



NEXT GENERATION OF MULTIFUNCTIONAL, MODULAR AND SCALABLE SOLID STATE BATTERIES SYSTEM

D2.2 Report on Design-for-eXcellence



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Glossary and Abbreviations	
Df-X	Design-for-Excellence
E-bus	Electric Bus
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
HDEV	Heavy-Duty Electric Vehicle
LDf-X	Lean Design-for-Excellence
MSM	Multi-Layer Stream Mapping
PBS	Product Breakdown Structure

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Executive Summary

This document outlines the pathway towards an optimized design of a battery pack with regard to improving material and energy efficiency during production, use and end of life. The goal is to increase the durability of the materials and components and to make it easier to recover and recycle them, in line with eco-design practices and standards. The Lean Design-for-X (LDf-X) methodology was used to identify areas for potential improvement in the pack's design, which will support the design decision-making process in Task 2.1. The LDf-X methodology encompasses 4 main pillars that aim to assess the design effectiveness and efficiency of the battery pack underdeveloped within the project. The EXTENDED project aims to assess the domains of Design-for-Manufacturing, Design-for-Second Life, and Design-for-Recyclability. The results reveal consistent opportunities to enhance the efficiency of control, safety, mechanical, and electrical systems across different domains. Key areas for improvement that would significantly boost overall system performance include reducing weight, optimizing coolant flow, and speeding up disassembly and assembly processes.

1. Introduction

The EXTENDED project aims to design, develop, and validate the next-generation battery pack systems to meet the current market needs. The project focuses on creating lightweight, eco-designed, and multi-life battery pack systems that come with reduced charging times and are optimized for various applications such as light-duty and heavy-duty vehicles, aeronautics, and stationary use. The goal is to produce a product that provides effective solutions while upholding the highest standards of quality and sustainability. The design and development of these battery packs will be the primary objective of Work Package 2.

1.1. Work Package 2 focus

Work Package 2 within the EXTENDED project is dedicated to the development of a modular battery system design, incorporating considerations of electrical, thermal, and mechanical aspects. The modularity of the battery is related to the ability to easily extend, assemble, and disassemble the pack into individual modules, interchangeable units that contain associated electronics and components. The scalability, easier repairability and customization are just a few of the various advantages of this modular concept. Thus, the work being developed in this Work Package is highly aligned with the SO1 "Development of modular battery systems for various applications" and KPI 2 of the project, "modular design of the battery for various applications, design of the battery systems according to sustainability approaches", where is expected to use the concept of modular design in this battery pack.

This design phase places significant emphasis on the assembly and disassembly processes of the battery pack, with a strategic focus on achieving (semi-) automated manufacturing processes. To enhance safety parameters, an evaluation of lightweight housing and packaging materials is conducted, taking into account temperature fluctuations and varying humidity levels throughout the operational lifespan of the vehicle. The design's robustness and adherence to safety regulations are ensured through the implementation of simulations and risk analysis methods, effectively preventing thermal runaway propagation and satisfying crash standards.

Furthermore, the comprehensive analysis extends to the thermal behavior of the modular battery system across diverse platforms, applications, and operating conditions. This holistic examination serves to establish specifications and functionalities, laying the groundwork for an effective framework for cost estimation. The overarching objective of Work Package 2 is to foster the development of a modular battery system that not only meets rigorous safety standards but also exhibits adaptability and efficiency across a spectrum of use cases within the Electric Vehicle (EV) landscape.

1.2. Task 2.2 Objective

The battery pack design aims to improve material and energy efficiency during its production and usage. It also aims to enhance the durability, recovery, and recycling of materials and components with high value-added, supported by eco-design principals and directives.

The eco-design directive focuses on optimizing the environmental performance of products while maintaining their functionality. It aims to promote sustainable

development by increasing energy efficiency, environmental protection, and security of the energy supply. The directive sets mandatory requirements for the design and manufacture of a wide range of products, such as appliances, electronics, and heating systems. It aims to encourage that these products meet specific environmental standards throughout their lifecycle. The directive's goals include reducing energy consumption, promoting energy efficiency, and minimizing environmental impact. For this project, batteries were designed taking into account eco design strategies, prioritizing safety, cost reduction, increased energy density, and minimized carbon and resource consumption (European Parliament & Council of the European Union, 2009).

Lookin into the eco design parameters for products, below, the key considerations for designing products with minimal environmental impact are listeted. (European Parliament & Council of the European Union, 2009)

The ecodesign approach focuses on the entire life cycle of a product, encompassing:

- **Raw Material Selection and Use:** Examining the environmental impact of sourcing and processing materials.
- **Manufacturing:** Assessing the energy consumption, emissions, and waste generated during production.
- **Packaging, Transport, and Distribution:** Evaluating the environmental footprint of packaging materials, transportation modes, and distribution networks.
- **Installation and Maintenance:** Analyzing the resources and potential environmental concerns associated with installation and maintenance needs.
- **Use:** Considering the product's energy consumption, water usage, and potential emissions during its intended use.
- **End-of-Life:** Addressing the environmental impact of product disposal, including possibilities for reuse, recycling, or responsible disposal.

As for the associated environmental aspects to be consider for each life cycle stage, the following environmental aspects should be assessed when relevant:

- **Resource Consumption:** This includes materials, energy, water, and any other resources used throughout the product's life cycle.
- **Emissions:** Air, water, and soil pollution caused by the product during its life cycle.
- **Physical Effects:** Noise, vibration, radiation, and electromagnetic fields generated by the product.
- **Waste Generation:** The amount and type of waste produced throughout the product's life cycle.

- **Reuse and Recovery:** The potential for reusing product components, recycling materials, or recovering energy from the product at its end-of-life.

While these are not exhaustive, some key parameters to consider for evaluating the environmental impact of a product include:

- **Weight and Volume:** Lighter and smaller products typically have a lower environmental footprint.
- **Recycled Content:** Using materials derived from recycled sources reduces environmental impact compared to virgin materials.
- **Resource Consumption:** Monitoring energy, water, and other resource consumption throughout the product's life cycle helps identify areas for improvement.

This breakdown provides a overview for ecodesign principles by considering the product's environmental impact throughout its lifespan and identifying opportunities for minimizing its environmental footprint.

In the below (Table 1), the effects of significant environmental aspects and the improvement objectives for each environmental aspect are presented.

Table 1 - Effects and objectives associated with each significant environmental aspect.

Environmental Aspect	Impact	Objective
Resource Consumption	A greater diversity of resources and raw materials, and their unnecessary consumption, increases the product/equipment's environmental impacts.	Reduce resource and raw material consumption to the essentials in terms of quantity and type, increasing the efficiency of the manufacturing process as much as possible.
Resource Selection	The environmental impacts of the product are directly proportional to the environmental impacts of the resources and raw materials used to produce it.	Select the resources and raw materials to be used in the manufacture of the product, checking if there are no viable alternatives with lower environmental impacts.
Assembly and Disassembly Processes	Since these processes are associated with the consumption of resources and raw materials, simplifying them will lead to a reduction in the environmental impacts of the product/equipment.	Simplify these processes to reduce assembly and disassembly time and resource and raw material consumption.
Efficiency of the Product/Equipment during the Use Phase	The resource consumption associated with the use phase is directly proportional to the environmental impacts of the product.	Reduce as much as possible the amount of energy and consumables used during the equipment's use phase.
End of Life of the Product	The easier it is to dismantle and dispose of an equipment at the end of its life, the easier it will be to reuse it.	Look for solutions that allow for quick and easy reuse or recycling.

The LDf-X may support the design decision process in order to achieve the objectives specifically in the "X" domains of "design-for-manufacturing", "design-for-second-life", and "design-for-recyclability". The LDf-X analysis was performed using a proper XLS software tool allowing the evaluation of the improvements in the battery's design through the quantification of indicators for efficient and effective manufacturing, second life, and recyclability domains. These indicators encompass safety, energy density, low-carbon and low-resource consumption, as well as durability for second-life applications and modularity for material/component recovery and recycling, all aligned with circular design principles.

1.3. Deliverable 2.2 Objective

This deliverable aims to describe the battery design optimization towards material and energy efficiency during production and use, as well as durability and recovery/recycling of materials and components of high-added value. The LDf-X methodology was implemented to measure and quantify the improvements being developed during the design stage. It aims to assess the effectiveness and efficiency of each system of the battery pack, compare the different concepts under development, and assist in decision-making.

The document is divided into 5 main sections. Firstly, the Introduction presents the focus of Work Package 2, the Objective of Task 2.2, and Deliverable 2.2. The second section presents the Methodology and the considered use cases. The third section represents the application of the methodology, followed by the fourth section presenting and discussing the obtained results. Finally, the last section presents the conclusions obtained.

2. Methodology

In this section of the deliverable the Lean Design-for-X methodology is outlined, as well as the use cases assessed.

2.1. Lean Design-for-X: Concept and Description

Industrial companies face a tough balancing act: increasing market demands versus cost-effectiveness and agility. This includes complex challenges like innovation, quality, budgets, and development timelines. Various methodologies have emerged to manage this growing complexity, but the landscape has shifted. Today, mass production of highly customized products with fast development cycles is key. Achieving this efficiently, with diverse customer demands, remains a crucial challenge. It is crucial to achieve product specifications quickly with minimal manufacturing steps and interactions. The Design-for-Excellence arises as a method to support such current product demands. The Df-X approach is a holistic product management strategy that has emerged as an effective means of achieving product excellence. The methodology is designed to optimize all aspects of product design with a focus on ensuring the highest quality standard. Since its historical use by AT&T Bell Laboratories, this approach has evolved and now takes into consideration multiple aspects or "X" domains. (Baptista et al., 2018)

The LDf-X methodology, developed by INEGI, employs quantitative metrics to simplify design analysis and facilitate comparisons. This approach enhances the precision of design evaluations and promotes more informed decision-making. This methodology was developed by 2015 combining the Df-X and Lean Thinking approach and is a comprehensive product design process that encompasses multiple phases. It evaluates the efficiency and effectiveness of a product or system design by leveraging the principles of Lean Thinking. (Atilano et al., 2019; Baptista et al., 2018)

The LDf-X framework is a holistic approach that combines modular design methodology and lean design principles. Assesses the effectiveness of design goals, offering a detailed analysis with a multi-dimensional evaluation of design across various domains ("X" domains) and relying on Modular Design Principles. Employing a Lean Thinking approach, it also emphasizes the reduction of waste resources throughout the product's life cycle phases, incorporating visual management concepts. (Atilano et al., 2019)

The foundation of the LDf-X framework rests on four essential pillars, Figure 1:

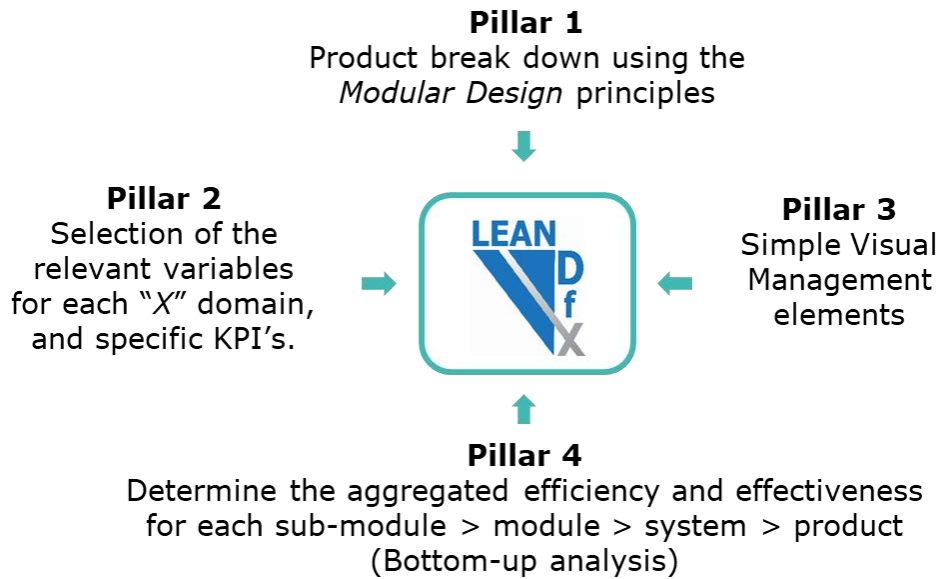


Figure 1. Essential pillars of LDf-X methodology.

