by applying the design strategies and LCA in the most crucial production phases, as explained in Table 4. The advantages of LCA include its ability to provide a perspective throughout the product's life, considering major ecosystems and all their parts. In the automotive industry, the LCA method can help reduce pollution, waste, and amounts of fossil fuels used. The aim is to create an ecologically sustainable production process for vehicles to make them more environmentally friendly by changing the design, materials used, manufacturing methods and techniques and making them easier to reprocess.

Table 4. Aspects for applying the LCA through Material Selection, Design, and End of Life phases.

Phase	**Aspects for the LCA**
Material Selection	The materials used in the manufacturing process can significantly impact a vehicle's environmental footprint. By selecting environmentally friendly materials, manufacturers can reduce the energy consumption and emissions associated with production. For example, lightweight materials such as *aluminium* and *carbon fibre* can be used to reduce the weight of a vehicle, which in turn can improve fuel efficiency and reduce emissions.
Product Design	By designing vehicles with sustainability in mind, manufacturers can reduce energy consumption, waste, and emissions associated with production and use. For example, using modular design allows for the reuse of parts across multiple vehicle models, reducing waste and lowering production costs.
End of Life	End-of-life management is the final stage of the product lifecycle. By designing vehicles with end-of-life management in mind, manufacturers can reduce the environmental impact of disposal and increase the potential for recycling and reuse. One common strategy in end-of-life management is using recyclable materials, such as aluminium and plastic, which can be easily recycled and reused to produce new vehicles. Additionally, manufacturers can design vehicles with disassembly in mind, making it easier to recycle or reuse components and materials [3].

Deciding how and why LCA will be applied through different design stages is essential. Some researchers classified the LCA as a tool that can be entitled under the Design for Environment strategy. As depicted in Figure 4, the design for disassembly, remanufacturing, and recyclability is controlled through the LCA and should be considered together to monitor the vehicle's circularity.

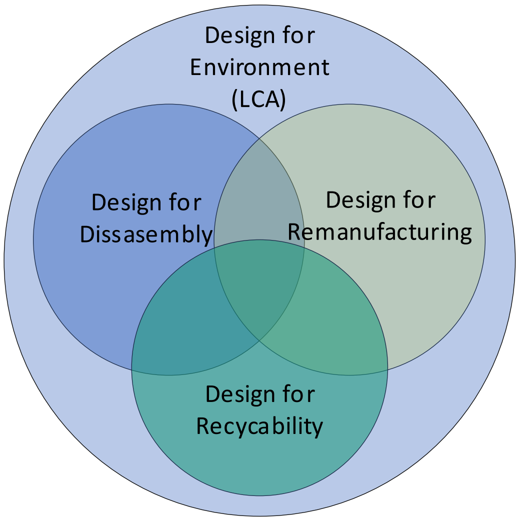

Figure 4. The interaction between design strategies and their impact on the LCA

The assessment should be applied early in the design process to assist designers in comparing various material options and identifying the areas with the peak impact. The assessment can be initialised with broad assumptions and optimised as the design becomes more mature. The analysis should be carried out according to ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) standards for LCA principles and framework, and requirements and guidelines, respectively[32, 33]. Additionally, partner-specific data should be used for environmental footprint evaluation. The assessment involves four essential steps:

1. Goal and Scope definition, where the framework of the study and its functional unit is also defined.
2. The life cycle inventory (LCI) is a register of material and energy flows
3. The life cycle impact assessment (LCIA) classifies LCI records depending on their environmental impact
4. and Interpretation.

To perform a complete LCA, a proper database should be selected. One of the most frequently used databases for sustainability analysis at the product level worldwide is the GaBi database. GaBi database can provide the designer with the following:

1. Emission (carbon footprint)
2. Waste production
3. Energy Consumption
4. Raw materials (resources) consumption

6. DESIGN ASPECTS AND METRICS

As stated in previous sections, the development of the optimum FES design is a multifactorial problem that must consider different aspects, not only the environmental aspects but also the cost-effectiveness and the manufacturability.