Pillar 1 - Product breakdown

Breaking down the product into modular components by employing modular design principles for product decomposition, forms a core pillar of the LDf-X evaluation framework. This approach minimizes analytical complexity, enabling granular assessments of effectiveness and efficiency at the module and submodule levels.

Pillar 2 - Selection of "X" domains and their specific design indicators;

LDf-X utilizes various design influence domains ("X"), each encompassing a group of relevant variables for analysis. These domains help assess the most suitable approaches for different design concepts, products, or even modules. To choose the most fitting domains, a preliminary evaluation is crucial.

In the figure below, Figure 2, are some examples of typical domains that are relevant at design phase for sustainability and cost improvement.

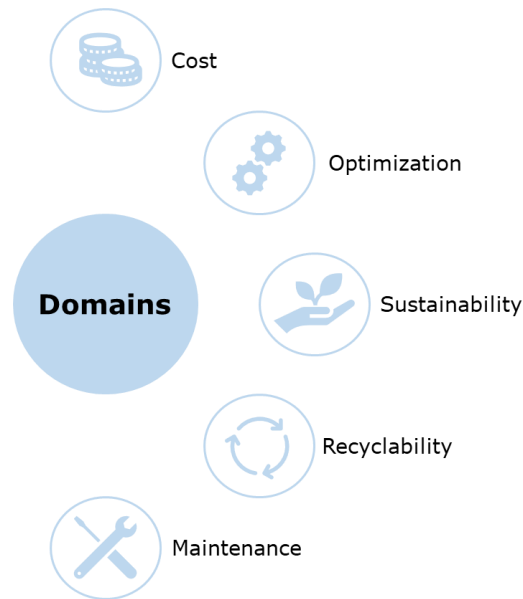


Figure 2. Examples of relevant domains.

Pillar 3 - Simple Visual Management attributes

The LDf-X methodology incorporates a visual grading system (0-100%) analogous to Multi-Layer Stream Mapping (MSM), enabling intuitive result analysis. This scale is further mapped to a four-color system (red, orange, yellow, green) corresponding to varying degrees of efficiency and effectiveness, as shown in Figure 3.

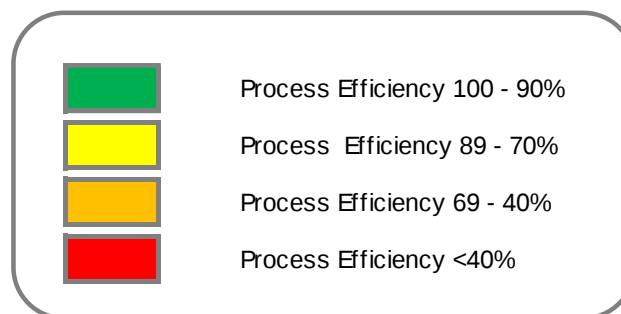


Figure 3. Color coding for the grading system.

Pillar 4 - Aggregation of efficiency and effectiveness through product modular hierarchy and "X" Design Domains

Effectiveness measures how closely the design meets its target, with 100% representing perfect achievement, Equation 1. To further assess whether the target is exceeded, an additional score is derived showing the extent of overachievement. However, if the target is not met (ineffective design), the efficiency ratio remains uncalculated, as efficiency in an ineffective design is irrelevant.

$$Effectiveness = \frac{Specific\ value - target\ value}{Current\ value} \quad (1)$$

Effectiveness scorecards, normalized to 0-100%, track the distance from the target for each variable, Equation 2.

$$Efficiency = \frac{Ideal\ value - target\ value}{Current\ value} \quad (2)$$

These steps, linked to the calculations of the ratios and subsequent interpretation and analysis of the results, guide the design iterations through continuous improvement refining the design to achieve full effectiveness.

2.2. Lean Design-for-X tool

The LDf-X software Excel tool, was used, in order to assess effectiveness and efficiency ratios at various levels, aggregating them from individual modules to the entire product, following a bottom-up analysis of the product breakdown structure. Starting from the lowest level, these ratios are calculated and aggregated progressively upward until reaching the entire product.

Figure 4 displays the 4-color scorecard, where green denotes a superior outcome and red denotes an inferior outcome. Each column refers to a system in the product's breakdown structure, while each horizontal line corresponds to an indicator that is being taken into consideration during the design stage. The measurement of effectiveness and efficiency for each indicator for each system precedes the calculation of aggregate effectiveness and efficiency by system (on the top of the figure) and by indicator (on the right of the image) and to finish, the overall effectiveness and efficiency are calculated (on the top right). To ensure consistency, all ratios are expressed as percentages between 0-100%.

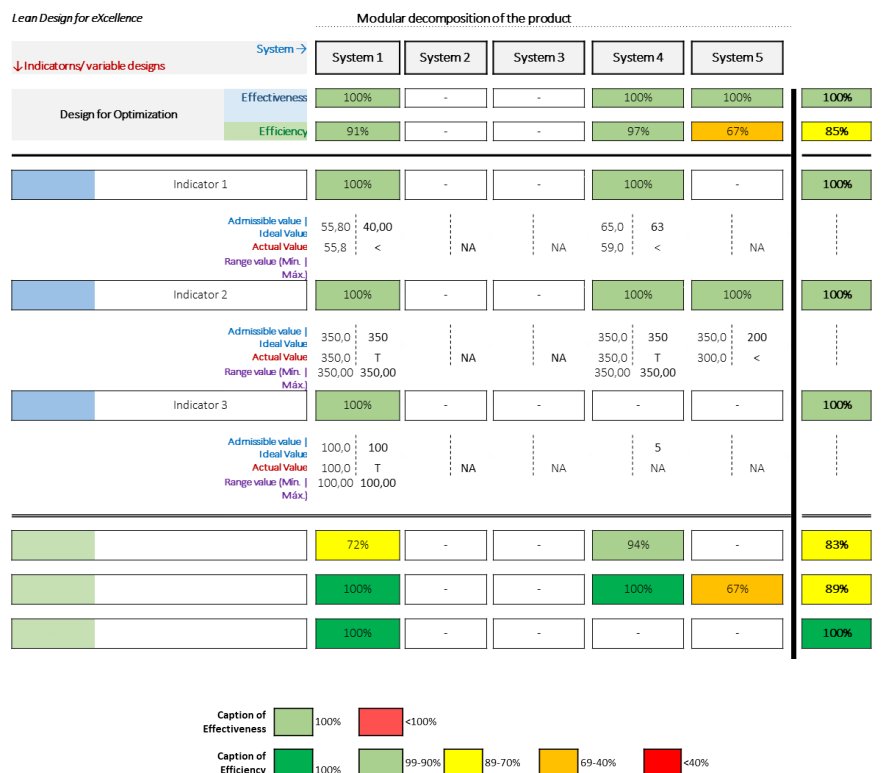


Figure 4. Scorecard of the LDf-X software Excel tool.

This tool requires inputs for effectiveness and efficiency calculations. Effectiveness is assessed to determine whether a variable meets a specific requirement, while efficiency quantifies the effort needed to achieve a particular goal or the excess effort being wasted. The inputs necessary for the assessment are present in Figure 5, and can be described as:

- Admissible value, serving as a benchmark for effectiveness and should be defined based on technical expertise or literature. This value can be a range of values and can also be a minimum or maximum limit of the tolerance value.
- Ideal value, that acts as a goal or target to achieve, also defined based on technical expertise or literature, and must be a singular value.
- Actual value represents the current value of the variable in the control state, i.e., the variable under assessment in the project.
- Operator, which defines if the admissible value is a tolerance range, a maximization or a minimization analysis.

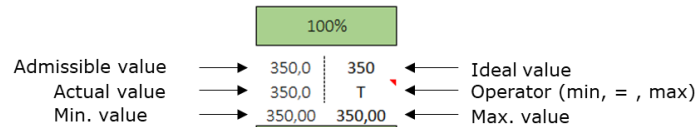


Figure 5. Tool input box and description of each parameter.

The final results are presented in LDf-X scorecards, offering a clear and summarized overview, as it is shown in Figure 6.

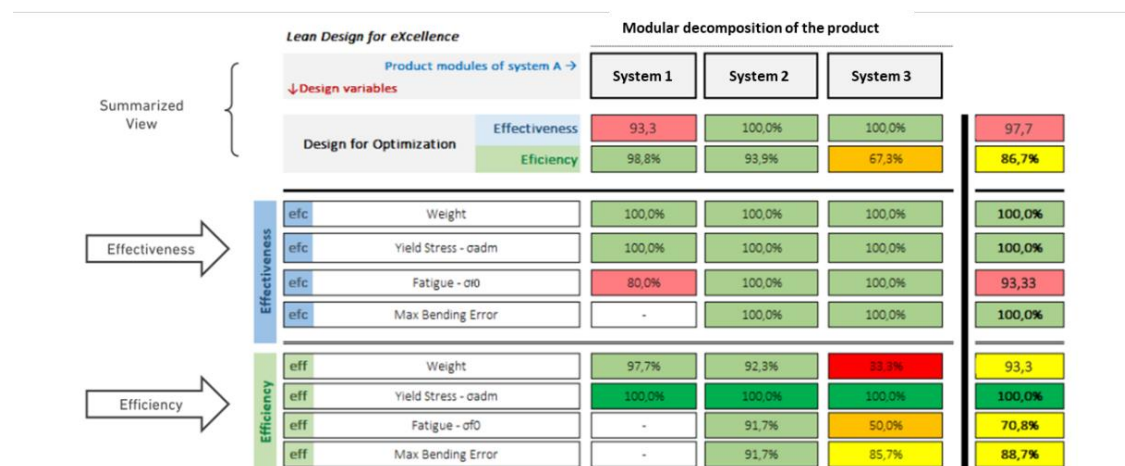


Figure 6 - LDf-X scorecards – Example.

Once the software is populated with data, analysis can be conducted through the scorecards. These scorecards provide insights into systems and their corresponding indicators, enabling targeted improvements in the ones with lower efficiency.

3. Application of the Methodology

The process of applying the methodology LDf-X comprised several steps. Besides the technical implementations of the methodology, as described in the previous section, several interactions with partners were performed in a systematic manner. Firstly, a workshop was conducted to explain the methodology to the technology experts and product designers and define the strategy for the implementation of LDf-X. Several technical discussions were held to deliberate on the indicators to be evaluated and to collect data on the selected indicators. Then, a meeting was convened to present the results and identify the areas with the greatest potential for improvement.

3.1. Use Cases

The LDf-X methodology, as employed within the EXTENDED project, was applied to evaluate the modular battery system across various design stages for different use cases. These scenarios encompassed light-duty Electric Vehicles (EV), Heavy-Duty Electric Vehicles (HDEV), stationary applications – Energy Storage Systems (ESS), and aeronautic applications.

One important consideration is related to the design of batteries for aeronautical applications, which are currently in their early stage of development. Therefore, it is essential to evaluate them in a way that is similar to light-duty vehicles batteries, also due to the design proximity and similarity. Such approach was decided in a dedicated technical discussion with partners of the project. Thus, it will be possible to make informed decisions that are based on well-researched and accurate data. As such, the evaluation will be restricted to only three scenarios, light-duty vehicles, heavy-duty vehicles, E-Bus, and stationary, Energy Storage systems.

3.2. Product Breakdown Structure

To implement this methodology, it's necessary to deconstruct the product into different modules utilizing modular design principles for the product decomposition. In this step, it was essential to maintain close interactions with battery design experts to ensure a comprehensive understanding of the technical aspects of the product. Thus, this approach was applied to the product in analysis, a battery pack, and the final Product Breakdown Structure (PBS) is presented in [Figure 7](#).