6.1 DESIGN TARGETS AND CONSTRAINTS

Any alternative for the new design of the FES must comply with the following requirements to be considered:

- **Weight reduction**: the agreed KPI of the SALIENT project for the new FES is a global reduction of 42% with respect to the baseline, which means 5 kg of weight reduction.
- **Portfolio of materials**: The advanced materials to be used in SALIENT are aluminium grades and UD-tapes based on different thermoplastic matrixes (PET, PPS, PA66 and PA6) reinforced with glass fiber or carbon fiber. The components to be designed must use one of these alternatives.
- **Manufacturability**: The manufacturing process to be used for aluminium-based components is extrusion, in combination with auxiliary operations (CNC machining, welding, bending, etc.). For thermoplastic parts, tape-laying assisted by the laser will be used. These manufacturing processes have constraints related to minimum and maximum thickness, manufacturable geometries, etc. For example, in the **aluminium extrusion**, the general shape is the result of a profile section that prevents complex geometries or changes in thickness; nevertheless, post-processes such as bending or drilling can widen the allowed geometries. Also, some good practices for the design are balanced walls, avoiding hollows, using generous tapers, minimising asymmetrical detail and minimising perimeter/cross-section ratio. In the case of **tape-laying,** which consists of layering UD-tapes around a substrate (generally a metallic one) to reinforce it, or simply using it as a guide that will be removed afterwards, the thermoplastic fraction will be geometrically very simple, without ribs or other interior complexities.

In any case, each design will be checked with the partners in charge of manufacturing the demonstrators to confirm the feasibility.

- **Technical performance**: the resultant FES must comply with all the crash tests defined in deliverable 1.2, "Technical Specifications and Requirements of Structural Components". This compliance will be checked through virtual crash validation, both at the component level using specific loads and at the whole vehicle level.
- **Maintenance**: the FES components connected to the vertical supports (crash boxes and bumper) should be easy to disassemble for repairability/replacement in case of a low-speed accident.

These constraints limit the pool of choice regarding the materials and the geometry of the components under the scope of SALIENT. A design that does not meet each one of these requirements will be automatically discarded and, therefore, will not be subsequently evaluated under the ecodesign methodology.

6.2 CONSIDERED ASPECTS OF ECO-DESIGN

The different design alternatives that fulfil the requirement listed in section 5.1 will be evaluated considering the eco-design principles.

The environmental footprint comprises different aspects of the life cycle (Figure 5): production phase, use during the vehicle lifespan (associated with energy consumption) and end-of-life options (recycling, landfilling, etc.).

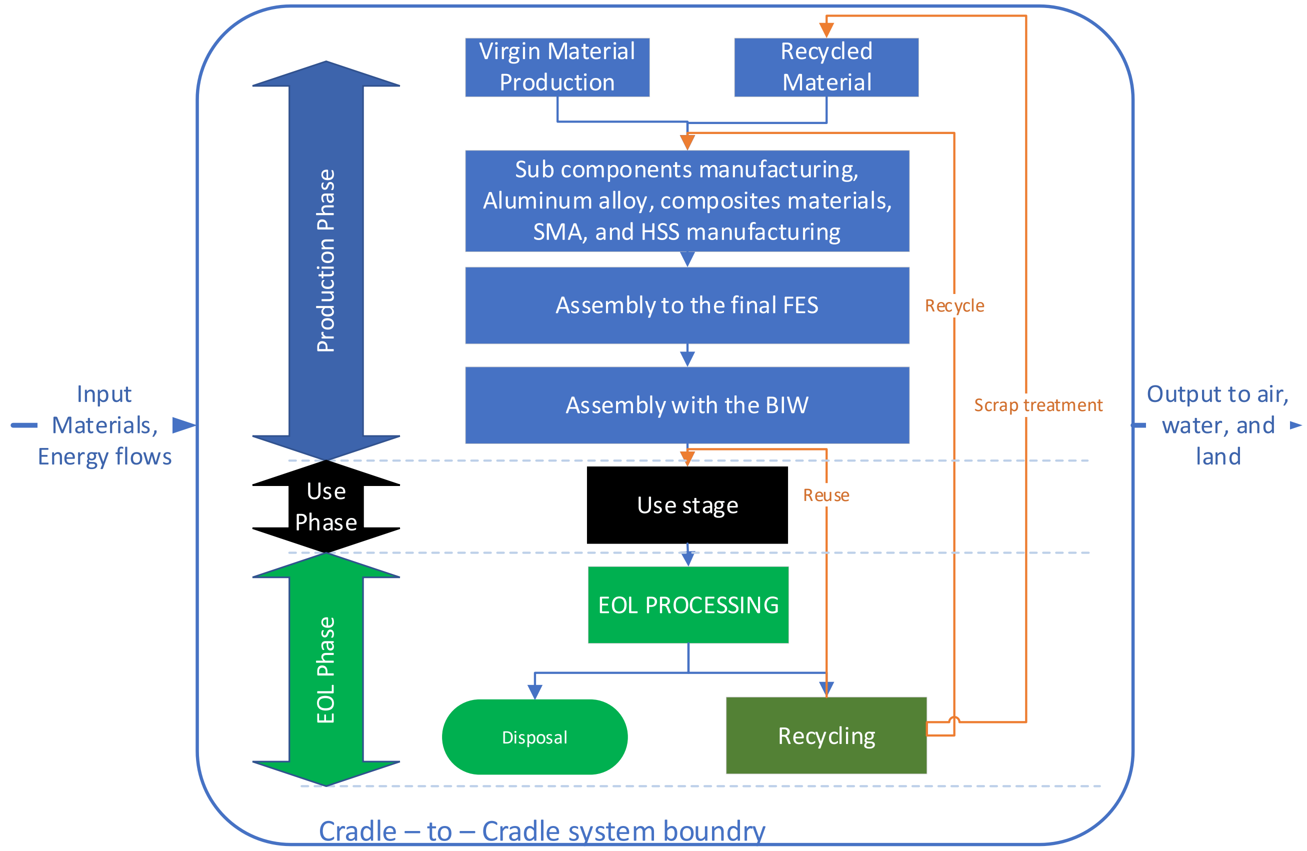

Figure 5. The cradle-to-cradle system boundary of the FES life cycle stages and main processes. The system includes the Eco-design principles of Reuse, recycling, and waste treatment.

6.2.1 Production Phase

This phase includes the raw material extraction, the overall part manufacturing process and the involved logistics. For both the raw material and logistics, the **part weight is relevant** and has a direct impact. The **manufacturing process efficiency** (scrap, faulty part ratio, energy and water consumption) is also considered here. There are different strategies to increase process efficiency:

- Some manufacturing processes are inherently less energy-consuming; we should ponder the energy consumption when different alternatives are possible.
- Reducing the number of references, whenever possible, would generally increase manufacturing efficiency.
- The compatibility with the current assembly line is also a significant factor since any change in Original Equipment Manufacturer (OEM) STELLANTIS facilities is complex and will lead to inefficiencies. This includes the changes in the joining processes (for example, in combinations such as composite/aluminium or composite/steel, welding is no longer an option) or in the assembly sequence (for example, all the components made with material incompatible with the E-

coat bath should be assembled afterwards). It is important to refer that the OEM is aware of the manufacturing plant and assembly process of different components provided by the supplier, i.e. during the joining process of different materials, which an external supplier in the STELLANTIS subsystem will provide; STELLANTIS will be aware of the final assembly operation in the Body in White BIW.

6.2.2 Use Phase

The environmental footprint of automotive parts is inherently associated with their weight since it has a direct relationship with the vehicle's energy consumption during the use phase. The mass-induced fuel consumption (MIF) is lower in BEV than in ICE vehicles, but it is still relevant (Figure 6).

	fuel consumption (L_e/100 km)	MIF (L_e/100 km 100 kg)
Fusion ICEV	6.8	0.28
Fusion HEV	4.0	0.13
C-MAX PHEV - CS	4.4	0.13
C-MAX PHEV - CD	1.9	0.056
Focus BEV	1.6	0.050

Figure 6. Comparison of equivalent fuel consumption and Mass-Induced Fuel consumption of different vehicles [34]

Therefore, the primary strategy to reduce the environmental footprint of a vehicle component during its use phase is lightweight.

6.2.3 End-of-Life Phase

The components of a vehicle can be reused, refurbished, recycled or landfilled. Each option for the end-of-life has an associated environmental footprint (from less to high). But, except for landfilling, which is the less suitable option, the first step is dismantling. Design for disassembly is particularly relevant in multi-material components, where specific joining methods add complexity to the sorting process, even preventing recycling[3].

6.3 METRICS

Considering the ecodesign aspects, we have selected the following parameters that combine the simplicity of the assessment with relevance regarding the environmental footprint.

- **Lightweight potential:** mass saving is a crucial parameter that positively contributes to decreasing the environmental footprint and costs. It is related to the energy consumed in both the production and the use phase. The lightweight potential is measured in terms of Kg-saved. The first assessment was made with a simplified assumption related to the density of the alternative materials compared to steel. Then, the real lightweight potential will be recalculated using the detailed final design, adapted to the material and manufacturing process specificities.