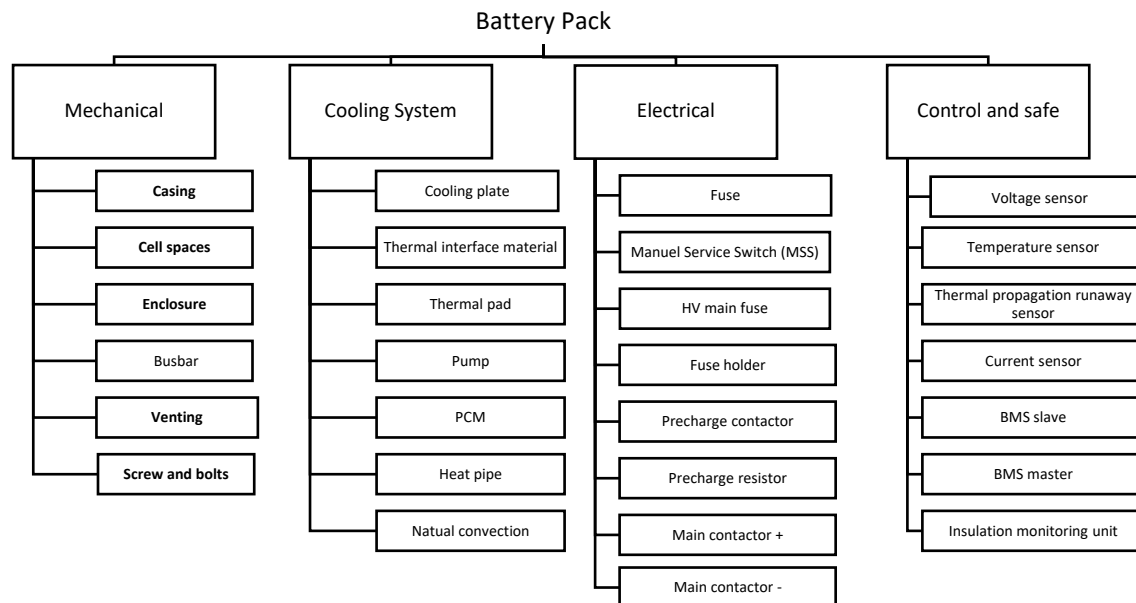


Figure 7. Product Breakdown Structure defined for the project's battery pack.

3.3. LDF-X Domains

After product decomposition, according to the PBS, it was necessary to define the domains that will be evaluated. Different design concepts or design versions of products integrate different 'X' domains.

In the EXTENDED Project, the domains to be assessed are clearly defined. These domains include **design-for-manufacturing, design-for-second life, and design-for-recyclability**.

Design-for-Manufacturing: is important because it helps reduce production costs, improve product quality, enhance manufacturing efficiency, and ensure compliance with regulations and sustainability goals.

Design-for-Second Life: is relevant because it ensures products are designed with reuse, refurbishment, recycling, or repurposing in mind, promoting resource efficiency.

Design-for-Recyclability: is crucial because it ensures products can be easily and effectively recycled at the end of their life, reducing waste and conserving resources.

After the domains to be analysed have been decided upon, it is crucial to select the appropriate indicators that will enable us to quantify the effectiveness and efficiency of those domains. The selected indicators represent various aspects of design that were developed on Task 2.1 with consideration given to the specific requirements for each use case and taking into account eco-design principles towards product desing.

These indicators differ for each domain of design, analysing specific elements in each domain. Table 2 shows the different indicators chosen for each domain and model of the battery pack for the EXTENDED project. The indicators were the same for every use case. The indicators were defined battery system desing expts, within the several technical worksesions

Table 2. Selected indicators for the EXTENDED project.

LDf - Manufacturing			
Mechanical	Cooling System	Electric	Control and Safety
Weight	Weight	Weight	Weight
-	Flow Rate of the Coolant	-	-
-	Climate change impacts of Graphite thermal pad	-	-
LDf - 2 nd Life			
Mechanical	Cooling System	Electric	Control and Safety
-	-	Total Time to disassembly	Total Time to disassembly
Time to disassemble with Cell Contact System	-	-	-
Time to disassemble with Thermal Pads	-	-	-
Time to disassemble with Laser Processes	-	-	-
LDf - Recyclability			
Mechanical	Cooling System	Electric	Control and Safety
-	-	Percentage of material for Landfill	Percentage of material for Landfill
Joint system wood	-	-	-
Joint system plastic	-	-	-
Joint system steel	-	-	-

Manufacturing

The manufacturing domain corresponds to the technical specifications of the battery design that need to be aligned with the objectives of the project. Regarding design for the manufacturing domain, the chosen indicators/variables include:

- Regarding the mechanical system's weight, it plays a significant role in maintaining the pack's structural integrity. Additionally, it affects the vehicle's dynamics, enhancing overall stability and handling. The lightweight design not only reduces costs but also minimizes the battery's weight, leading to improved energy efficiency.
- Considering the weight of the cooling system, lighter systems can optimize space and energy efficiency, simplify the manufacturing and assembly processes, and improve the handling of the vehicle. On the other hand, heavier cooling systems can be more difficult to handle and may require more energy to operate, which can affect the effectiveness of the thermal management.
- In terms of the electric system, a lighter design reduces costs and minimizes battery weight, leading to improved energy efficiency.

- Regarding the control and safety system's weight, a lighter design can lower costs, reduce battery weight, and improve energy efficiency. It also simplifies installation.
- The flow rate of the coolant is important because it ensures efficient heat dissipation, uniform cooling, battery health and longevity and safety.
- Regarding the thermal pad, the chosen materials for the different parts of the battery pack should have low carbon emissions, when possible. To achieve this, it is important to assess the life cycle of the proposed solutions evaluating the climate change impacts of using different materials. The thermal pad assessed was the graphite thermal pad, and the benchmark considered was the steel one.

The admissible, ideal, and actual values were all defined by technical experts in dedicated meetings with the responsible partner for each system.

Second Life

Extending the life of batteries can significantly reduce the environmental impact of battery disposal and delay the need for energy-intensive recycling. The European Union is committed to a circular economy that minimizes waste and maximizes resource use, and extending battery life aligns perfectly with this goal. The EU Battery Directive includes ambitious recycling targets for Lithium-ion batteries, and by maximizing battery utilization in a second life, there will be a reduced need for immediate battery material recycling, thereby improving the strain on future recycling infrastructure (European Parliament & Council of the European Union, n.d.). To achieve this, during the design stage it is important consider how easy it is to transition from the first life to the second life to facilitate the transition in order reduce the efforts involved in the process. The selected indicators/variables include:

- Total time required to disassemble the mechanical part using cell contact systems, thermal pads, and laser processes. The shorter the disassembly time, the easier it will be the transformation process to a second life. Also, with time reduction for disassembly, the consumption of the resources it will decrease resulting in a reduction of carbon emissions . As for benchmarking the admissible values and ideal values were defined by technical specialists based on their knowledge.

The admissible, ideal, and actual values were all defined by technical experts in dedicated meetings with the responsible partner for each system.

Recyclability

The European Union (EU) Battery Regulation has stipulated a minimum recovery rate for both batteries (65 wt%) and materials in the recycling process, to ensure a minimum recycling efficiency by 2025. The regulation highlights the importance of managing waste streams promoting the efficient use of resources and reduce the environmental impact of batteries.

The established indicators for this field are the percentage of materials that can be recycled. Currently, according to the experts, only the cell components of a battery

are subject to the recycling process, whereas the remaining materials are not currently being recovered (European Parliament & Council of the European Union, n.d.).

Thus, concerning design for the recyclability domain, the selected indicators/variables encompass:

- The percentage of materials from the cooling system, electrical, control, and safety components that are directed to landfills;
- The recyclability of the joint material used. The considered materials for the joint system were wood, plastic, and metal (steel). The chosen material for the connection system was subject to an evaluation that is based on a scale of 1-5, in which 1 represents the highest degree of recyclability and 5 signifies the least desirable level. This indicator was used to measure the extent to which the material is susceptible to being recycled.

Once the product has been broken down into different models and the domains to be analyzed have been decided, it is important to select the indicators to be evaluated and then choose the appropriate data to calculate the effectiveness and efficiency of those domains.

As discussed in the previous chapter, it is necessary to determine an admissible value, an ideal value, and an actual value. The admissible value acts as a benchmark for effectiveness and serves as a reference point to assess whether the analyzed value meets or exceeds the worst acceptable value. The ideal value serves as a goal or target to achieve. This value is used to measure the effort required to reach that specific goal or target. This means that if the actual value is significantly higher or lower than the ideal value, the desired level of effectiveness will not be achieved. This could be due to the need for improvements to reach the ideal value, or because there is unnecessary excess effort, depending on whether the current value is below or above the ideal, respectively. The current value represents the present value of the variable being assessed in the project. The admissible, ideal, and actual values were all defined by technical experts in dedicated meetings with the responsible partner for each system.

4. Results

The LDf-X methodology was implemented to measure and quantify the design efficiency and effectiveness. The results are presented by use case, allowing a comprehensive understanding of the effectiveness of each system concerning the optimization parameters that are being developed during the design stage. The use cases considered were EV, E-BUS, and ESS. The aeronautics use case is depicted by the EV use case due to its design proximity. Therefore, only one assessment was made for EV and Aeronautics applications, which represent the improvements that need to be made for both use cases. Each decision was evaluated for its efficiency, considering a reference value that cannot be exceeded or must not be lower than a certain value defined as admissible. This approach will enable us to determine how effective and efficient the decision-making process is for each system, thereby facilitating informed decision-making.

4.1. Results for the Electric Vehicle and Aeronautics Use Case

EV & Aeronautics Manufacturing:

Figure 8 represents the scorecard for EV and aeronautics use cases for the manufacturing domain. In [Annex 1- LDf-X Results –Extended Scorecards](#), it is possible to find a comprehensive scorecard for each domain and use case, providing detailed information.

Regarding the weight of the battery pack, it is possible to observe that effectiveness is attained for this design stage for all systems, meaning that the selected indicators meet the admissible requirements established. As for the flow rate of the coolant in the cooling system, the design efficiency is achieved with a 33% deviation from the ideal reference target for efficiency assessment, meaning that the actual value that is being designed exhibits a deviation from the ideal value defined, which indicates that there's room for improvement. Concerning the climate change emissions for the selected material for the thermal pad of the cooling system, the calculations show that the use of graphite yield a reduction of climate change emissions in comparison with the conventional material (steel), being this decision effective and efficient. For the manufacturing domain, the overall effectiveness of integrating the four key systems modules was 100%, and an efficiency overall ratio of 85% for the indicators that passed the thresholds.

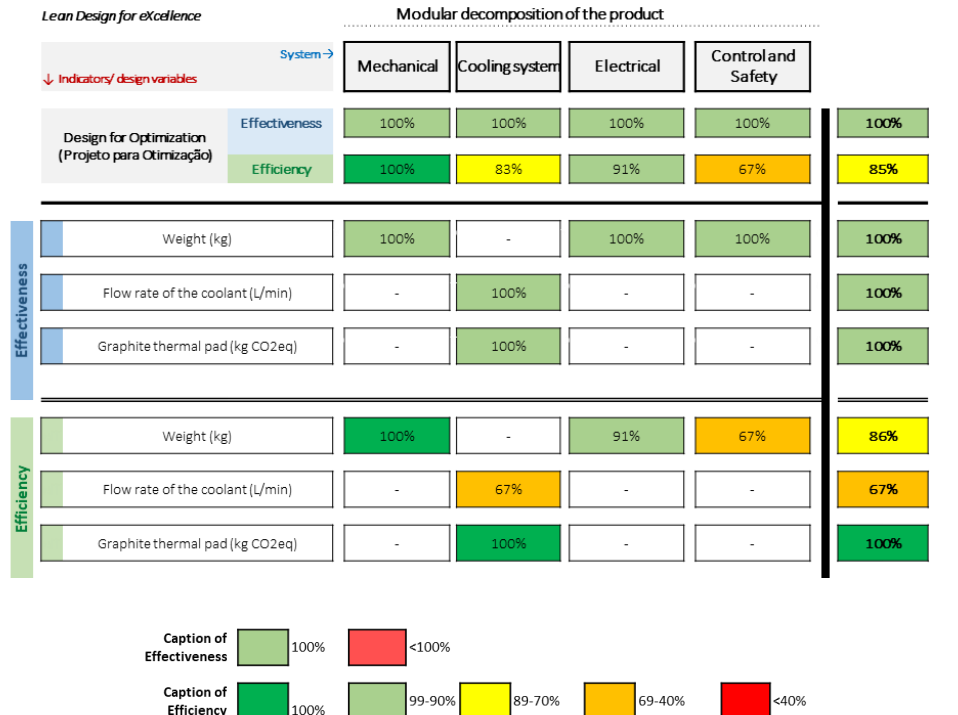


Figure 8. Scorecard for EV and aeronautics use cases for manufacturing domain.