- **Recyclability:** This factor considers the recyclability of the material. It is evaluated on a scale of 1 to 3: 1." Not recyclable with conventional technics" 2." Difficult to recycle with conventional technics" 3. "Easily recyclable".
- **Assembly/disassembly:** the complexity of the assembly/disassembly is related to the lifecycle: production (simple assembly methods increase the manufacturing efficiency), use (to allow maintenance) and end-of-life (to allow an easy sorting for reuse, refurbishment and recycling). 1. "Currently not disassemblable, medium complexity for assembly (welding)", 2. "Difficult to assemble/disassemble" (adhesives) 3. "Easily assemblable/disassemblable" (bolts)
- **Reduction of references:** integrating different functions in fewer parts contributes to cost-effectiveness and environmental footprint reduction. This metric is measured in terms of the total number of parts saved.
- **Compatibility with the current assembly line:** As stated, significant changes in the assembly line of OEM are expensive and can lead to inefficiencies, which will be guided through the production phase, as explained in section 5.2.1. This metric is evaluated on a scale of 1 to 3: 1. "Significant changes on the assembly line are required", 2." Minor changes on the assembly line are required" 3. "No changes required".

7. TAILORING THE DESIGN STRATEGIES INTO THE DESIGN SCOPE OF SALIENT

7.1 DESIGN SCOPE OF SALIENT

The SALIENT project focuses on the re-design of the following components, corresponding to the Panda model (Figure 7):

- Frontal bumper
- Vertical supports
- Crash boxes
- Crash box cross member
- Reinforcing struts and lateral tie
- Longitudinal rail

Currently, all those parts are made of steel, with a total weight of 14,02 Kg.

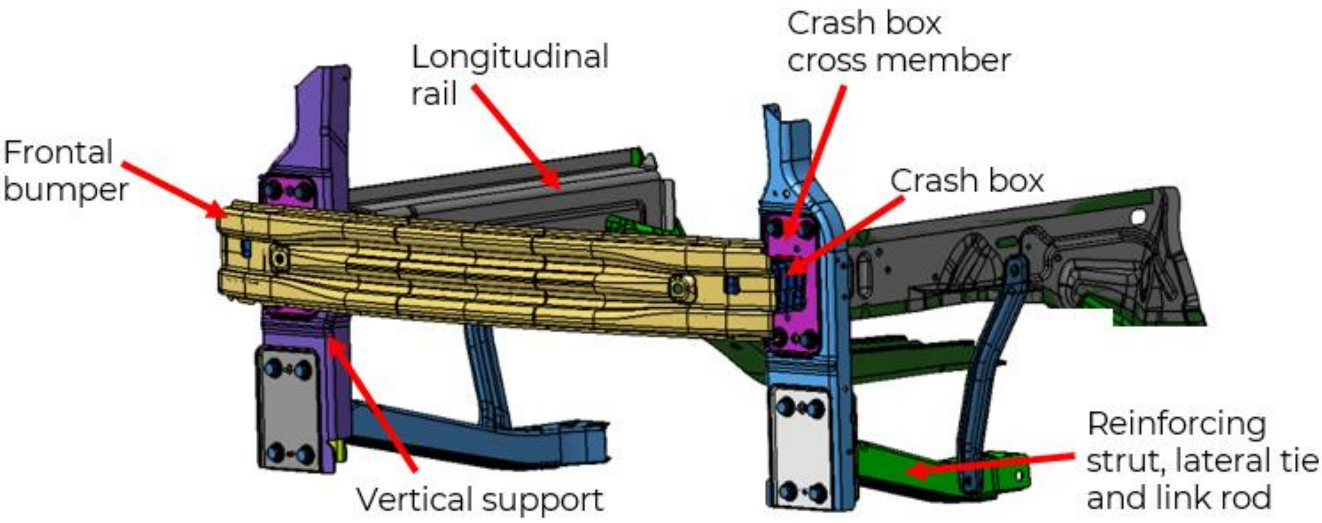

Figure 7. Components under SALIENT scope

7.2 ECO-DESIGN MATRIX FOR FES

As mentioned in section 5.1, there are some requirements that any design should fulfil to be considered as a potential alternative to the current FES: a minimum weight reduction, the use of available materials in SALIENT, the manufacturability, the technical performance and the maintenance.

Each design will be evaluated in such terms (for example, checking the manufacturability with the part manufacturers and experts on the processes and simulating the crash performance to guarantee compliance with safety requirements).

The designs that pass the listed thresholds will be evaluated from an environmental point of view using the metrics explained in section 5.3. Finally, a score for each category will be given and weighted accordingly (Table 5).

To calculate the global score of each alternative design, the different scores of each parameter will be weighted as follows:

- 40% of the final global score will correspond to weight saving, which is the primary goal of SALIENT and a factor related to several eco-design strategies.
- 10% of the final score will be recyclability, which is related to the "recyclable by design" strategy.
- 20% will be related to assembly/disassembly, which is not only related to recyclability and reuse but also to the maintenance and, therefore, the life extension of the system.
- 5% of the final score will then° of reference saved, which help in the manufacturing step.
- 25% of the global score will be compatible with the current assembly line related to the manufacturing step.

Table 5. Ecodesign matrix

	(a)Weight saving	(b) Recyclability	(c) Assembly/ Disassembly	(d) n° References saved	(e) Assembly line compatibility	(f)Overall score
Design option	*1. <30% saved* *2. 30-40% saved* *3. >40% saved*	*1. "Currently not recyclable"* *2. "Difficult to recycle"* *3. "Easily recyclable"*	*1. "Currently not disassemblable"* *2. "Difficult to disassemble"* *3. "Easily disassemblable"*	*1. "No references saved"* *2. "1 reference saved"* *3. "More than 1 reference saved"*	*1. "Significant changes required"* *2. "Minor changes required"* *3. "No changes required"*	*f= a·0,4 + b·0,1 + c·0,2 + d·0,05 + e·0,25*
Design 1						
Design 2						
Design 3						
Design [n]						

The final design for the demonstrator will be the one with a better global score and a better compromise of features to decrease the environmental footprint.

To illustrate the methodology, an imaginary scenario will be presented in which three viable designs are obtained (i.e., designs that comply with the constraints of section 5.1) and that will need to be analysed according to the eco-design matrix exposed:

- Design 1 is a fully aluminium solution that integrates some functions, saving two references. The FES is welded and reaches a weight-saving of 25% compared to the baseline. In addition, aluminium is fully recyclable and compatible with the assembly line, with some minor changes to join the FES with the steel-based BIW.
- Design 2 is a multi-material solution (thermoplastic reinforced with carbon fibre + aluminium) where most parts are assembled through bolts. The FES saved 35% of the weight and is compatible with the current assembly line.
- Design 3 is a multi-material solution with parts joined by adhesives, saving 45% of the weight. However, the assembly line should be changed to avoid E-coating.

Based on the above scenarios, the matrix will be the following:

Table 6. An imaginary Scienaro for the Eco-design matrix evaluation

	(a)Weight saving	(b) Recyclability	(c) Assembly/ Disassembly	(d) n° References saved	(e) Assembly line compatibility	(f)Overall score
Design option	*1. <30% saved* *2. 30-40% saved* *3. >40% saved*	*1. "Currently not recyclable"* *2. "Difficult to recycle"* *3. "Easily recyclable"*	*1. "Currently not disassemblable"* *2. "Difficult to disassemble"* *3. "Easily disassemblable"*	*1. "No references saved"* *2. "1 reference saved"* *3. "More than 1 reference saved"*	*1. "Significant changes required"* *2. "Minor changes required"* *3. "No changes required"*	*f= a·0,4 + b·0,1 + c·0,2 + d·0,05 + e·0,25*
Design 1	1	3	1	3	2	**1,55**
Design 2	2	2	3	1	3	**2,40**
Design 3	3	1	1	1	1	**1,80**

According to this methodology, the most suitable design would be Design 2.

8. CONCLUSIONS

This report presented general tactics and guidelines to support designers in turning their designs toward an eco-friendly route. The best design approaches were implanted to fulfil the SALIENT project objective to re-design the FIAT Panda FES. By applying DFX strategies to eco-design approaches, environmentally-friendly products can be created by reducing costs and improving their overall sustainability performance. The SALIENT new FES design must comply with some requirements, e.g. weight reduction, portfolio of materials, manufacturability, technical performance and maintenance. In SALIENT, the material matrix assessment will be used to select the appropriate material for the best component.

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