EV and aeronautics Second life:

Figure 9 represents the scorecard for EV and aeronautics use cases for the second life domain.

Regarding the mechanical system, it is possible to observe that effectiveness was attained for this design stage, meaning that all the selected indicators meet the admissible requirements. However, the time to assembly due to the cell contact system, the time to disassembly due to the use of thermal pads and due to use of laser process, exhibit deviations of 4%, 25%, and 37%, respectively for efficiency assessment, meaning there is room for improvement. For the manufacturing domain, the overall effectiveness of the mechanical system was 100%, and an efficiency overall ratio of 82%. Concerning the time to disassembly of the electrical and control and safety systems, effectiveness was accomplished but there's room for efficiency improvement of 11% and 29% respectively for electrical and control and safety systems. For the second life domain, the overall effectiveness of the evaluated systems was 100%, and an efficiency overall ratio of 81%.



Figure 9. Scorecard for EV and aeronautics use cases for second life domain.

EV and aeronautics recyclability:

In the context of the recyclability domain, the evaluation of effectiveness and efficiency was conducted through three distinct concepts for the connection system of the mechanical system, each based on different connection systems and materials (wood, plastic, steel), and based on the percentage of material that goes to landfill of the electrical and control and safety systems at the end of life, that is the same for all the concepts, Figure 10 , Figure 11 and Figure 12.

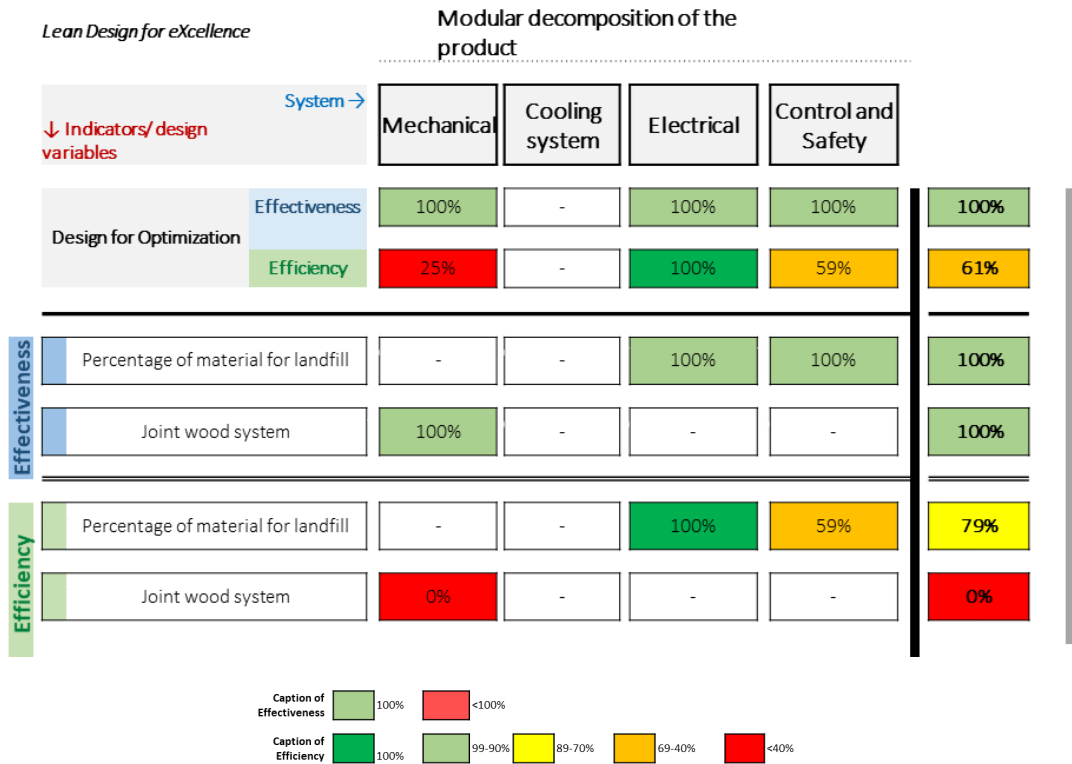


Figure 10. Scorecard for EV and aeronautics use cases for recyclability domain.
Concept 1 – Wood Joint System.

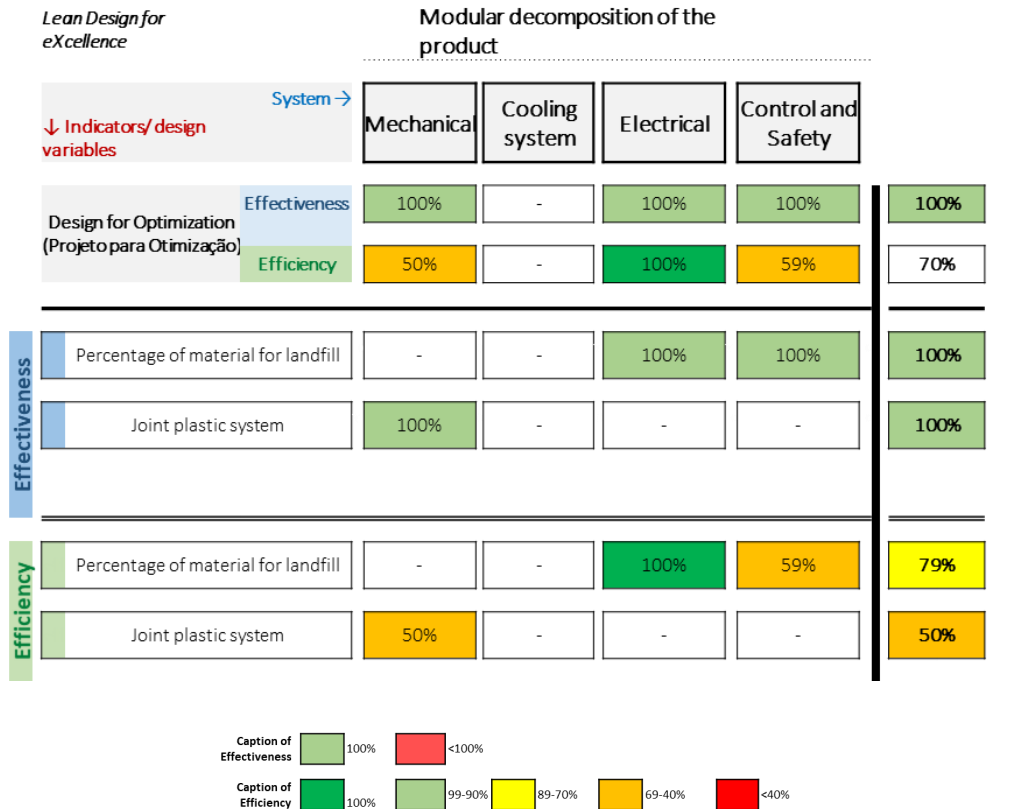


Figure 11. Scorecard for EV and aeronautics use cases for recyclability domain.
Concept 2 – Plastic Joint System.

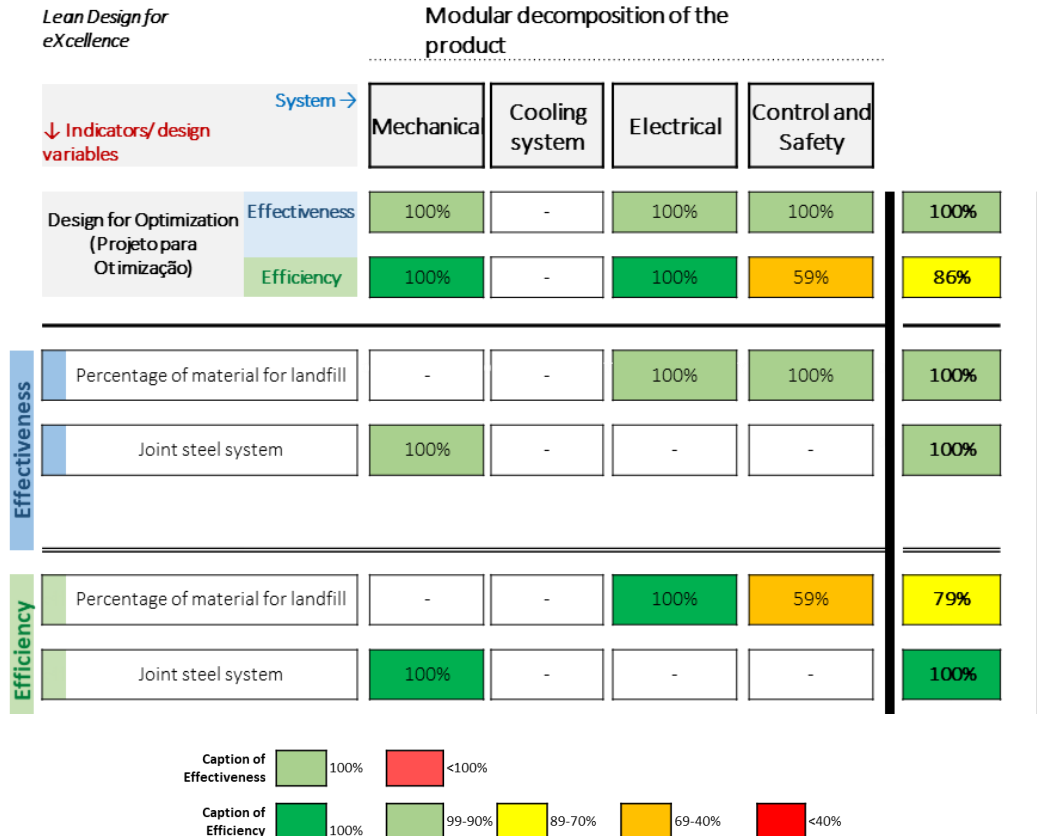


Figure 12. Scorecard for EV and aeronautics use cases for recyclability domain.
Concept 3 – Steel Joint System.

The percentage of material for landfill of electrical and control and safety systems, attained the effectiveness for this design stage, meaning that meets the admissible requirements. Nonetheless, the control and safety systems exhibit deviations of 41%, for efficiency assessment, meaning there is room for improvement. As for the connection system of the mechanical part of the battery pack, the wood connection system concept, Figure 10, does not achieve the design effectiveness, whereas the plastic and steel concepts, Figure 11 and Figure 12, respectively, do achieve it with a deviation of 50% for effectiveness for the plastic connection system and without any deviation for the steel connection system. For the recyclability domain, the overall effectiveness is 100%, and the overall efficiency ratio is 61%, 70% and 86%, meaning that the most efficient concept is the third one, with the steel connection system.

4.2. Results for the Electric Bus Use Case

E-BUS manufacturing:

Figure 13 represents the scorecard for BUS for the manufacturing domain.

Regarding the weight of the mechanical and electric systems of the battery pack, it is possible to observe that effectiveness and efficiency are attained for this design stage, meaning that the selected indicators meet the admissible requirements established and also are totally optimized, considering the ideal values defined. About control and safety systems, the weight indicator is effective, but there is room for a 29% improvement in efficiency.

As for the flow rate of the coolant in the cooling system, the design efficiency is achieved with a 33% deviation from the ideal reference target for efficiency assessment, meaning there is room for improvement.

For the manufacturing domain, the overall effectiveness of integrating the four key systems modules is 100% and the overall effectiveness is 85%.



Figure 13. Scorecard for E-BUS use case for manufacturing domain.

E-BUS Second life:

Figure 14 represents the scorecard for E-BUS for the second life domain. Regarding the time to disassemble the mechanical part of the battery pack due to different systems was possible to observe that effectiveness was attained for this design stage, meaning that all the selected indicators meet the admissible requirements. However, the use of thermal pads and the use of laser process, exhibit deviations of 25%, and 37%, respectively for efficiency assessment, meaning there is room for improvement. For the manufacturing domain, the overall effectiveness of the mechanical system is 100%, and the efficiency overall ratio is 79%.

In the context of the second life domain, similar to what was done for EV use case, the evaluation of effectiveness and efficiency was conducted through three distinct concepts for the connection system of the mechanical system, each based on different connection systems and materials. It was also evaluated the percentage of material that goes to the landfill of the electrical and control and safety systems at the end of life, which is the same for all the concepts, Figure 15, Figure 16 and Figure 17.

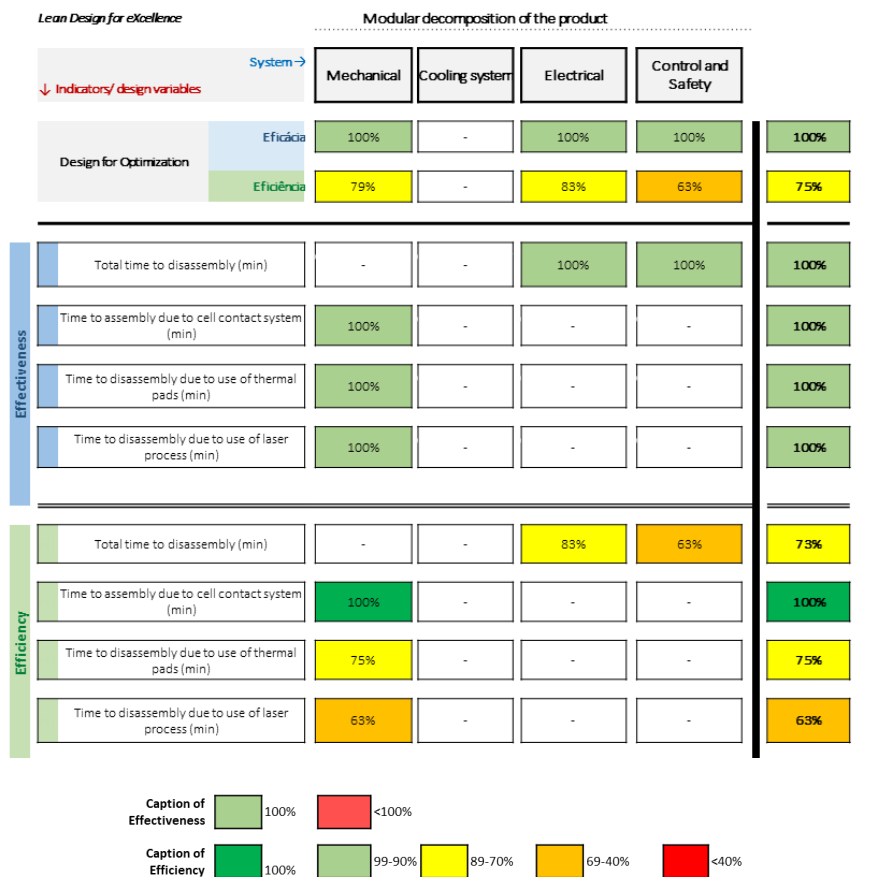


Figure 14. Scorecard for E-BUS use case for second Life domain.

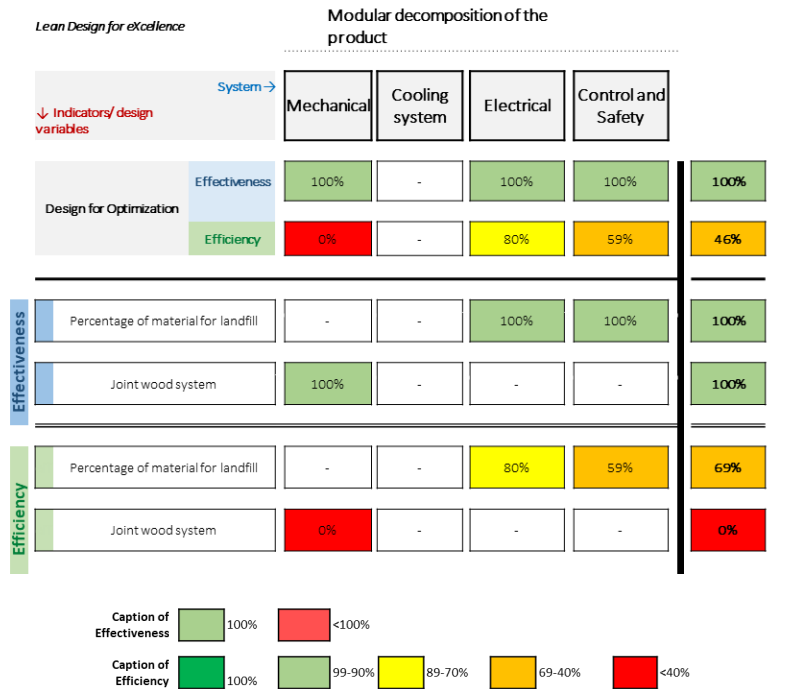


Figure 15. Scorecard for E-BUS use case for recyclability domain. Concept 1 – Wood Joint System.

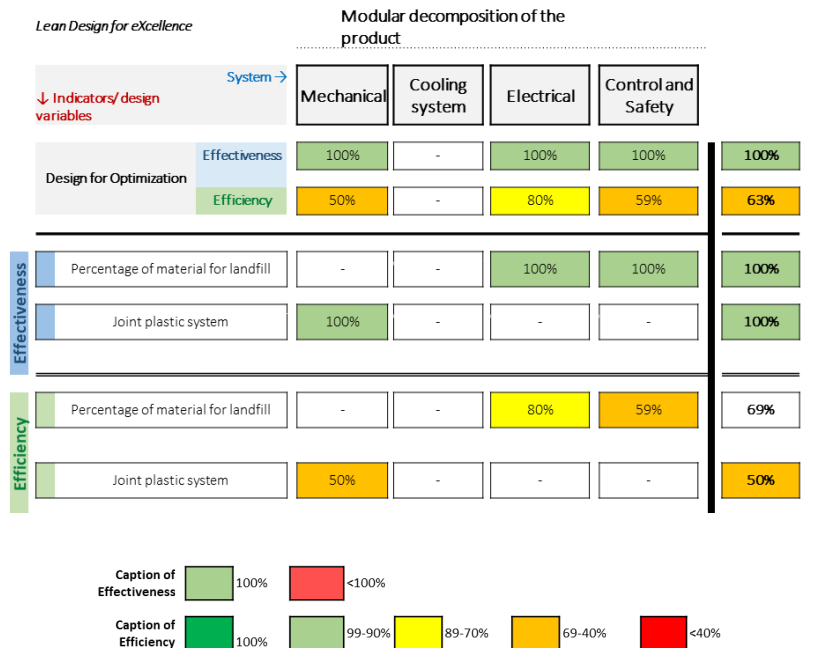


Figure 16. Scorecard for E-BUS use case for recyclability domain. Concept 2- Plastic Joint System.

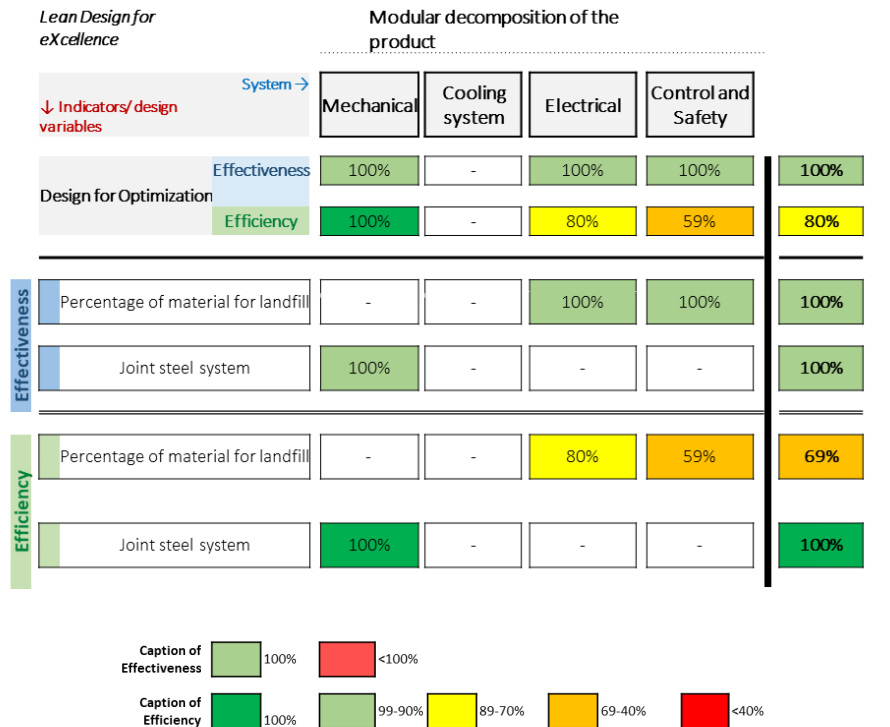


Figure 17. Scorecard for E-BUS use case for recyclability domain. Concept 3- Steel Joint System.

The percentage of material for landfill of electrical system attained the effectiveness for this design stage, meaning that meets the admissible requirements defined. Nonetheless, the percentage of material going to landfill of the control and safety systems don't meet the requirements, being ineffective. As for the connection system of the mechanical part of the battery pack, the wood connection system concept, Figure 15, does not achieve the design effectiveness, whereas the plastic and steel concepts, Figure 16 and Figure 17, respectively, do achieve it with a deviation of 50% for effectiveness for the plastic connection system. For the recyclability domain, the overall effectiveness of integrating the four key systems modules is 67% for the tree concepts, and the overall efficiency ratio is 53%, 63% e 86%%, meaning that the most efficient concept is the third one, with the steel connection system.

4.3. Results for the Energy Storage System Use Case

ESS manufacturing:

Figure 18 represents the scorecard for ESS for the mechanical domain. Regarding the weight of the mechanical and electric systems, it is possible to observe that effectiveness and efficiency are attained for this design stage, meaning that the selected indicators meet the admissible requirements established. Therefore, there are deviations in effectiveness of 30% for mechanical and electrical systems, and 31% for the control and safety system, meaning there's room for improvement.

For the manufacturing domain, the overall effectiveness is 100% and the overall efficiency is 70%.

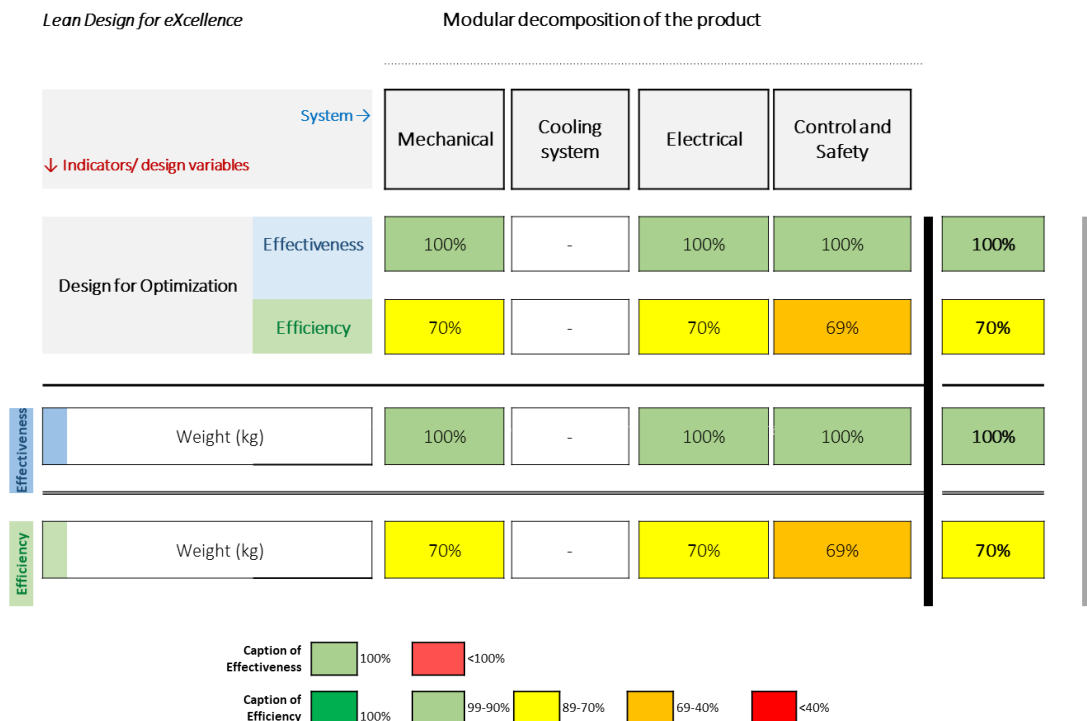


Figure 18. Scorecard for ESS use case for mechanical domain.

Figure 19 represents the scorecard for ESS for the second life domain.

Regarding the total time to disassemble the tree of four systems, it was possible to observe that effectiveness was attained for this design stage, meaning that the admissible requirements were met. However, the efficiency was 70% for mechanical and control and safety systems meaning that there's space for improvement.

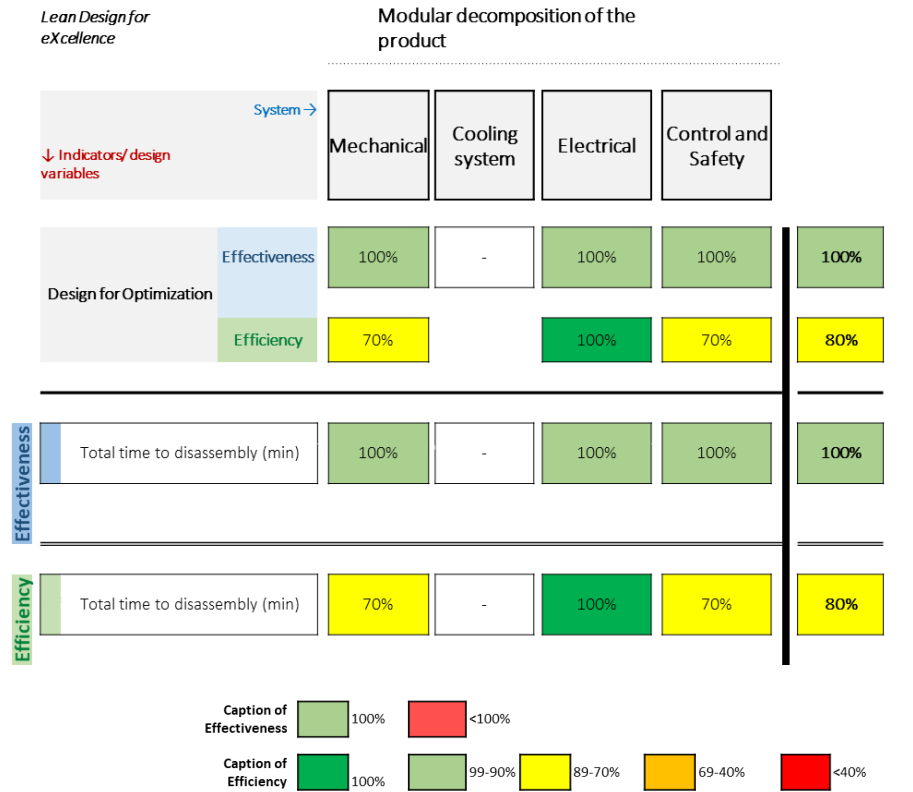


Figure 19. Scorecard for ESS use case for second life domain.

5. Conclusion

The battery design aims to improve material and energy efficiency, durability, and recycling of materials and components with high value-added, supported by eco-design directives. The objective of this task is to provide a description of the optimization stages of the battery design towards three different domains: manufacturing, second life and recyclability. This was developed through the Lean-based Df-X excel software tool, which evaluates the battery pack design efficiency and effectiveness against defined target values in the battery's design allowing the identification of areas where design improvements can be made.

Regarding the EV use case for the manufacturing domain, it can be concluded that there is an opportunity for improvement in the control and safety system, which has the lowest efficiency, and in the cooling system. Although the requirements have been met, there is still room to reduce the weight of the control and safety system, as well as the flow rate of the coolant.

Concerning the EV use case for the second life domain, there is an opportunity for improvement in the control and safety system, which is the system with the lowest efficiency and also there's space for improvement in mechanical and electrical systems. Although all the requirements have been met, there is still room to reduce the total time to disassemble of the electrical and control and safety systems, and time to assembly due to the use of thermal pads and due to use of laser process for the mechanical system.

About the EV use case for the recyclability domain two conclusions can be drawn from the evaluations. One relates to the mechanical system, which was evaluated through three different concepts of joint systems. The other conclusion relates to the remaining systems, which were kept fixed throughout the three different concepts. The steel joint system was considered the most effective and should be selected for future implementations. When it comes to the other systems, there is potential for enhancement in the control and safety aspects.

Regarding the E-BUS use case for the manufacturing domain it can be concluded that there is an opportunity for improvement in the control and safety system, which has the lowest efficiency, and in the cooling system. Although the requirements have been met, there is still room to reduce the weight of the control and safety system, as well as the flow rate of the coolant.

Concerning the E-BUS use case for the second life domain, there is an opportunity for improvement in the control and safety system, which is the system with the lowest efficiency and also there's space for improvement in mechanical and electrical systems.

In the context of recyclability domain, the evaluation of the E-BUS use case led to two main conclusions. The first conclusion pertains to the mechanical system, which was assessed through three different joint system concepts, similar to what was done for the EV use case. The second conclusion pertains to the remaining systems, which were kept constant across the three different concepts. The steel joint system was deemed the most effective and should be chosen for future implementations. As for the other systems, there is potential for improvement in the electrical, control, and safety aspects.

Regarding the ESS use case for the manufacturing domain, it can be concluded that there is an opportunity for improvement in the control and safety system, which has the lowest efficiency, followed by mechanical and electrical systems, although all the requirements have been met, there is still room to reduce the weight of these systems.

Concerning the ESS use case for the second life domain, it can be concluded that there is an opportunity for improvement in the mechanical and in control and safety systems.

Implementing these improvements would enhance the systems' efficiency and bring them closer to reaching their full potential.

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Annex 1- LDf-X Results – Extended Scorecards

LDf-Manufacturing for EV use case

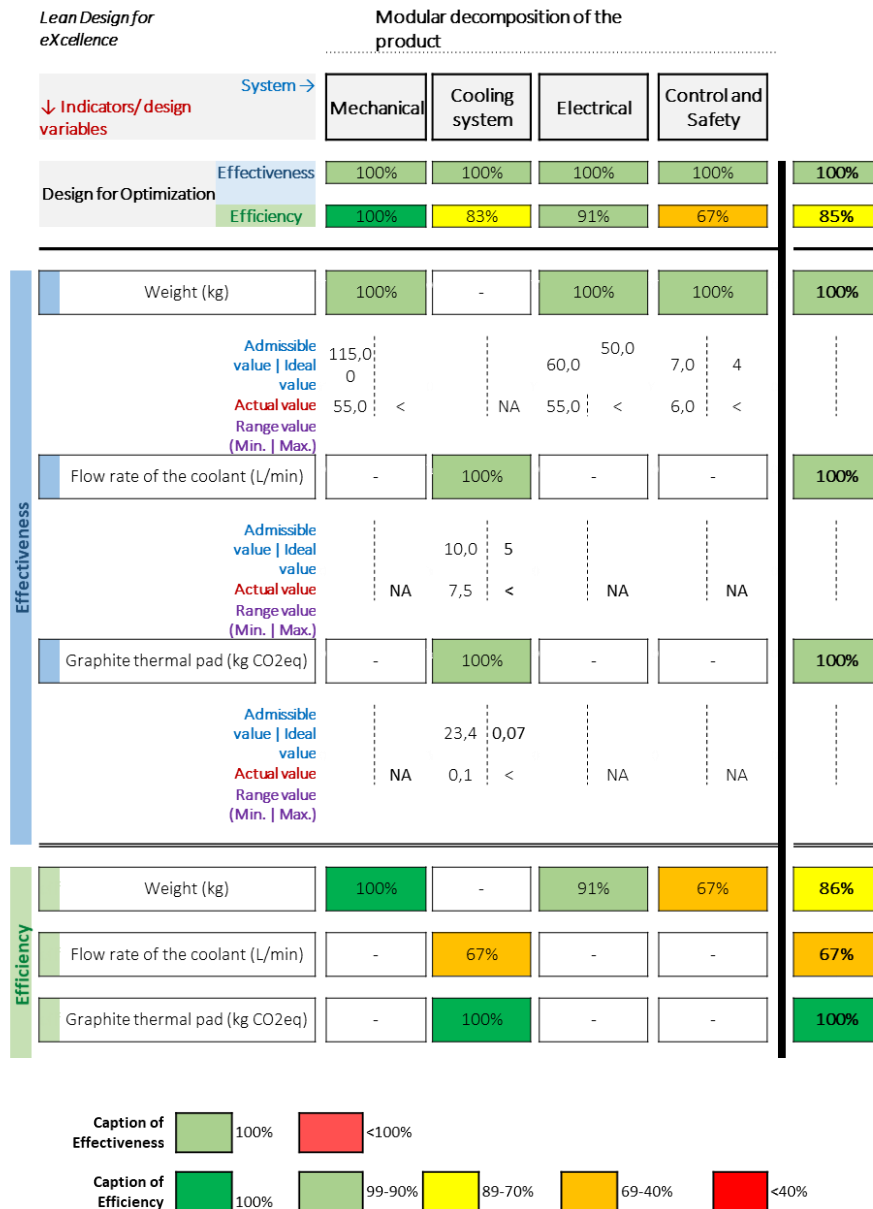


Figure 20. LDf-Manufacturing for EV use case.

LDF-Second Life for EV use case



Figure 21. LDF-Second Life for EV use case.

LDF-Recyclability for EV use case



Figure 22. LDF-Second Life for EV use case. Concept 1.

LdF-Recyclability for EV use case

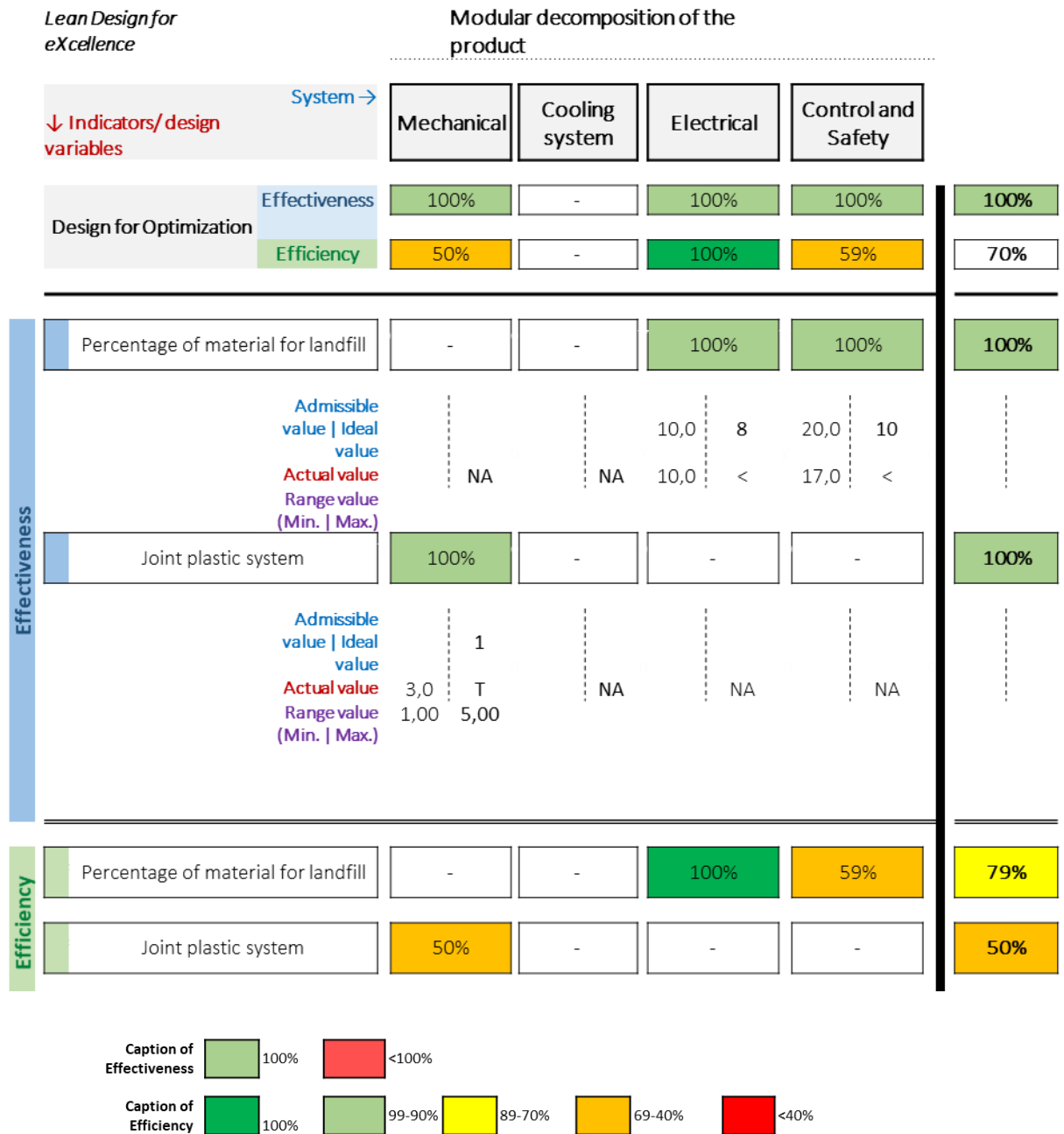


Figure 23. LdF-Second Life for EV use case. Concept 2.

LDF-Recyclability for EV use case

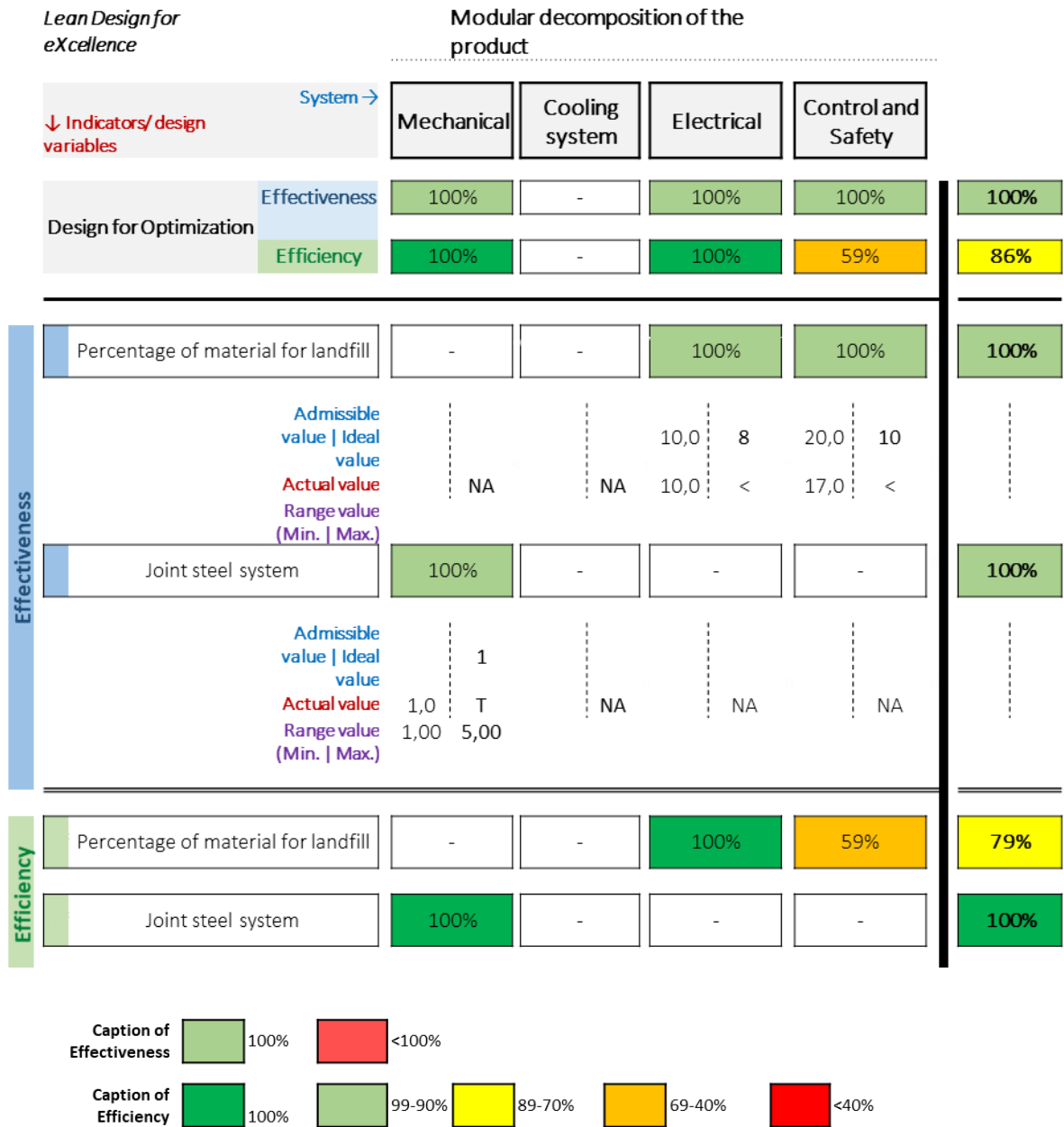


Figure 24. LDF-Second Life for EV use case. Concept 3.

LdF-Manufacturing for E-BUS use case

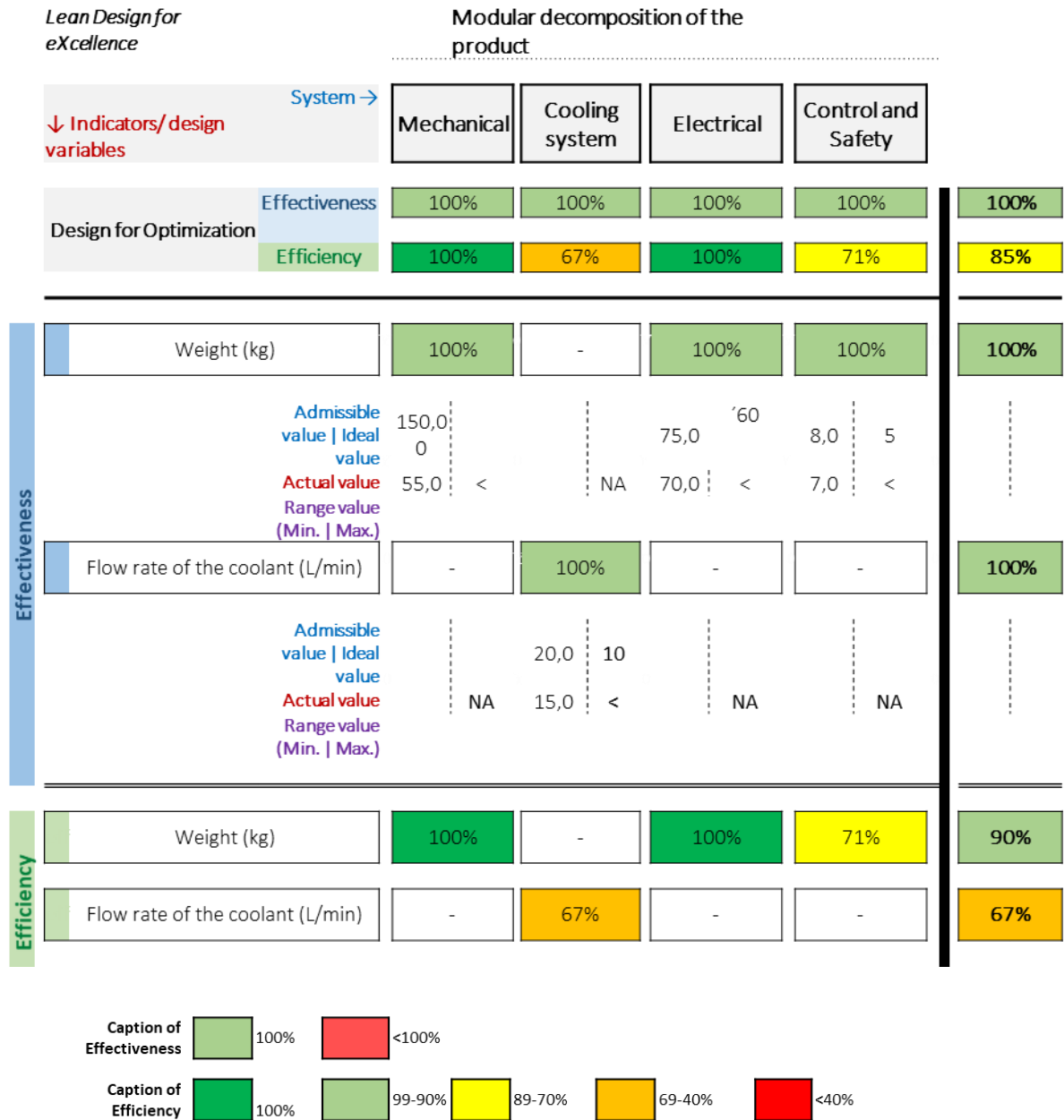


Figure 25. LDf-Manufacturing for E-BUS use case.

LDF-Second Life for E-BUS use case

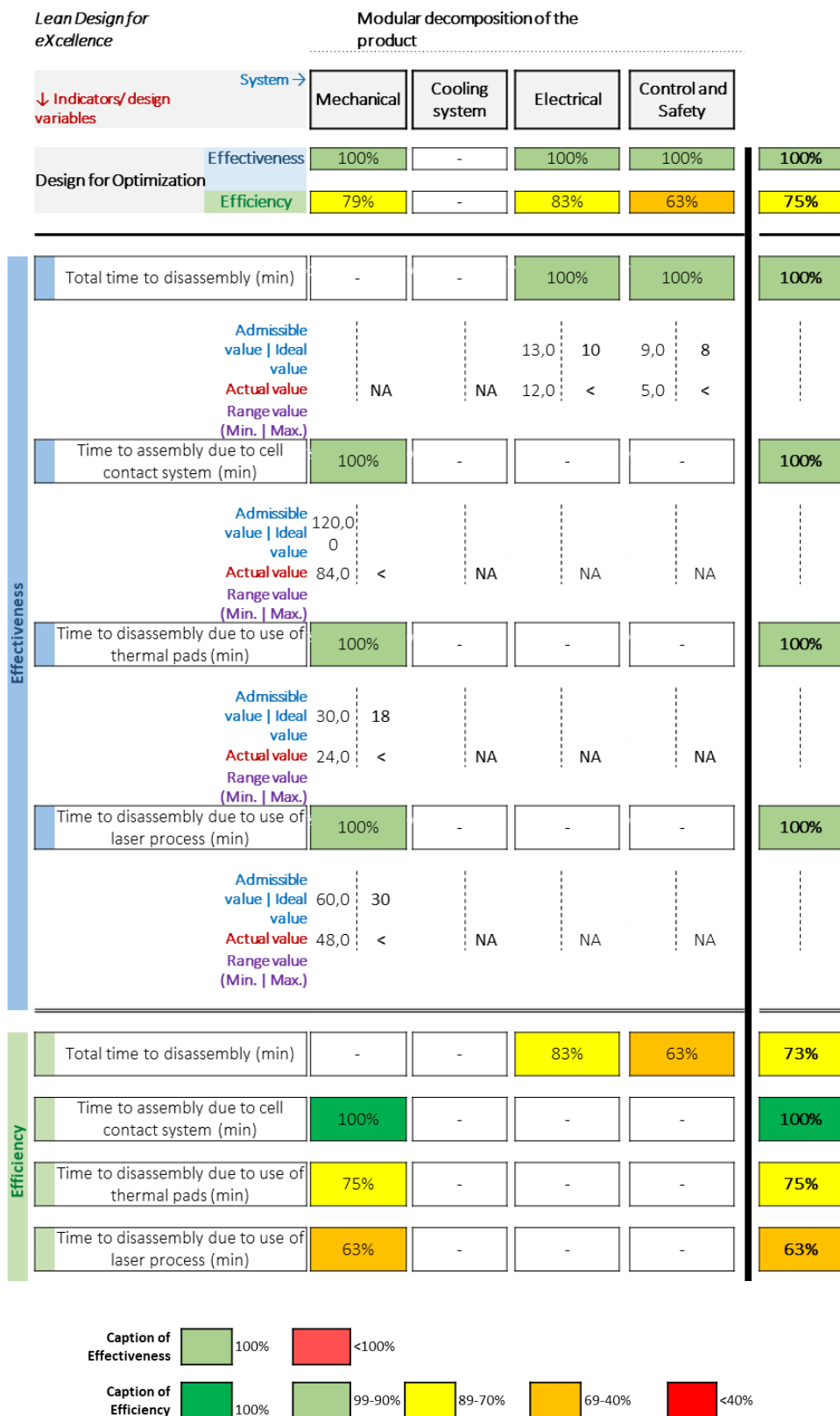


Figure 26. LDF-Second life for E-BUS use case.

LdF-Recyclability for E-BUS use case

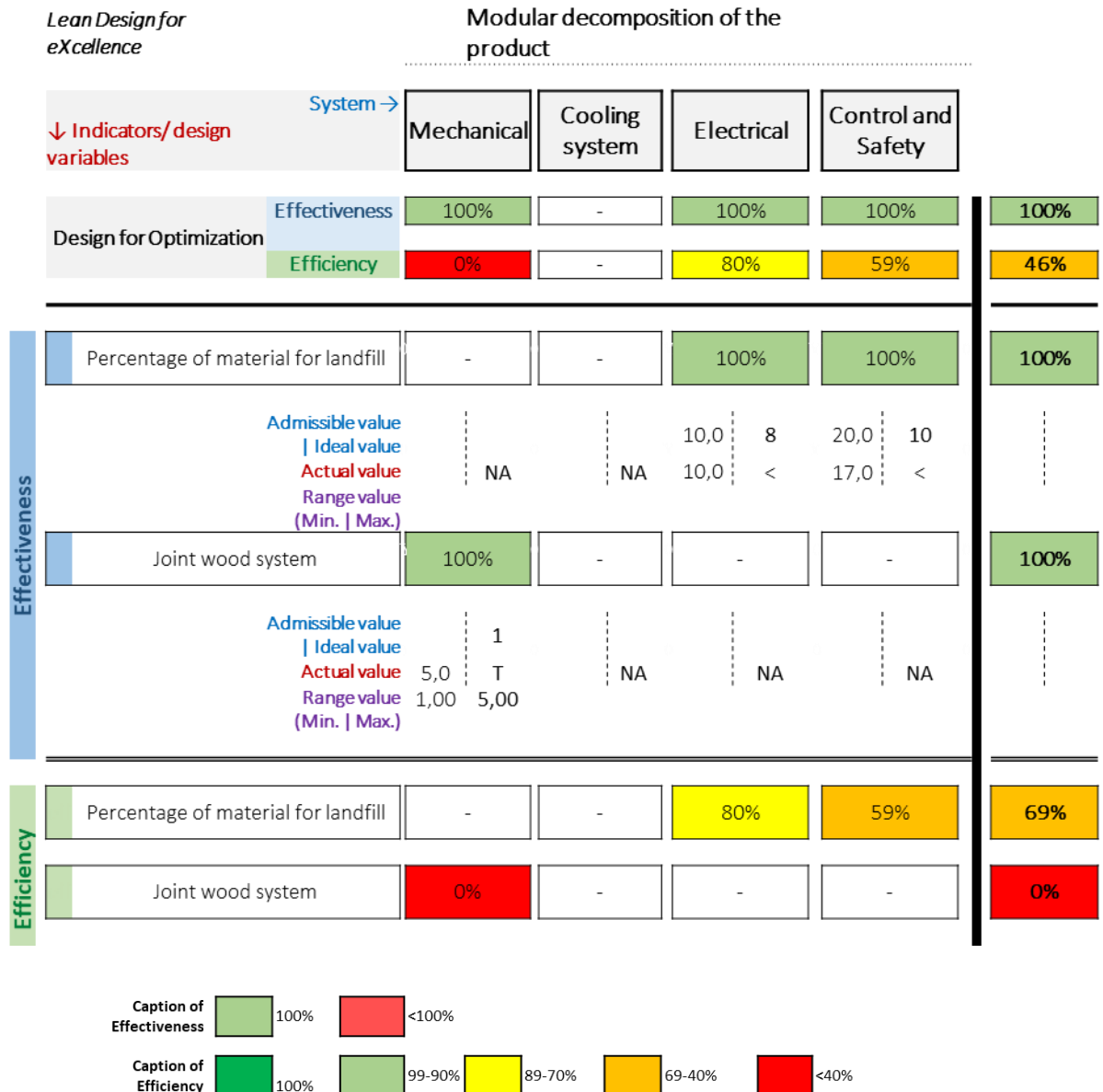


Figure 27. LdF-Recyclability for E-BUS use case. Concept 1.

LdF-Recyclability for E-BUS use case



Figure 28. LdF-Recyclability for E-BUS use case. Concept 2.

LDf-Recyclability for E-BUS use case



Figure 29. LDf-Recyclability for E-BUS use case. Concept 3.

LDF-Manufacturing for ESS use case

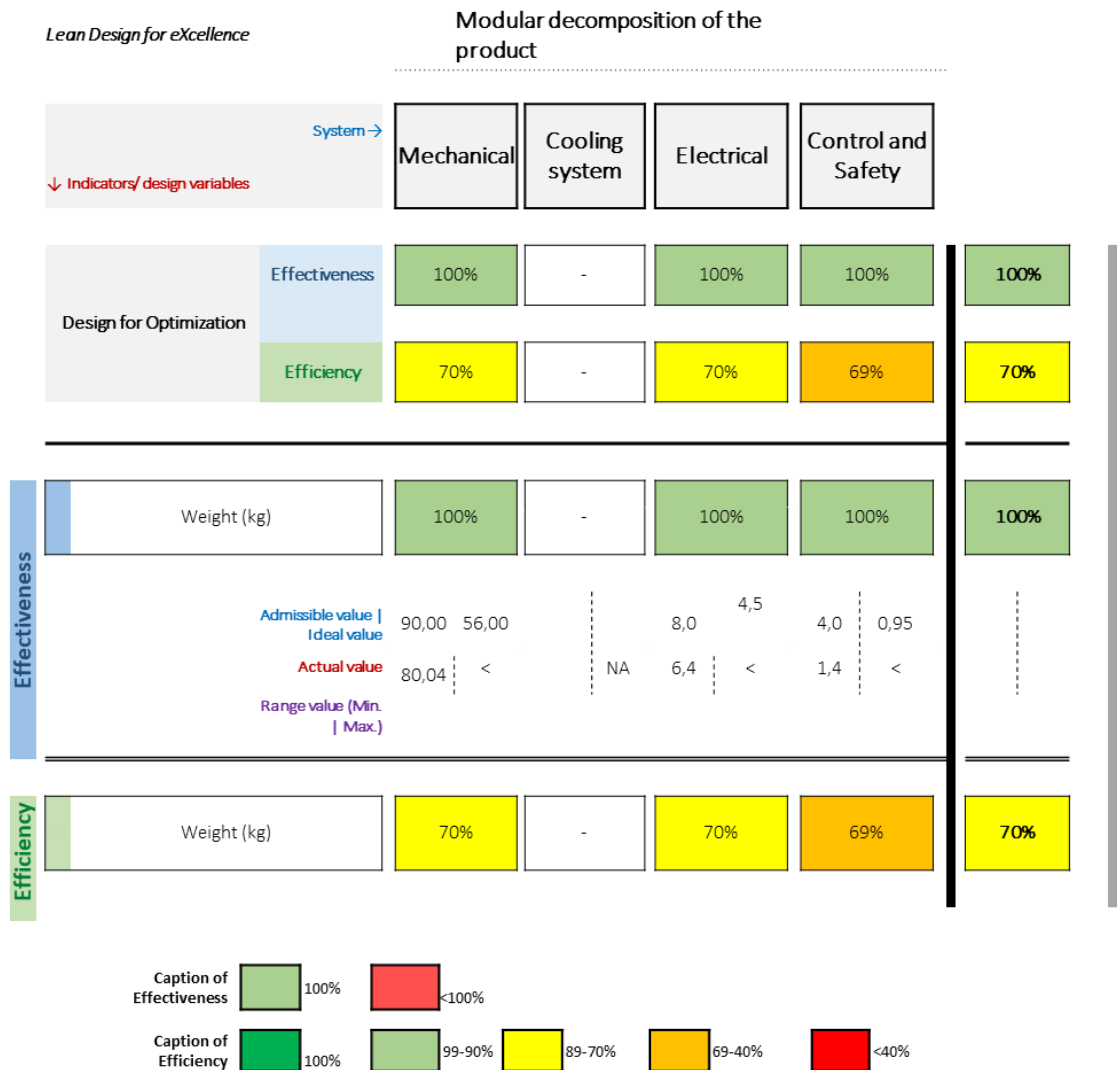


Figure 30. LDF-Manufacturing for ESS use case.

LDF-Second Life for ESS use case

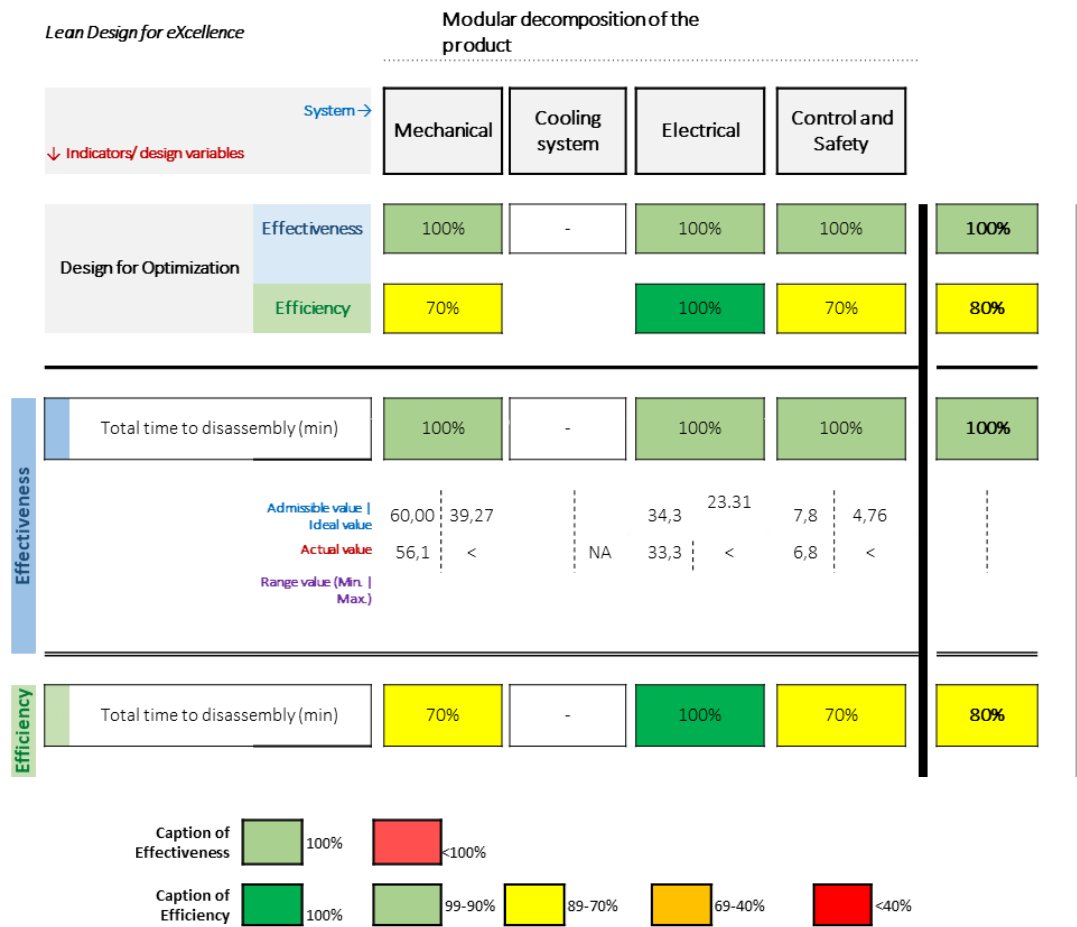


Figure 31. LDF-Second life for ESS use case.